



**REPUBLIC OF TÜRKİYE**

**KIRŞEHİR AHI EVRAN UNIVERSITY**



**INSTITUTE OF NATURAL AND APPLIED  
SCIENCES**

**DEPARTMENT OF MECHANICAL  
ENGINEERING**

# **DESIGN AND MODELING OF DUAL FLOW SOLAR AIR HEATER IN VARIABLE ABSORBER PLATE GEOMETRIES**

**LAYTH THAMER ZUBAIRI**

**MSc THESIS**

**KIRŞEHİR  
2023**



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MSc THESIS

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2023

**KIRŞEHİR AHI EVRAN UNIVERSITY**  
**INSTITUTE OF NATURAL AND APPLIED SCIENCES**  
**MSc THESIS**  
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Student  
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I dedicate my thesis.

To the person who provided me with generosity, strength, and dignity... my dear father.

To the person who gave me love, tenderness, giving, and loyalty... my dear mother.

To my support, my pride, my joy, and my honor...my dear brothers.

October, 2023

LAYTH THAMER ZUBAIRI

## GENİŞLETİLMİŞ ÖZET

### YÜKSEK LİSANS TEZİ

## DEĞİŞKEN EMİCİ PLAKA GEOMETRİLERİNDE ÇİFT AKIŞLI GÜNEŞLİ HAVA ISITICISININ TASARIMI VE MODELLENMESİ

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Bu çalışmada farklı tipte emici plakalara sahip çift akışlı güneş enerjili hava ısıtıcıların deneysel ve sayısal analizi sunulmaktadır. Çalışmada, optimum termal verimliliği belirlemek için ANSYS Fluent yazılımı kullanılmak üç tip emici plaka (düz plaka, trapez plaka ve iki farklı akıştaki U-oluklu plaka) hesaplamalı akışkanlar dinamiği (HAD) analiz yapılacak sonuçlama şümül edilmiştir. Deneysel açışmayı içeren düz plakalı, u-oluklu plakalı ve trapez plakalı bir güneş enerjili hava ısıtıcısının deneysel araştırması, Irak'ın Bağdat şehrinde açık havada gerçek hava koşullarında test edilmiştir. Oluklu ve düz plâkalı emicilerle birlikte kullanım ak üzere adaptif boyutlarda (100 x 50 x 15 cm) çift akışlar bir güneş enerjili hava ısıtıcı imal edilgi. Kollektörler arasındaki tek ayırım emici plakalardır. Geometri, kesit yüzey alan ve yalıtım malzemeleri dahil olmak üzere diğer tüm öz ellikler aynı kalmıştır. Tüm kolektörler, aynı meteorolojik koşullar ve eğim açıları altında güneşe maruz kalırken aynı hava kütlesi ve akış hızında çalıştılar. Bu çalışma esas olacak, düz plakalı güneş hava ısıtıcısını, sıradan pürüzsüz plaka ve oluklu plakalar gibi çeşitli emici plaka şekilleriyle deneysel ve sayısal olacak analiz etme ve karşılaştırmalı olacak verimlerini ortaya kaymağı amaçlamaktadır. Is transfer alanını arttırmak, elde edilecek güneş enerjili hava ısıtıcısının termal performansını ve buna bağlı olacak akış koşullarına göre sonunda kollektör verimliliğinin artmasını sağlar. Güneş enerjili hava ısıtıcılarının çalışma mekanizmaları genellikle basittir ve ısı transferindeki pasif iyileştirmeler en çok başvuru olan yöntemdir. Akış havasının plaka etrafında alt ve üst yüzeyi dolanarak ısı emiliminin sağlanması faydalıdır. Hava, emici plakaların üzerindeki çift akışlı güneş enerjili ısıtıcısıya girer ve hava sıcaklığını mümkün olduğunca maksimum düzeyde arttırmak için plakanın arka tarafına geri döner. Testlerde hava giriş hızı için dört farklı değer kullanıldı. Bu değerler 0.5, 1, 1.5 ve 2 m/s olmak üzere hava koşullarındaki minimum ve maksimum adaptif koşulları temsil etmektedir. Nümerik çalışmada, modelin geometrisi SOLIDWORKS 2018 yazılımı kullanılacak oluşturuldu ve ANSYS Fluent Workbench 2020 R2 kullanılarak hesaplamalar yapıldı ve simüle

edilgi. Deneysel testte, simülasyon kurulumunu doğrulamak ve simülasyonu belirlemek için Nisan 2022 ve Mayıs 2022'de Bağdat'ta birkaç gün boyunca gerçek hava koşullarında çift akışlı bir güneş hava ısıtıcı test edildi ve sistemin termal performansı belirlendi. Sonuçlar; düz plakalı, U-oluklu plakalı ve trapez plakalı güneş enerjili hava ısıtıcısının termal verimliliğinin sabit 0,0046 kg/s değerindeki kütle debisinde sırasıyla %43, %51, ve %54 olduğunu gösterdi. Bununla birlikte, çift akışlı güneş enerjili hava ısıtıcısının termal verimliliği, akışın yönü paralelden karşıt akışa değiştirildiğinde %51'den %56'ya yükseldiği belirlendi. U-oluklu plakalı güneş enerjili hava ısıtıcısının karşıt akışla diğer plakalardan optimum konfigürasyon sağladığı sonucuna varıldı. Ayrıca, yapılan testler, oluklu plakaların kullanılmasının, kollektörlerin verimliliğini ve havanın çıkış sıcaklığını arttırdığını ortaya koymuştur. Deney ve teorik araştırma sonuçlarına göre, aynı çalışma koşulları altında, çift akışlı oluklu i güneş hava ısıtıcısı, çift akışlı ve geleneksel düz plakalı güneş enerjili hava ısıtıcısından termal olarak daha iyi performans gösterir. Düz plaka üzerindeki oluk, emici plaka boyunca iyi bir hava akışı sağlar ve ısı transfer hızını artırır. Kollektörün akış yönünden ölü bölgelerini en aza indirir ve türbülanslı akış ortamları oluşturur. Hava akışına ters akışlı U-oluklu plaka en iyi modeldir ve 0.0046 kg/s kütle akış hızında termal verimlilik %56 olarak hesaplandı. Aynı kütle akış hızında iken düz plaka için %43, u-oluklu paralel hava akışına için 51% ve trapez plaka 54% değerleri hesaplandı. Ayrıca, sonuçlar  $\Delta T$  maksimum sıcaklık farkının, 0.0011 kg/s kütle akış hızında hava akışına zıt yöndeki U-oluklu plaka için 51 °C olduğunu göstermektedir. Aynı kütle akış hızında iken düz plaka için 47.4 °C, u-oluklu paralel hava akışına için 48.2 ve trapez plaka için 48.5 °C olarak ölçüldü. Nihai değerlendirme olarak nümerik analiz sonuçlarının ve deneysel sonuçların karşılaştırılmasında termal verimlilik ortalama değerinin %5.7 varyasyonla iyi bir uyum içinde olduğunu göstermektedir.

**Anahtar Kelimeler:** Güneş kollektörü, Hava Isıtıcı, HAD, Oluklu plaka, Trapez Kanal

## **ABSTRACT**

### **MASTER'S THESIS**

#### **DESIGN AND MODELING OF DUAL FLOW SOLAR AIR HEATER IN VARIABLE ABSORBER PLATE GEOMETRIES**

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This paper presents an experimental and numerical analysis of a dual-flow solar air heater (SAH) with 4 different types of absorber plates: flat, trapezoidal, and u-corrugated parallel and counter flow. The experimental study was conducted in Baghdad, Iraq (33.31°N, 44.36°E) and was carried out on different days between April and May 2022. It includes tests conducted under different outdoor weather conditions. The surface azimuth angle was zeroed by positioning the solar collector in a southerly orientation with a tilt angle from the horizontal. For the inlet conditions of the dual-flow SAH, the evaluation was performed using air flow rates ranging from 0.0011, 0.0023, 0.0036, and 0.0046 kg/s. Furthermore, numerical calculations were performed using ANSYS Fluent commercial software to compare the optimum thermal efficiencies of these three types of absorber plates, determine their performance, and validate them by computational fluid dynamics (CFD). The experimental results showed that the thermal efficiencies of solar air heaters with flat, U-groove, and trapezoidal plates were 43%, 51%, and 54%, respectively, at an inlet flow condition of 0.0046 kg/s. However, it was determined that the thermal efficiency of the SAH increased from 51% to 56% when applied for an airflow that is not parallel to the direction of the plate (counter flow). At this flow rate, the average efficiency of the dual-flow SAH with a flat plate was calculated to be 42.80%, 51.33% for a u-corrugated with parallel airflow, 54.38% for a trapezoidal corrugated plate with the reverse flow and 55.53% for a u -corrugated plate with the counter flow. It is concluded that the counter-flow u-corrugated plate heater is the optimum configuration and gives the best results compared to the other plates. A comparison of the simulated numerical calculations and experimental results showed good agreement with an average variation in thermal efficiency of 5.7%.

**Keywords:** Solar Air Heater (SAH), Solar collector, CFD, U -corrugated plate

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## LIST OF ICONS AND ABBREVIATIONS

| Abbreviations   | Explanation                                                                              |
|-----------------|------------------------------------------------------------------------------------------|
| Dual-Flow SAH   | : Dual-Flow Solar Air Heater                                                             |
| DPSAH           | : Double Pass Solar Air Heater                                                           |
| SPSAH           | : Single Pass Solar Air Heater                                                           |
| SAH             | : Solar Air Heater                                                                       |
| CFD             | : Computational fluid dynamic                                                            |
| Symbols         | Explanation                                                                              |
| $A_c$           | : Collector absorber area ( $m^2$ )                                                      |
| $A_{duct}$      | : Cross- sectional area of the round duct ( $m^2$ )                                      |
| $C_p$           | : Specific heat ( $J/kg\ K$ )                                                            |
| $d_{duct}$      | : Duct diameter (m)                                                                      |
| $D_h$           | : Hydraulic diameter (m)                                                                 |
| $h$             | : Convective heat transfer coefficient, $W/m^2\ K$                                       |
| $h_a$           | : Convective heat transfer coefficient between the glass and the ambient air, $W/m^2\ K$ |
| $h_r$           | : Radiation heat transfer coefficient, $W/m^2\ K$                                        |
| $I$             | : Solar radiation intensity ( $W/m^2$ )                                                  |
| $k$             | : Thermal conductivity of air ( $W/mK$ )                                                 |
| $\dot{m}$       | : Mass flow rate of air ( $kg/s$ )                                                       |
| $Q_u$           | : Energy gained (W)                                                                      |
| $Re$            | : Reynolds number                                                                        |
| $T_a$           | : Ambient air temperature ( $^{\circ}C$ )                                                |
| $T_{ap}$        | : Mean absorber plate temperature ( $^{\circ}C$ )                                        |
| $T_c$           | : Cover temperature ( $^{\circ}C$ )                                                      |
| $T_f$           | : Fluid temperature ( $^{\circ}C$ )                                                      |
| $T_i$           | : Fluid inlet temperature ( $^{\circ}C$ )                                                |
| $T_p$           | : Absorber plate surface temperature ( $^{\circ}C$ )                                     |
| $T_{base}$      | : Bottom plate temperature ( $^{\circ}C$ )                                               |
| $\Delta T$      | : Temperature difference of air flow ( $^{\circ}C$ )                                     |
| $U$             | : Overall heat loss coefficient $W/m^2\ K$                                               |
| $U_b$           | : Back loss coefficient $W/m^2\ K$                                                       |
| $U_e$           | : Edge loss coefficient $W/m^2\ K$                                                       |
| $U_t$           | : Top loss coefficient $W/m^2\ K$                                                        |
| $V_a$           | : Air velocity (m/s)                                                                     |
| Greek symbols   | Explanation                                                                              |
| $\varepsilon_p$ | : Emittance of absorber plate                                                            |
| $\varepsilon_c$ | : Emittance of glass cover                                                               |
| $\sigma$        | : Stephen-Boltzman constant                                                              |
| $\alpha$        | : Solar absorptance of collector plate                                                   |
| $\rho_a$        | : Air density ( $kg/m^3$ )                                                               |
| $\tau$          | : Solar transmittance of glazing                                                         |
| $\eta$          | : Thermal efficiency                                                                     |
| $\eta_d$        | : Daily thermal efficiency                                                               |
| $\mu$           | : Air viscosity ( $m^2/s$ )                                                              |

# 1. INTRODUCTION

## 1.1. Purpose

Along with increased worldwide population and energy demand, traditional fuel use is increasing. So order to supply the demand for energy in the coming years and for future generations to come, it is vital to find other sources of energy due to the quick depletion of fossil fuel supplies. We should remember that climate change and its close link to our global society's present and future energy requirements are arguably the greatest pressing threat to our planet. To counteract the adverse impacts of global changes in the climate, the growing threat of supply shortages, market instability, and air pollution, we must undertake efforts to make today's energy systems more sustainable.

The most widely used non-traditional energy source is solar power. When transformed into usable forms and used, it is high in performance, quantitatively plentiful, widely accessible, almost endless, and has no negative environmental effects (Smil, 2006).

The amount of energy from the sun reaching the Earth's surface is so massive that in only one year, it is more than double as much as what can be gotten using all of the planet's fossil fuels combined—natural gas, oil, coal, and mining nuclear fuel (Hermann, 2006). Nevertheless, it is available only occasionally or during the day. Additionally, it is affected by climatic and meteorological factors. Renewable energy from the sun is an important source of energy, and numerous applications for this abundant, clean, and secure source have been investigated. The major uses of solar energy are photovoltaic systems and solar agricultural drying. One of the key prerequisites for making solar energy economically feasible (Sukhatme, 1999).

Solar heating methods are categorized into two types: passive heating and active heating. Passive and active heating. Passive solar strategies include creating rooms for natural circulation, orienting buildings toward the Sun, and using high thermal conductivity materials. Active solar methods involve converting solar energy into usable output using solar panel collectors, pumps, or fans (Sukhatme, 1999).

SAHs are technologies that make use of solar irradiance for several applications. These technologies are easy and inexpensive to build. SAHs are primarily made up of a translucent cover, an absorbent surface, and insulating material. The air flows into the passage produced by the absorbent surface and the translucent cover. The absorber plate absorbs solar irradiance. The heat the air collects as it flows through the passage raises its

temperature. This hot air may be utilized for a variety of purposes, including agricultural drying, room cooling, heating, heating water, and industrial process heating (Duffy and Beckman, 2013).

This work aims to analyze experimentally and numerically the flat plate SAH with several shapes of absorber plates, such as ordinary smooth plate and corrugated plates that were to enhance the area of heat transfer, and the solar air heater's thermal performance will be attained if the air flows separately over and under these types of plates, resulting in enhanced collector efficiency. The work will be carried out experimentally by building a test rig, including the double pass flow collector and all measurement devices required to evaluate the collector's efficiency. Moreover, a numerical study using the latest version of the ANSYS Fluent Workbench 2020 R2 software will be used to validate the experimental results and give an extension to the experimental work by taking some important dimensions related to the geometry of the absorber plate that cannot be estimated during the experimental procedure. The effect of many parameters will be examined and discussed to get the optimal efficiency value.

## 1.2. Types of Solar Collectors

The solar collector is at the core of any solar energy collection technology suited for operating in low to medium temperatures. The two main types of solar collectors are fixed and tracked collectors. Tracking collectors move with the sun, whereas fixed collectors remain stationary, so outgoing solar irradiance always falls straight to collectors, as illustrated in Fig. 1.1. Tracking solar collectors are classified into two types: single-axis tracking and dual-axis tracking. There are three types of fixed collectors: evacuated tube collectors (ETC), compound parabolic collectors (CPC), and flat plate collectors (FPC). There are three types of single-axis tracking collectors: parabolic trough collectors, cylindrical trough collectors, and linear fresnel reflectors (Hirahara and Prasad, 2018; Kafais et al., 2015).

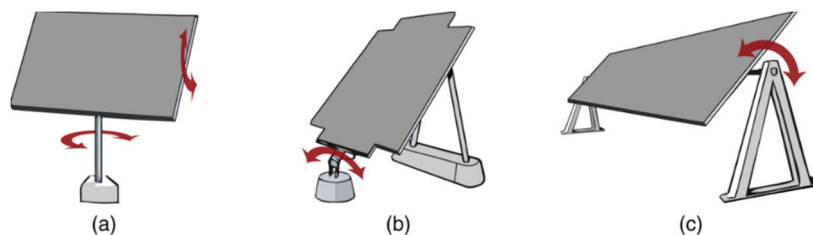


**Figure 1.1. Solar tracker schematic**

(a) double tracker, (b) polar aligned single-axis tracking system, (c) horizontal single-axis tracking system

A flat plate collector is the most common form since it is easy to design, inexpensive to build, simple to operate, and requires minimal maintenance. It is suitable for a wide range of temperatures and uses (Sukhatme, 1999). The commonly used technique is to expose a black surface to solar irradiance for the energy to be absorbed. In addition, it is regarded as a form of heat exchanger that turns solar irradiance into heat. A solar collector varies from more traditional heat exchangers in various ways. The latter often achieve a fluid-to-fluid exchange at maximum heat transfer rates, with radiation as a minor influence. The solar collector transfers energy from a distant source of radiant radiation to a fluid (Duffy and Beckman, 2013)

Furthermore, solar collectors are classified into two categories according to the fluid that is used: air and water. Water is commonly utilized in fluid collectors, whereas air is employed in gas collectors. Because gas has poorer thermodynamic characteristics for heat transport than water, SAH efficiency is inherently low. As a result, various types of SAHs have been presented in past years to enhance their effectiveness (Irfan and Emre, 2006).

### **1.3. Solar Air Heaters**

Solar air heating is a technology that utilizes solar irradiance. The irradiance is gathered and utilized to heat air via an absorbing layer. Is often the least expensive of all solar technologies, especially in industrial and commercial processes, because it meets the most common uses of the energy of building in heating climes, namely heating systems and industrial operations heating (Duffy and Beckman, 2013).

SAHs are devices that make use of solar irradiance to obtain clean energy for a number of applications and are primarily made up of a transparent cover, an absorbent plate, one or more airflow passages, and insulating material for the bottom and lateral edges of the solar collector. The utilization of a blower for air supply is optional (Duffy and Beckman, 2013; Irfan and Emre, 2006).

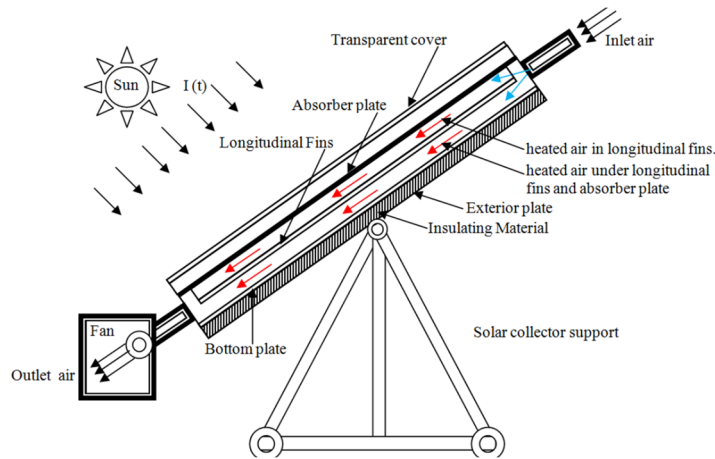


**Figure 1.2.** Schematic of the SAH using air blower

## 1.4. Solar Air Heaters Types

SAHs can be divided into two types. The first type is concerned with the airflow channel arrangement. Several airflow passage arrangements will be developed to enhance system efficiency. This category contains four sub-titles that express the various configurations. Single-flow double pass, single-flow single pass, single-flow recycled double-pass, and double-flow single-pass are the subcategories (Maraba, 2012).

The second category is concerned with the design of the air passage. The air passage design has a considerable impact on system efficiency. As a result, solar collectors may be designed in several ways. Furthermore, this type can potentially be divided into three sub-types, which are as follows: porous media assisted, extended surface assisted, and flat plate. All major and minor types are detailed further below (Maraba, 2012).

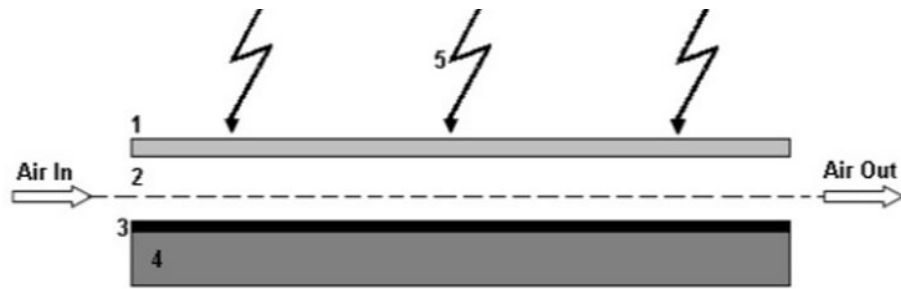
### 1.4.1. Categorization based on airflow channel

In solar air heater research, the first category is “Categorization based on airflow channel”. This classification is separated into four major configurations. Because the airflow passage layout affects the effectiveness and output temperature of the SAH, studies investigate a wide range of airflow channel configurations (Maraba, 2012). The objective and techniques for creating various air channel flow configurations are detailed in this section of the thesis.

#### 1.4.1.1. Single flow single pass

This is the most common and fundamental form of air heating equipment. This form of SAH included a passageway for airflow, insulation for storing lost heat energy and converting it to usable energy, and transparent material (a cover made of glass to

transmit solar irradiance on absorbent) as shown in Fig.1.1. Polyurethane, glass wool, or rock wool can be used as insulation, which is for limiting heat loss to the surroundings. In contrast, the absorber plates can use copper or aluminum, which have high absorptivity and higher thermal conductivity values. Solar irradiance gets captured by the absorbent plate after passing through the glazing cover. Since the absorbent plate bottom is isolated, its temperature rises. The heated absorbent plate transfers heat to the air passing above it (Kumar et al., 2019).



**1. Galss cover (one or more), 2. Air flow channel, 3. Smooth absorber plate, 4. Insulation, 5. Solar radiation**

**Figure 1.3.** A single flow single pass schematic

#### 1.4.1.2. Double flow single pass

The single flow single pass SAH and the double flow single pass solar air heater are extremely similar. The main distinction is that two absorber plates are placed between the glass and insulation materials. As illustrated in Fig. 1.2, a double flow single pass SAH has two air passages. A cover glass and absorber plate are used in the top passage. The second passage, constructed under the first one, comprises the same absorber plate (above) and insulation plate as the first (on the bottom). The air entering the collector is split into two halves, which promotes thermal heat transfer from the absorber plate and raises the air temperature at the output. The airflow enters and exits the upper and lower channels directly in one direction; for this cause, this type of SAH is called a "double flow single pass." This type's thermal performance may be higher than that of a single pass flow type for the same mass flow rate (Velmurugan and Kalaivanan, 2016).

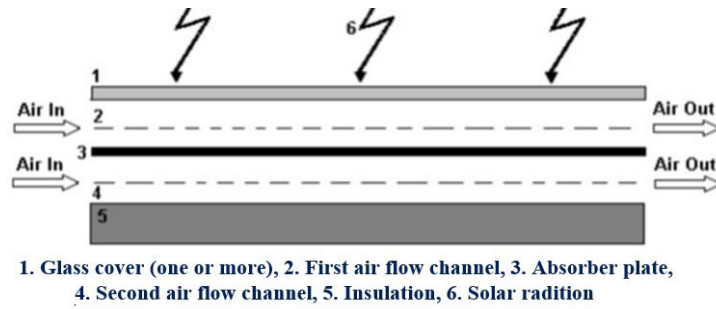
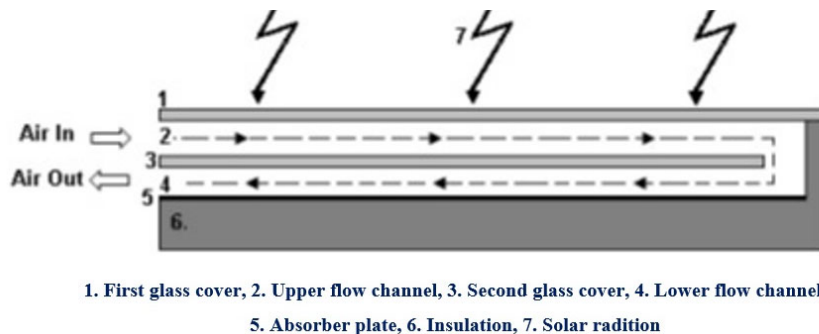


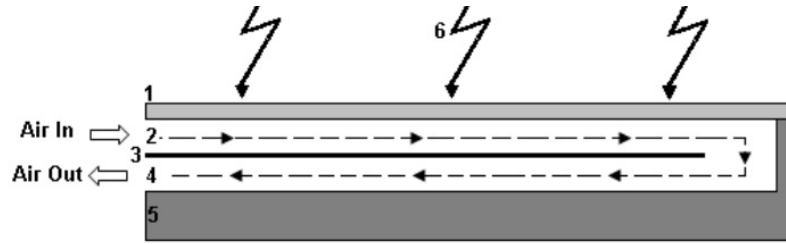
**Figure 1.4.** Double flow single pass schematic

#### 1.4.1.3. Single flow double pass

The primary purpose of using a two-pass configuration is to limit the loss of heat to the external environment from the front of the SAH surface while simultaneously boosting the system's thermal efficiency. A single-flow double-pass SAH has two overlapping airflow channels. Air flows from the top passage, turns around at the top passage's end, and enters the lower passage. It flows directly through the bottom passage. This is the primary reason why a SAH is classified as a single-flow double-pass in the literature. Two various configurations of a single-flow double-pass SAH are mentioned. One of these is shown in Fig. 1.3 (a). Two overlapping air flow passages can be seen. A glass (or transparent layer) separates these channels, and an absorbent plate is put on the bottom side of the lower passage. The absorber receives air from the primary and secondary glazing panels. The absorber's bottom side is insulated. The absorbent plate is used as a divider between the upper and lower passages in the second configuration, as shown in Fig. 1.3 (b). The glass cover and the absorbent plate create the top airflow passage, while the lower airflow passage is produced by the same absorbent plate and the bottom plate that is insulated (Maraba, 2012; Velmurugan and Kalaivanan, 2016; Fatah et al., 2015).



(a)



1. Glass cover (one or more), 2. First air flow channel, 3. Absorber plate,  
4. Second air flow channel, 5. Insulation, 6. Solar radiation

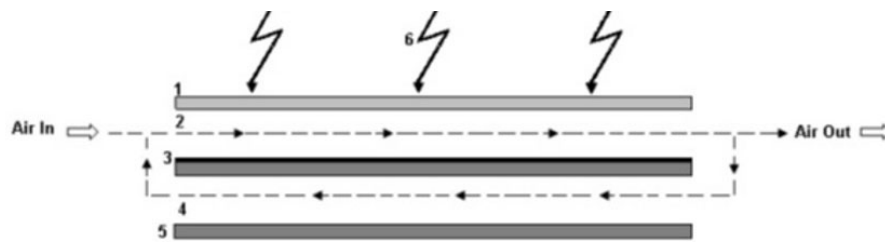
(b)

**Figure 1.5.** A schematic of double pass single-flow SAH

(a) Double-pass SAH with transparent layer, (b) Double-pass SAH with absorbent plate

#### 1.4.1.4. Single-flow recycled double- pass

Using recycled hot air in the construction of a SAH may increase its effectiveness and allow the temperature of air output to be modified (Choudhury and Garg, 1995). If the outlet temperature differs from the desired temperature, a partial recirculation of the heated air could deliver the appropriate temperature of the air at the airflow departure. Fig. 1. 4 shows the solar air heater is made up of two passages. The cover is glass cover and the beneath-positioned absorber plate makes up the upper passage (on top). The other channel's walls are lined with insulation. The hot air passes into the bottom passage and enters the primary airflow passage. The system only has a single input and outflow. Therefore, this model of the SAH is known as a single-flow recycled double-pass heater (Alvarez et al., 2004).



1. Glass cover (one or more), 2. Air flow channel, 3. Absorber plate,  
4. Recycling channel, 5. Insulation, 6. Solar radiation

**Figure 1.6.** A single-flow recycled double-pass

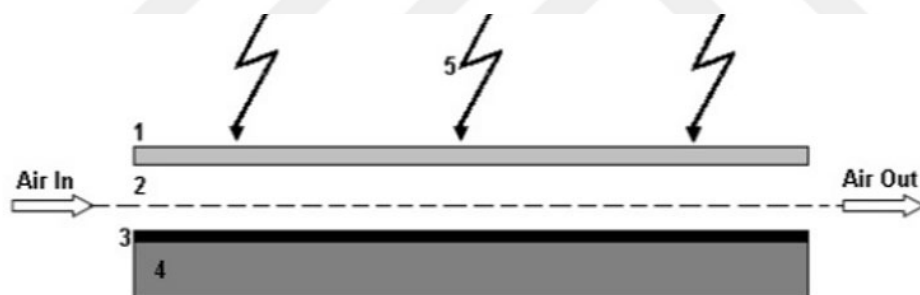
#### 1.4.2. Categorization based on air channel design

SAHs in the study can also be classified depending on their air channel design. The SAH channel design may be categorized into four types. The thermal performance

of a SAH may be considerably increased by modifying the design of the air channel. The various types of air channel designs will be illustrated.

#### 1.4.2.1. Flat plate

Researchers have focused their efforts on analyzing flat plate SAH through experimental tests for costs and performance study of SAH with two passes (Gaur, 2010). The flat plate is the most basic type of SAH. As illustrated in Fig. 1.5, this type of SAH comprises an absorbent plate and one or more coverings of glass. To avoid heat loss, all edges of the SAH, except the cover of glass, should be insulated adequately. The airflow might be below or above the absorbent plate. Flat plate SAHs are available in double-pass, single-pass, double-flow, and recycling configurations. The absorbent plate is normally flat, with no fins, obstacles, or roughness elements. As a result, this form of SAH is known as a "Flat Air Channel." A flat air channel SAH is inexpensive due to its basic design. As no system or technology is applied to improve channel heat transmission, the performance of this type of SAH is lesser than that of other models (Gupta et al., 2013).



**1. Glass cover (one or more), 2. Air flow channel, 3. Smooth absorber plate, 4. Insulation, 5. Solar radiation**

**Figure 1.7. A flat plate SAH**

#### 1.4.2.2. Extended surface

Many configurations have been developed to improve the poor performance of flat air passage SAHs. Many absorber changes were investigated because the type of absorbent plate is one of the most critical parameters affecting the efficiency of SAH. Extending the absorbent plate's surface area can be an effective technique to increase the effectiveness of SAHs. Attaching ribs, fins, barriers, or any other rougher factor (any feature that generates rougher on the absorbent plate) to the absorbent plate, as shown in Fig. 1.6, may enhance the SAH's surface area. A SAH with an expanded surface of the air passage features a translucent covering, an insulating substance, and a rough absorber

plate that absorbs solar irradiance. The rough features or fins on the absorbent plate enhance the absorbing area and mix the air passing through the passage, increasing the heat transfer coefficient. A SAH with an extending surface channel can be constructed as a double-pass, single-pass, double-flow, or recycled type. Despite the inclusion of the features of rough features or fins enhancing the area of surface and coefficient of heat transfer, it also increases the pressure drop down the passage. A rise in the channel's pressure drop will ensue, as will an increase in the required power of the blower or fan that supplies air to the heater. As a result, many studies have focused on developing roughness elements or fin geometries (Omojaro and Aldabbagh, 2010).

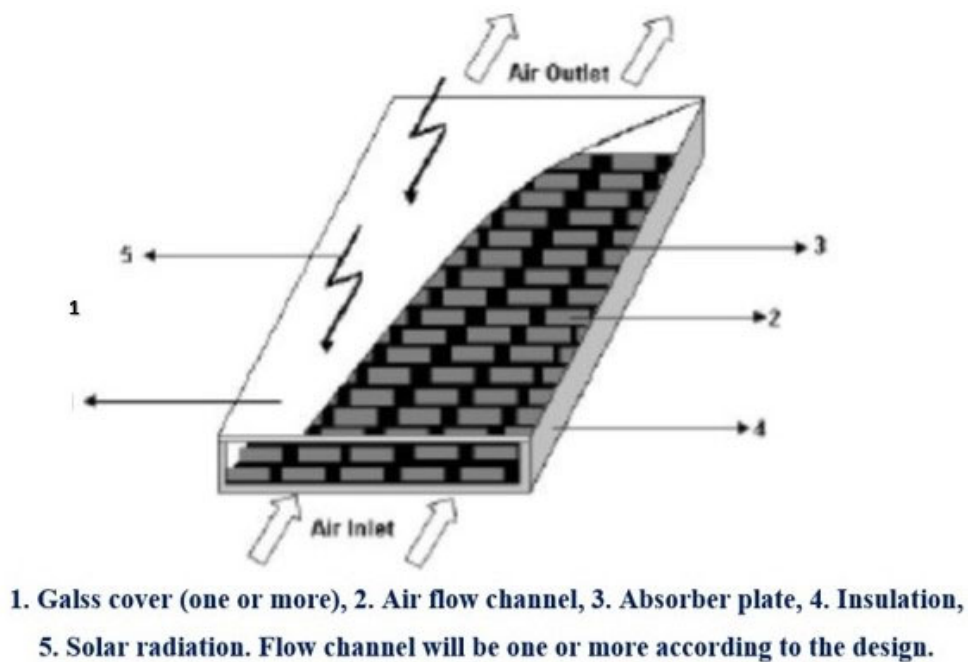


**Figure 1.8.** The absorber plate with fins

#### 1.4.2.3. Porous media

Experimentation with single-pass SAH and various porous mediums was carried out (Prasad et al., 2009). Their results showed that employing metal wool as a porous medium for solar heating was more efficient than using glass wool or a typical SAH. The SAH passage with a porous media may be a good technique to enhance the output temperature of air and thermal performance. These SAHs comprise a transparent cover, a layer of insulation, an absorbent plate, and a porous media, as shown in Fig. 1.7. The porous media was placed in the SAH's channel flow. The air passes through the passage in touch with the porous media, which is in touch with the absorbent plate..

Porous media SAHs may be configured as double-pass, single-pass, or recycled assistance. However, they were often single-flow double-pass systems. To expedite heat transmission between the porous material and the air moving through the passage, the porous material can be used as a highly conductive material. Although lowering the porosity enhances the efficient heat transfer coefficient, it also raises the pressure drop through the passage. As a result, studies on the properties of porous media have been done to construct a system having a low-pressure drop but a high heat transfer rate (Sopiana et al., 1999).

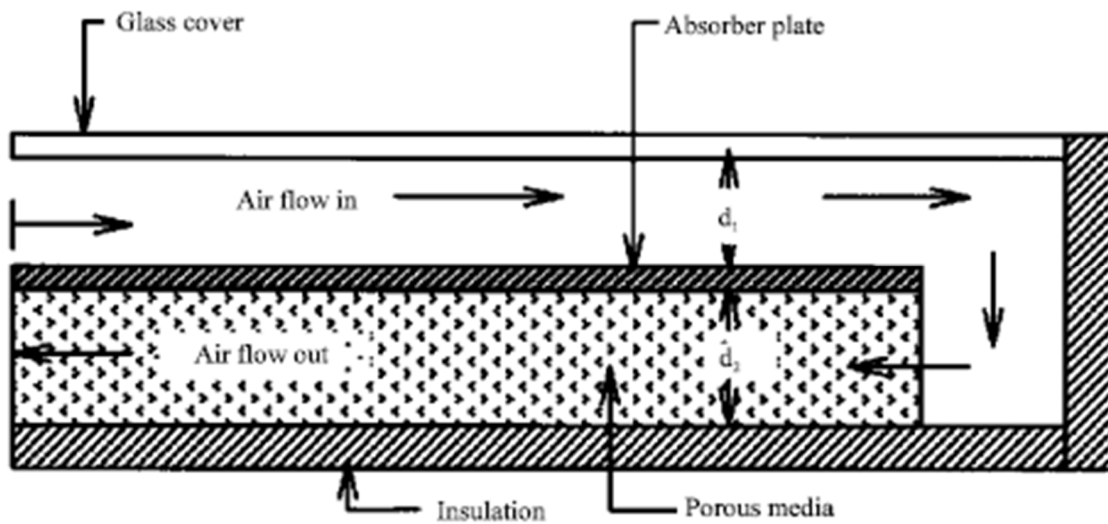


**Figure 1.9.** A cross-section of a DPSAH

#### 1.4.2.4. Corrugated absorber plate

Air moving parallel to the corrugation patterns, i.e., over the highs and lows, causes turbulence across the plate, increasing the convective heat transfer coefficient, as seen in Fig. 1.8. Several studies have found that the inclination of the corrugation angle is a significant factor in determining collector performance. This is because pressure drop and heat transmission rely entirely on the flow pattern, which is greatly influenced by the tilt angle. Corrugated absorber plate SAH can be configured as double-pass, single-pass, or recycled assistance. It is advised to employ a tilt angle between  $60^\circ$  and  $30^\circ$  for an optimal balance between increasing the heat transfer coefficient and increasing the pressure drop (Metwally et al., 1997).

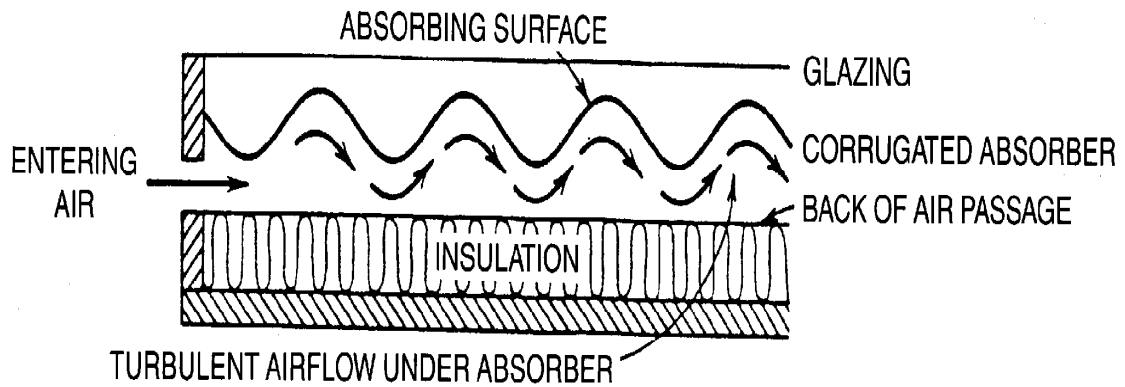


**Figure 1.10.** A cross-section view of corrugated absorber plate

### **1.5. Advantages of Solar Air Heaters**

- Improved solar heat timing using a thermal wall; heat is released from the wall without sun irradiation.
- They reduce the building's energy consumption costs.
- Compared to water collectors, they do not require antifreeze chemicals and do not cost the building anything if broken.
- They can work with HVAC systems to pre-heat air, for example.
- They may be used in highly low-energy residential, commercial, and institutional buildings (Piotr, 2010).



## **2. LITERATURE REVIEW**

### **2.1. General**

This chapter comprehensively reviewed theoretical and experimental studies on various types of SAHs that utilized different absorber plates in conformance with various methods for improving the efficiency of the SAH mentioned in previous chapters of this study. At last, an overview of certain significant study results is provided.

Considering its safety and efficacy, typical SAH applications have two main drawbacks: first, SAH has a poor convection coefficient and loses energy to the surroundings. As a result, multiple investigators have enhanced the performance of SAH by expanding convection area and inducing turbulent flow, which was accomplished through various ways such as expanded surfaces, i.e. fins or obstacles, (Alam and Kim, 2016) investigated numerically into the enhancement of thermal-hydraulic performance in a solar air heater duct featuring obstructions (Gilani et al., 2017) used of pin protrusions on the absorber to improve the performance of a free convective solar air heater, porous materials, (Dissa et al., 2016) a solar air collector with a combined 'porous' and 'non-porous' combined absorber was investigated, (Bayrak et al., 2013) energy and exergy evaluations of SAHs with porous baffle for use in construction, corrugated or grooved absorber, (Gao et al., 2007) The thermal efficiency of cross-corrugated and flat-plate SAHs has been studied experimentally and analytically, (Liu et al., 2007) a comparison of the thermal efficiencies of cross-corrugated and v-groove SAH, and roughened absorber, (Kumar et al., 2017) thermal and thermohydraulic effectiveness of three-sided artificially roughened SAHs, (Hans et al., 2010) heat transfer and coefficient of friction relationships for a SAH duct roughened artificially with several v-ribs. Also, a new method helps to improve the exchange of energy and reduce energy losses by applying various techniques, such as collector double-pass flow (Ramaniet al., 2010) study a DPSAH's performance, and double-glazed coverings (Alta et al., 2010). A DPSAH is one of the most current ways used to increase thermal performance by expanding the total area passing double channels.

### **2.2. Experimental Studies**

There are some researchers conducted studies and experimentation on the effectiveness of a conventional DPSAH with various constructions and airflow rates. Wijeyesundera et al. (1982) conducted a comparison of SPSAH and DPSAH systems. The SAH area was 1269 mm<sup>2</sup>, and the air gaps were 38.1mm. Within the designed conditions

(air mass flow rate ( $\dot{m}$ ) = 0.005-0.1 kg/sec.m<sup>2</sup>, solar irradiance = 600-1000 W/m<sup>2</sup>, and  $T_{am}$  = 28 °C). Under the same operating circumstances, they conducted that the thermal performance of a DPSAH was 10-15% greater than that of a SPSAH.

Moreover, Ucar et al. (2006) found in this experimental study that the form and configuration of collector absorbent surfaces were rearranged to produce improved heat transmission surfaces appropriate for passively efficient heat transmission methods. The performance of such SAHs with staggered absorbent plates and connected fins on the absorbent surface was examined, as illustrated in Fig. 2.1. The energy relationships for several SAHs were provided. It was discovered that the largest irreversibility appears at the traditional SAH, where the SAH efficiency is the lowest. Using the current techniques, which include dividing 3 or 6 panels to the absorbent surface, adding fins to the absorbent surface, and providing a tilt angle (2°) to the 3 panels absorbent surface, the performance of the SAH has enhanced from 10% to 30% in contrast to the traditional SAH. The traditional SAH has maximum irreversibility since merely a tiny percentage of the solar energy captured by the collector may be utilized.

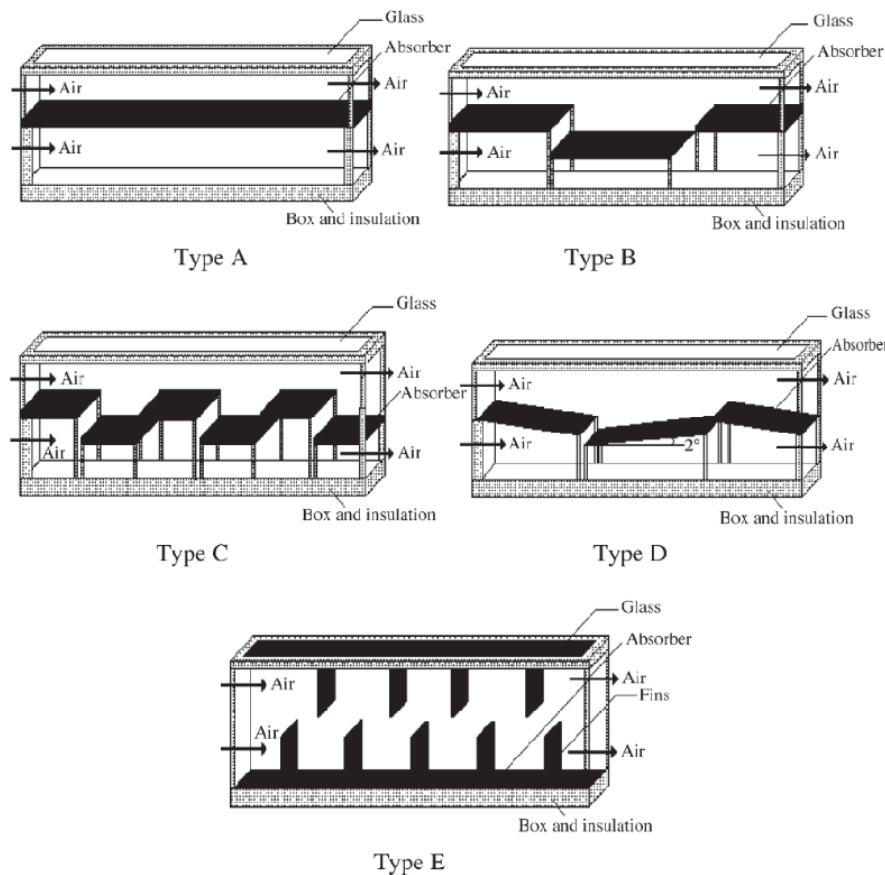


**Figure 2.1.** Schematic of a cross-sectional view of some studies SAHs (Ucar et al., 2006)

In addition, double and single-pass SAHs using wire-mesh steel sheets were experimentally studied by Aldabbagh et al. (2010). The structure was made with a thickness of 2 cm, black-painted plywood with a size of 150 x 100 cm, as indicated in Fig 2.2. The construction of the SAH utilized double regular window glasses with a 4 mm thickness. The top and the bottom glazing covers were 5 cm separated, while the gap between the bottom glass and wire-mesh steel sheets was 10 cm. The design might be utilized as a SPSAH by removing the top glass cover. In the collector's second channel, ten black-coated steel wire meshes were installed. The wires had a cross-sectional size of 2 x 2 mm and were separated 10 mm apart. Since the layers worked as absorbers in this configuration, no additional absorbent plate was required in the SAH. The airflow rate of the mass was changed during the tests from 0.012 to 0.038 kg/s to investigate the effect of airflow of the mass on the effectiveness of the SAH. It was found that the performance of the SAH may be enhanced in comparison to the standard type by employing wire-mesh steel sheets as the absorbent plate. Furthermore, when the flow rate increased, the performance of the SAH enhanced in both cases. Maximum efficiency for SPSAH and DPSAH at a mass flow rate of 0.038 kg/s was 45.93 % and 83.65 %, respectively.

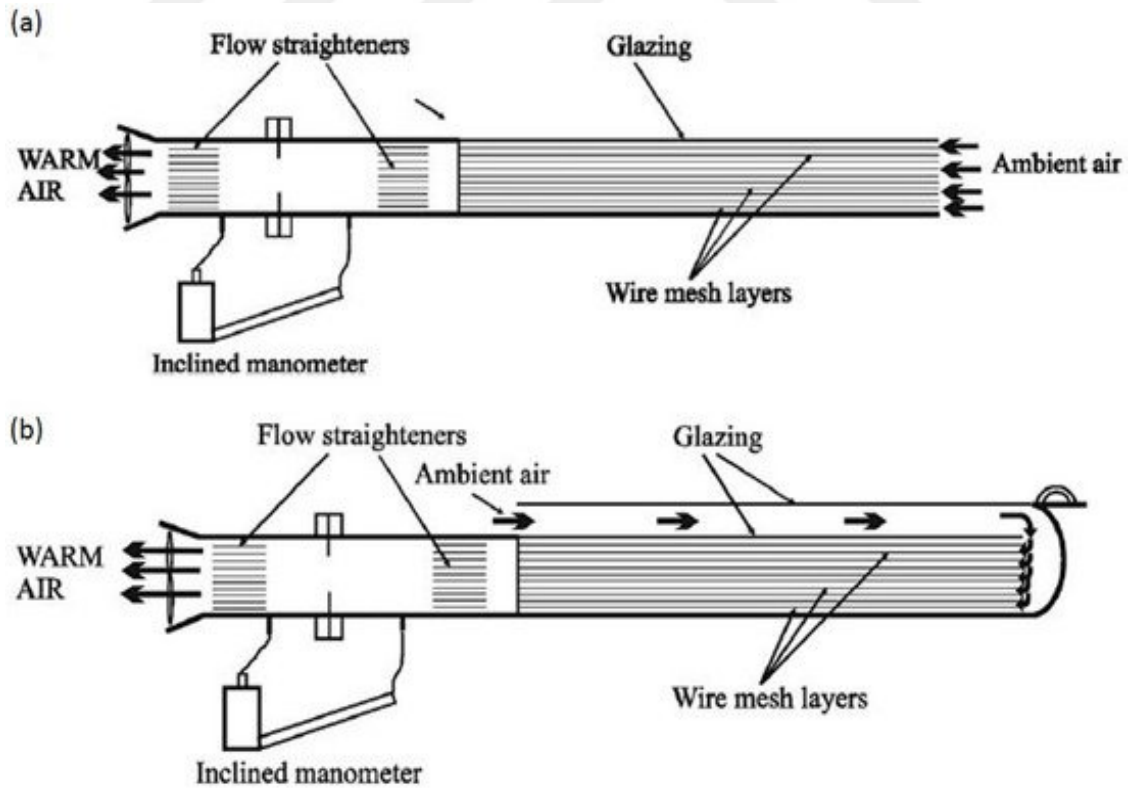


**Figure 2.2.** Schematic view of SAH  
(a) SPSAH , (b) DPSAH using a packed bed (Aldabbagh et al., 2010)

Chabane et al. (2013) observed that introducing manufactured rougher on the hot surface (i.e., the absorbent plate) of a SAH channel can improve heat transfer. Vertical fins were utilized under the absorbent plate to improve heat transfer and equalize the flow of air in the passage, as illustrated in Fig. 2.3. The relationship between the airflow rate of mass flow rate and the solar collector's thickness and heat transfer, and outlet air temperature has been investigated. The influence of factors on heat transmission was compared to the conclusion of a flat channel according to comparable flow circumstances. In tests, an airflow rate of mass of  $m = 0.016 \text{ kg/s}$  was used. Thus, the highest efficiency rates with and without utilizing fins were 51.50 % and 43.94 %, respectively.

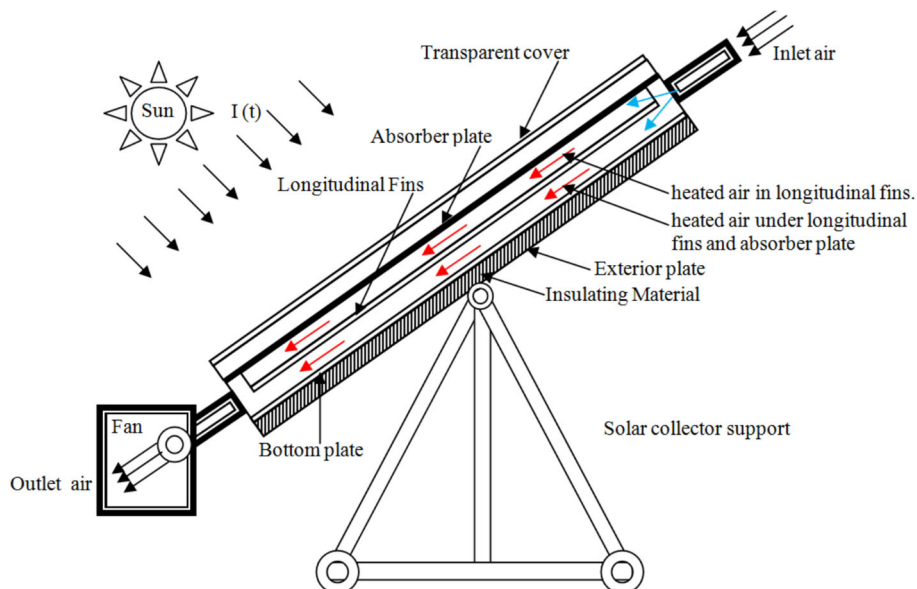


**Figure 2.3.** Schematic of the SAH  
(Chabane et al., 2013)

Also, different types of SPSAH and DPSAH were designed by Hernandez and Quinonez (2013); the dimensions of all three SAHs were 200 cm x 90 cm x 2.5 cm. The findings showed that, according to the same operational conditions (wind speed 1.7 m/sec, mass flow rate 0.04 kg/sec, and  $T_{am}=20-24 \text{ }^{\circ}\text{C}$ ), the counter flow DPSAH had a better outlet air temperature, maximum gained energy, and maximum efficiency when compared to SPSAH and parallel DPSAH, as shown in Fig. 2.4. It also was determined that for the 10 hours of sunshine, the thermal performance with a maximum output air temperature was 57 % with 46.4  $^{\circ}\text{C}$  for the counter DPSAH, 51% with 42.5  $^{\circ}\text{C}$  for the parallel DPSAH, and 46 % with 40.7  $^{\circ}\text{C}$  for the SPSAH.

However, in comparison to other SAHs, the air gains a lot of gained energy by passing over the absorber and flowing under the absorber plate of a DPSAH with the

counter flow and a larger convective area. Furthermore, energy losses were decreased, and the SAH's efficiency and design were optimized.

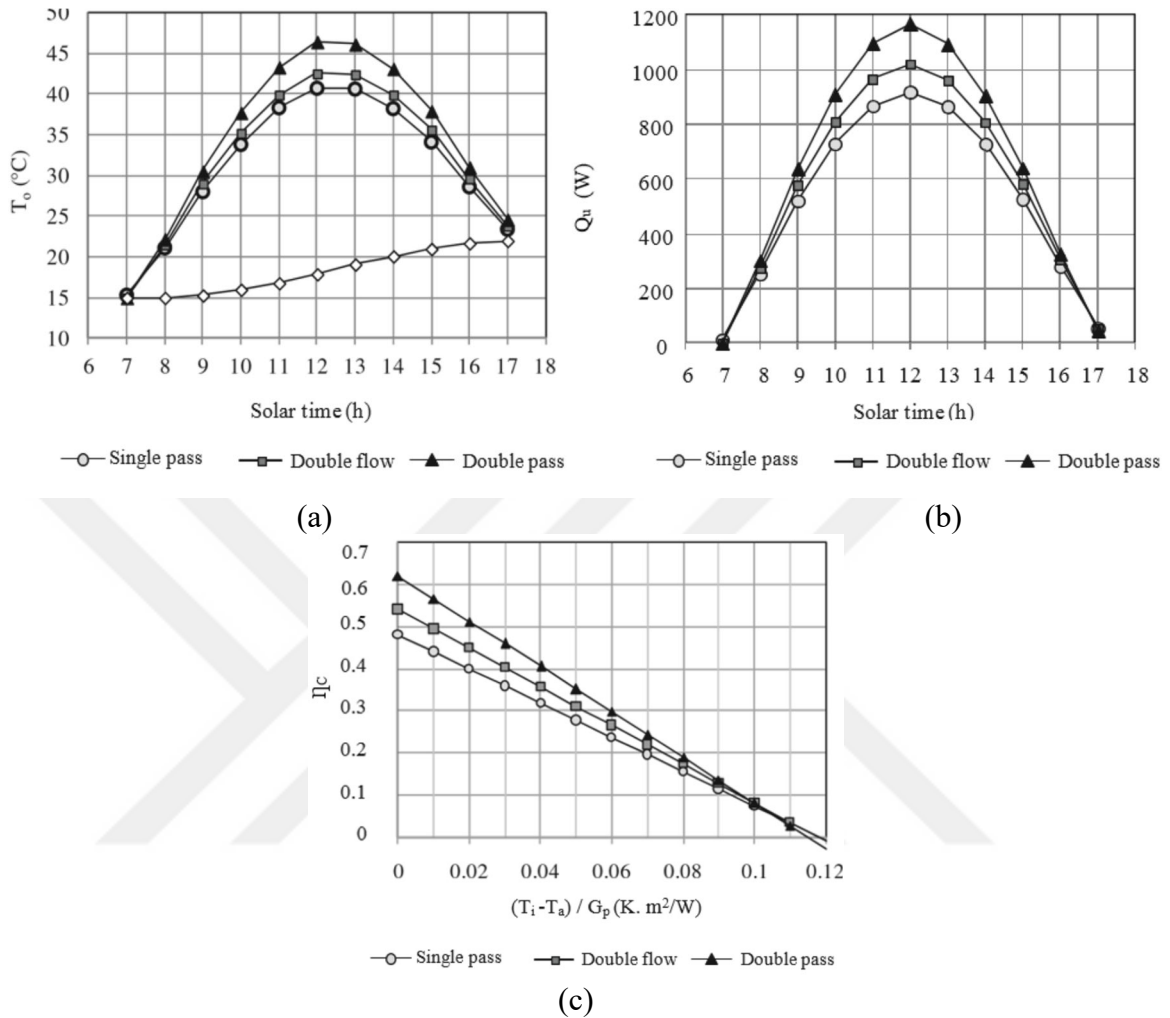


**Figure 2.4.** A compared of the 3 types solar air heaters  
(a) Out put air temperature ( $T_o$ ) vs time of the solar, (b) Gained energy ( $Q_u$ ) vs time of the solar, (c) SAH effectiveness ( $\eta_c$ ) vs  $((T_i - T_a) / G_p)$  ratio (Quinonez, 2013)

Akpinar et al. (2010) tested the efficiency of a new flat-plate SAH with various obstructions on the absorber surface experimentally. Four different types of absorbent plates with sizes of 1200 mm x 700 mm and a thickness of 120 mm were evaluated in this study. Various obstacles are present at various angles in all styles of absorbent plates. At various angles, all types of absorber plates have various types of obstacles. Type I has triangle-formed obstacles with 50 mm x 50 mm size; type II has leaf-formed obstructions with the same size; type III has rectangular-formed obstacles with dimensions of 100 mm x 100 mm, while type IV absorbent has no obstructions in its designs. Stainless steel with a black chromium selective coating has been used to make each absorber plate. As a glazing cover, standard window glass with a thickness of 5 mm was utilized. The research

also investigated the exergy and energy analyses of SAHs. Furthermore, SAHs were evaluated in terms of exergy and energy. It was discovered that Type II SAH had the maximum efficiency, while the SAH without obstacles had the lowest. It additionally demonstrated that the efficiency of SAHs was significantly affected by the solar irradiance, collector surface shape, and extension of airflow channels.

Ozgen et al. (2009) tested experimentally the effectiveness of a DPSAH with and without aluminum cans for three various examples, as shown in Fig. 2.5. The thickness and plate dimensions of the three investigated designs are 1 mm and 2140 mm x 840 mm, respectively. The tests revealed that the highest efficiency of DPSAH was achieved by utilizing a stagger configuration of aluminum cans, which increased the area of convection as well as excellent turbulence and airflow on the absorbent plate at a mass flow rate of 0.05 kg/s.



Type I

Type II

Type III

**Figure 2.5.** Different absorber plates with and without aluminium obstacle (Typ I, Stagger configuration of aluminium cans Type II, Straight configuration of aluminium cans Type III, Flat plate) (Ozgen et al., 2009)

Esen (2008) constructed and investigated the impact of obstructions on the thermal exergy and energy of a flat plate DPSAH. Four different models of absorbent plates with constructed obstructions were utilized, as illustrated in Fig. 2.6. Four SAHs have dimensions of 1250 mm x 800 mm and a plate thickness of 1mm. When the absorbent plate was free of obstacles, the optimum thermal performance was measured at about 37%. The findings demonstrated that the efficiency of DPSAH using obstacles was significantly improved compared to a SAH without obstacles. It was discovered that model III has better efficiency than the flat DPSAH. The tests showed that the flat DPSAH achieved maximum irreversibility compared to other heaters.

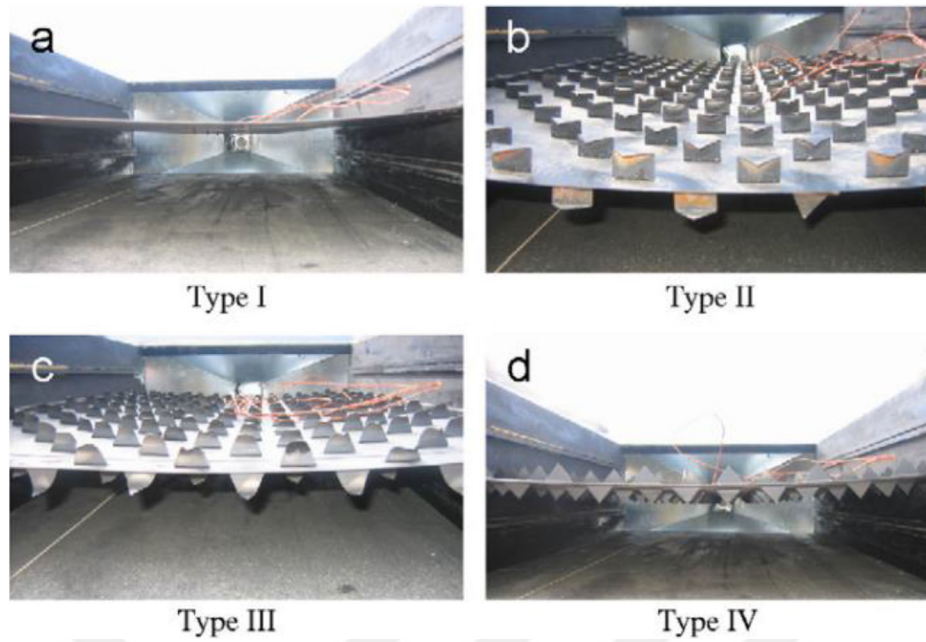


**Figure 2.6.** Four various types of absorber plates  
(Esen, 2008)

### 2.3. Theoretical Studies

Three models were used by Fudholi et al. (2011) to conduct a theoretical investigation of the effect of fin height and arrangement on DPSAH performance. As indicated in Fig. 2.7, the design specifications were 2400 mm x 1000 mm x 105 mm. They solved steady-state energy equations using a matrix inversion method and some algebraic rearrangements. It was also found that adding several fins and their height improved SAH efficiency for various mass flow rates between 0.02 and 0.1 kg/s and solar irradiance of 700 W/m<sup>2</sup>. Furthermore, the effectiveness of DPSAHs is around 36 % and 73 % in top fins, 37 % and 75 % in bottom fins, and 46 % and 74 % in the top and bottom fins arrangement, respectively. The collector's efficiency of around 35% was discovered to be an increased function of the mass flow rate.

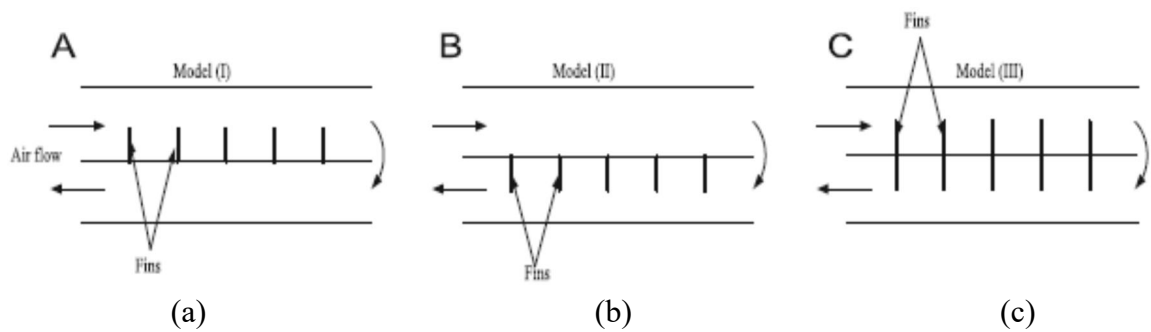


**Figure 2.7.** DPSAH schematic with three fin types  
(a) Top fins, (b) bottom fins, (c) top and bottom fins (Fudholi et al., 2011)

Bhandari et al. (2012) conducted a descriptive investigation of the efficiency of several models of flat-plate SAHs. To conduct the entire analysis, a MATLAB software code was developed. The efficiency of SAHs was examined in relation to mass flow rates, input air temperature, and solar irradiance intensity. As illustrated in Fig. 2.8, the three types of SAHs utilized for the analysis are traditional SAH, double glass SPSAH, and DPSAH with inner fins. The results show that for the same flow rate of the mass, the analysis of different types of SAHs, a finned DPSAH has the maximum performance. It was also observed that when the mass flow rate increases, the readings of output air temperature and mean absorbent plate temperature  $T_{pm}$  drop.

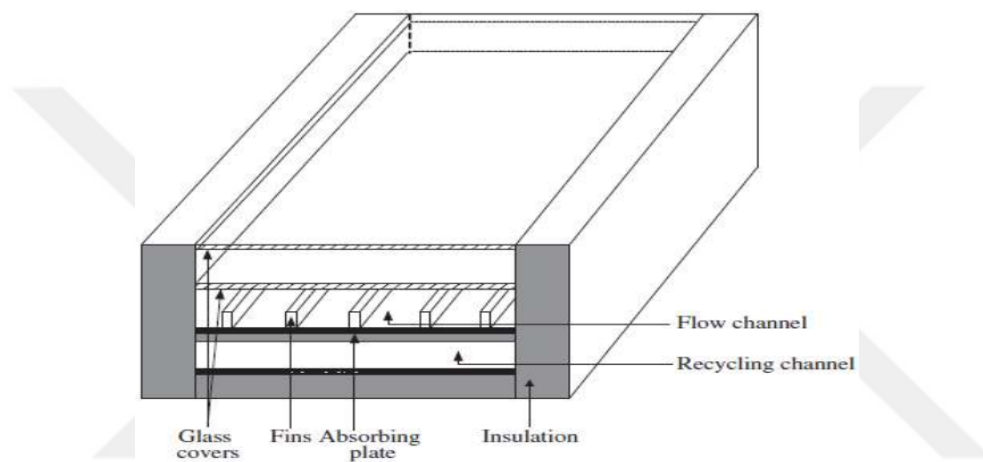


**Figure 2.8.** Schematic of a finned DPSAH  
(Bhandari et al., 2012)

Hedayatizadeh et al. (2016) investigated a mathematical design of a glazed DPSAH with a V-corrugated absorbent plate. They projected the effects of V-corrugated plates on an exergy loss for a glazed DPSAH. With the results of the available literature, the computational predictions were validated. Additionally, it was observed that increased efficiency reached 6.27 % attained with an air mass flow rate of 0.005 kg/s, a collecting surface of 1.76 m<sup>2</sup>, a height of corrugation of 0.0122 m, and a gap of 0.0023 m between both covers.

Abdullah et al. (2013) use a software program to find numerical methods for single-glazed flat plate SAH heat balance equations. For the designing or simulation of the efficiency of the SAH, it is critical to calculate the heat loss from the SAH to its surroundings. The upper heat loss factor ( $U_T$ ) values derived from calculations of heat balancing equations were compared to the values gathered from multiple relationships found in the literature. For a wide range of factors, the percentage errors in calculating the upper heat loss factor (and thus the gained energy) of a single-glazed flat plate SAH

derived by applying different relations of  $U_T$  as opposed to numerical solutions of heat balancing equations were studied: The absorbent plate temperature was 323-423 K, the ambient temperature was 273-318 K, the distance between air gaps was 10-50 mm, the coefficient of wind heat transfer was 5-45 W/m<sup>2</sup>.K, the SAH tilt angle was 0°-70°, and the absorber plate emittance was 0.1- 0.95. The investigation found that the equations of  $U_T$  estimate values near numerical solutions only under particular assumptions and create considerable mistakes in the computation of the upper heat loss factor and gained energy over a wider range of parameters.

## **2.4. Theoretically And Experimentally Studies**

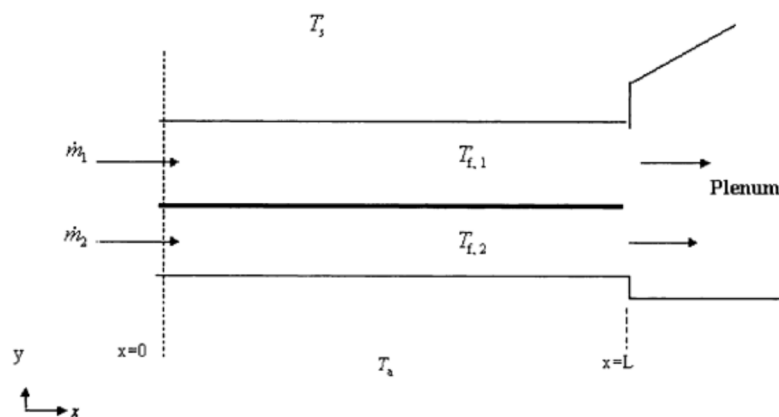
Many comprehensive investigations are presented in this chapter to enhance the thermal efficiency of SAHs. Several studies have clearly described experimentally and theoretical investigations by utilizing different methods, described in the following: Utilizing extended surfaces, such as corrugated or grooved surfaces, obstacles, fins, porous materials, and other features, helped achieve two goals. First, the convective surface was enhanced, which decreased thermal convection resistance and improved heat convection. Second, it breaks the sub-laminar boundary condition to produce vortexes in the turbulence zone, increasing the coefficient of heat convection.

Ramani et al. (2010) investigated the efficiency of a DPSAH with and without porous material, both theoretically and experimentally. The influence of factors on SAH performance and pressure drop was also investigated. Double 4 mm thick glass covers were utilized in the collector. The SAH included two airflow channels, as illustrated in Fig. 2.9. The area between the main and second glass covers served as the foundation for the main channel, while the second channel was constructed between the absorber plate and the second glass cover. To compare the findings, two SAHs were built. One featured two clear airflow channels, whereas the other's collector's second airflow passage was packed with porous medium. As a porous medium, black painted wire mesh was utilized. The dimensions of the two channels were 2100 mm x 540 mm x 21 mm. The absorbent plate in both collectors was created of a 1mm thick black painted aluminum.

Furthermore, for the tests, a numerical equation based on the volumetric heat transfer coefficient was constructed to characterize the heat transfer properties of such a SAH. It was found that utilizing a DPSAH made of porous material considerably increased thermal performance. A DPSAH with porous media has a 20 %-25 % higher

1. Air flow in  
2. Outlet air to blower  
3. Orifice meter  
4. M.S. Pipe  
5. Flexible Pipe  
6. Transition Piece  
7. Inlet & Exit sections  
8. Perforated Plates  
9. Pressure taps on collector  
10. First glass cover  
11. Second glass cover  
12. Absorber plate  
13. U-turn section  
14. First air pass  
15. Second air pass  
16. Insulation  
17. Manometer for collector pressure drop  
18. Manometer for orifice meter  
19. Thermocouples  
20. Selector switch & temp. indicator  
21. Support or Stand  
22. Porous material

Forson et al. (2003) conducted an experimental and theoretical investigation of SPSAH and DPSAH. A numerical model was investigated and used to estimate SAH efficiency. The traditional type was used to validate the two types' results, as shown in Fig. 2.10. Two models were used in the studies; the first was 400 mm x 740 mm x 75 mm in size, while the second was 6750 mm x 1260 mm x 280 mm. These models were combined with a drying chamber. According to the results, an increase in both systems' depth ratios is due to enhancing of the system's thermal efficiency. Additionally, it was mentioned that the system should be designed with an inexpensive depth ratio of air passage for optimum performance. The mass airflow rate has a major effect on the SAH's thermal efficiency.



22

Peng et al. (2010) investigated the theoretical and experimental efficiency of a SAH with fins mounted to the absorbent plate. They wanted to improve the efficiency of SAH by using a low-cost, easily accessible collector design with a sturdy construction. An experimental setup was built up specifically for this purpose. This research examined 25 pin-finned SAH and a flat plate SAH. The pins had lengths of 10, 20, 30, 40, and 45 mm with widths of 12, 16, 20, 24, and 28 mm. Over the finned absorbers, 4 mm thick single glass with the size of 1100 mm x 580 mm was utilized. Stainless steel that has been painted black served as the absorbent plate. To theoretically evaluate the performance of pin-finned collectors, a mathematical model was generated. Thus, with theoretical results, the numerical analysis of efficiency for all 26 SAHs was gained. The pin-fin configuration in a SAH was shown to be capable of improving the heat transfer coefficient up to three times when compared to a flat plate SAH at a  $19 \text{ m}^3/\text{h}$  air flow rate.

A finned DPSAH was examined both experimentally and theoretically by Yeh et al. (2002). In the studies conducted with the manufactured solar simulator, the model measurements were  $30 \times 30 \times 2.75 \text{ cm}$ , and the fins sizes were 55 mm and 60 mm, respectively, and attached parallel to the absorbent plate, as illustrated in Fig. 2.11.. The outcomes showed that the optimal flowing rate in both flowing ducts is 0.5 for the highest performance of DPSAH compared to two DPSAH without fins. Furthermore, adding fins to the absorbent surface significantly enhances the efficiency of DPSAH.

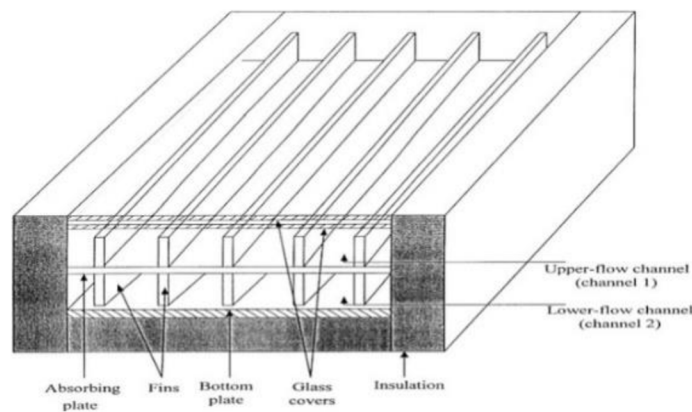


**Figure 2.11.** Parallel DPSAH has fins  
(Yeh et al., 2002)

Fudholi et al. (2013) investigated the effect of solar irradiation and a wide variety of mass flow rates of  $0.03 - 0.1 \text{ kg/s}$  on a finned DPSAH efficiency utilizing 45 halogen bulbs of the solar simulation, each rated 500 W, where the max estimate of solar irradiance could be attained  $800 \text{ W/m}^2$ . The SAH size was 2400 mm long and 1200 mm

wide, as illustrated in Fig. 2.12. They found that the collector's maximum efficiency was 77 % when the mass flow rate was 0.09 kg/s. It was also discovered that a solar irradiance of 425-790 W/m<sup>2</sup> provides a potential energy improvement of 740-1070 W.

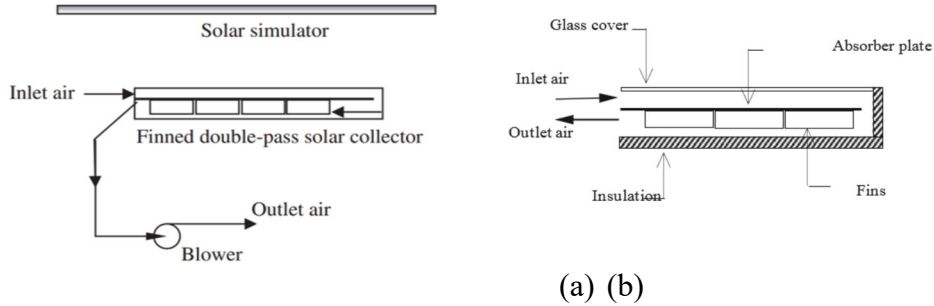


**Figure 2.12.** DPSAH have a fins  
(a) General DPASAH, (b) Schematic DPSAH (Fudholi et al., 2013)

Ho et al. (2009) examined the efficacy of staggered baffles in a DPSAH both numerically and experimentally. The model sizes were 60 cm × 60 cm x 5 cm, as shown in Fig. 2.13. The working circumstances were as follows: solar radiation = 830-1100 W/m<sup>2</sup>, mass flow rate 38.52-77.04 kg/hr, wind velocity = 1 m/sec, and ambient air temperature 30 °C. According to the findings, the baffled expanded fins produce a turbulence pattern stream and improve the thermal efficiency of DPSAH with recycles processes. Additionally, it was also discovered that an increase in recycling ratio and in mass flow rate because of the enhancement of performance of SAH with minimum energy losses caused by the pressure drop penalty.

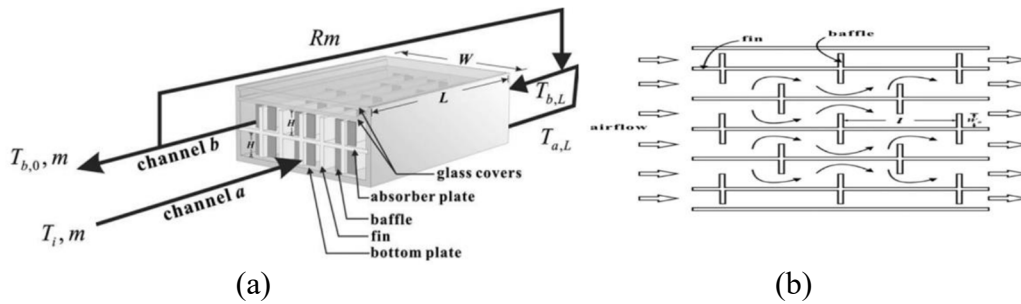


**Figure 2.13.** A design of the DPSAH using staggered baffles  
(a) General DPASAH, (b) Schematic DPSAH (Ho et al., 2009)

Karim and Hawladar (2006) examined the efficiency increase of SPSAH and DPSAH utilizing three different configurations experimentally and computationally. Three SAHs with sizes of 1800 mm x 700 mm and plate thicknesses of 1 mm, respectively. They found that the DPSAH with V-corrugated had better efficiency than other collectors, about 5-11 % and 10-15 %, respectively, when compared to flat plate DPSAH and SPSAH. In addition, EI-Sebaai et al. (2011) studied the efficiency enhancement for different forms

of SAHs experimentally and theoretically. The design sizes were 100 cm x 100 cm x 10 cm, as shown in Fig. 2.14. They observed that when the flow rate of the mass is 0.02 kg/sec, a V-corrugated DPSAH is 11-14 % more effective than a flat plate DPSAH.

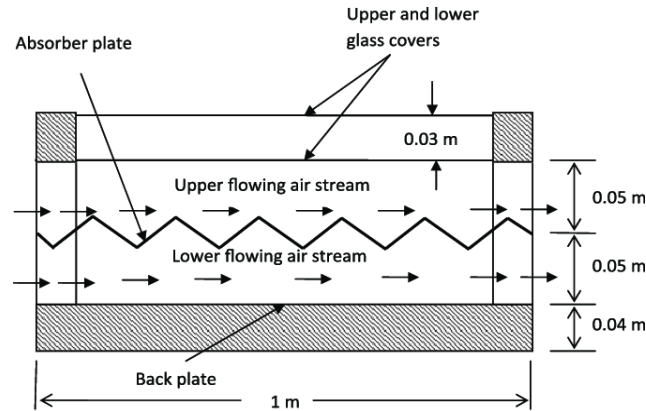


**Figure 2.14.** V-corrugated DPSAH  
(Karim and Hawladar, 2006)

## 2.5. Summary of Previous Studies

Based on a prior literature review, the experimental and theoretical investigations focused on various methods and specific features affecting DPSAH efficiency, such as the influence of utilizing fins or rougher absorber plate technologies, solar irradiation intensity, input air temperature, and airflow rates. A summary of the past studies as the following in Table 2.1 below: -

**Table 2.1.** Summary of the previous studies.

| No. | Researcher name     | Year | Type of Research             | Summary of the conclusions                                                                                                                                                                                                   |
|-----|---------------------|------|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1   | Wijeysundera et al. | 1982 | Experimental                 | Conducted that the thermal efficiency of a DPASH was 10-15% higher than that of a SPSAH.                                                                                                                                     |
| 2   | Yeh et al.          | 2002 | Theoretical and Experimental | The optimal flow ratio in both flow ducts is 0.5 for the maximal performance of DPSAH compared to two DPSAH without fins. Furthermore, adding fins to the absorbent surface significantly enhances the performance of DPSAH. |
| 3   | Forson et al.       | 2003 | Theoretical and Experimental | The system should be designed with an inexpensive depth ratio of air passage for optimum performance. The mass air flow rate has a significant effect on the efficiency of the SAH.                                          |
| 4   | Ucar et al.         | 2006 | Experimental                 | In comparison to the typical SAH, the efficiency has been improved from 10% to 30% by dividing                                                                                                                               |

|    |                     |      |                              |                                                                                                                                                                                                                                                         |
|----|---------------------|------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    |                     |      |                              | three or six panels to the absorbent surface, adding fins to the absorbent plate, and providing a tilt angle ( $2^\circ$ ) to the three absorber plates.                                                                                                |
| 5  | Karim and Hawladar. | 2006 | Theoretical and Experimental | The DPSAH with V-corrugated had better efficiency than other collectors about 5-11 % and 10-15 %, respectively, when compared to flat plate DPSAH and SPSAH.                                                                                            |
| 6  | Esen.               | 2008 | Experimental                 | The thermal efficiency of DPSAH using obstacles was significantly improved as compared to a collector without obstacles. Moreover, the flat DPSAH achieved maximum irreversibility when compared to other heaters.                                      |
| 7  | Ozgen et al.        | 2009 | Experimental                 | The highest performance of DPSAH was obtained by utilizing a staggering configuration of aluminum cans which enhanced the convection surface and also the airflow and turbulent on the absorbent plate at a flow rate of mass 0.05 kg/s.                |
| 8  | Ho et al.           | 2009 | Theoretical and Experimental | The baffled expanded fins produce a turbulence pattern stream and enhance the performance of DPSAH with recycling processes.                                                                                                                            |
| 9  | Aldabbagh et al.    | 2010 | Experimental                 | When the flow rate improved, the efficiency of the system increased in both cases. Maximum efficiency for SPSAH and DPSAH at a flow rate of mass is 0.038 kg/s was 45.93 % and 83.65 %, respectively.                                                   |
| 10 | Akpınar et al.      | 2010 | Experimental                 | The Type II SAH had the maximum efficiency, while the SAH without obstacles had the lowest.                                                                                                                                                             |
| 11 | Ramani et al.       | 2010 | Theoretical and Experimental | Utilizing a DPSAH made of porous material considerably increased the performance. A DPSAH with porous media has a 20 %-25 % higher thermal efficiency than a DPSAH without porous media, as well as a 30 %-35 % higher thermal efficiency than a SPSAH. |
| 12 | Peng et al.         | 2010 | Theoretical and Experimental | The pin-fin configuration in a SAH was shown to be capable of improving up to three times the heat transfer coefficient when compared to a flat plate SAH at a 19 m <sup>3</sup> /h air flow rate.                                                      |
| 13 | Fudholi et al.      | 2011 | Theoretical                  | The addition of a number of fins and its height improved SAH efficiency. Furthermore, the effectiveness of DPSAHs is around 36 % and 73 %                                                                                                               |

|    |                         |      |                              |                                                                                                                                                                                                                                           |
|----|-------------------------|------|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    |                         |      |                              | in top fins, 37 % and 75 % in bottom fins, and 46 % and 74 % in the top and bottom fins arrangement, respectively.                                                                                                                        |
| 14 | El-Sebaei et al.        | 2011 | Theoretical and Experimental | When the flow rate of mass is 0.02 kg/sec, a V-corrugated DPSAH is 11-14 % more effective than a flat plate DPSAH.                                                                                                                        |
| 15 | D. Bhandari et al.      | 2012 | Theoretical                  | A finned DPSAH has the maximum performance. It was also observed that when the mass flow rate increases, the values of mean absorbent plate temperature $T_{pm}$ and output air temperature drop.                                         |
| 16 | Hernandez and Quinonez. | 2013 | Experimental                 | The counter DPSAH's thermal efficiency with a maximum output air temperature was 57% at 46.4 °C, the parallel DPSAH's were 51% at 42.5 °C, and the SPSAH's was 46% at 40.7 °C.                                                            |
| 17 | Abdullah et al.         | 2013 | Theoretical                  | The equations of $U_T$ predict values that are near to numerical solutions only under particular assumptions and create considerable errors in the computation of upper heat loss factor and gained energy over a wider range of factors. |
| 18 | Fudholi et al.          | 2013 | Theoretical and Experimental | The collector's maximum efficiency was 77 % when the flow rate mass was 0.09 kg/s. Moreover, a solar radiation of 425-790 W/m <sup>2</sup> provides a potential energy improvement of 740-1070 W.                                         |
| 19 | Hedayatizadeh et al.    | 2016 | Theoretical                  | Increased efficiency reached 6.27 % attained with an airflow rate of mass is 0.005 kg/s, a collecting area of 1.76 m <sup>2</sup> , a 0.0122 m corrugated length of 0.0122 m, and a gap of 0.0023 m between both covers.                  |

## 2.6. Justification

As a conclusion of this literature review, the studies conducted in the latest years have been thoroughly examined. The design choices, the aims of additional studies, and the conclusions of such techniques are determined. Some features of the experimental settings, such as size, materials, and testing techniques, are thoroughly investigated. Based on the information obtained from these studies, the test rig that will be designed and evaluated for this thesis has taken shape.

This study will be extremely useful for researchers who would be investigating newly designed roughness (inexpensive as well as easy to use) for SAHs to improve heat

transfer rate and compare with artificial roughness already investigated by different researchers and then include a solution to the poor thermal physical characteristic of air that is employed as various absorber plate of SAHs.



### 3. MATERIAL AND METHOD

In this section, we explain the experimental and theoretical work for this study.

#### 3.1. Theoretical Work

##### 3.1.1. Numerical analysis

A physical model of the dual-flow solar air heater dual-flow SAH and numerical simulation based on the governing equations (GE) were employed to describe the fluid flow heat transfer. A computational model is constructed for heating air mode. This mode consists of a steady state component to explain the heat transfer and fluid flow behavior for air. Solar radiation strikes the absorbent plate and represents heat flux in (ANSYS Fluent Workbench 2020 R2). The incident radiation can be transformed into thermal energy and then to useful benefit by using a solar collector (absorber plate) painted in mat black (black body). The dual-flow solar air heater was investigated in this study. The radiation will be transferred to the absorber as solar radiation happens on the cover, where a significant amount of radiation will be absorbed, and the rest will be reflected within the collector channel. Because invisible to long wavelength radiation is one of the properties of the glassing cover, virtually all of the irradiance emitted to the collector via the cover will be converted to thermal energy.

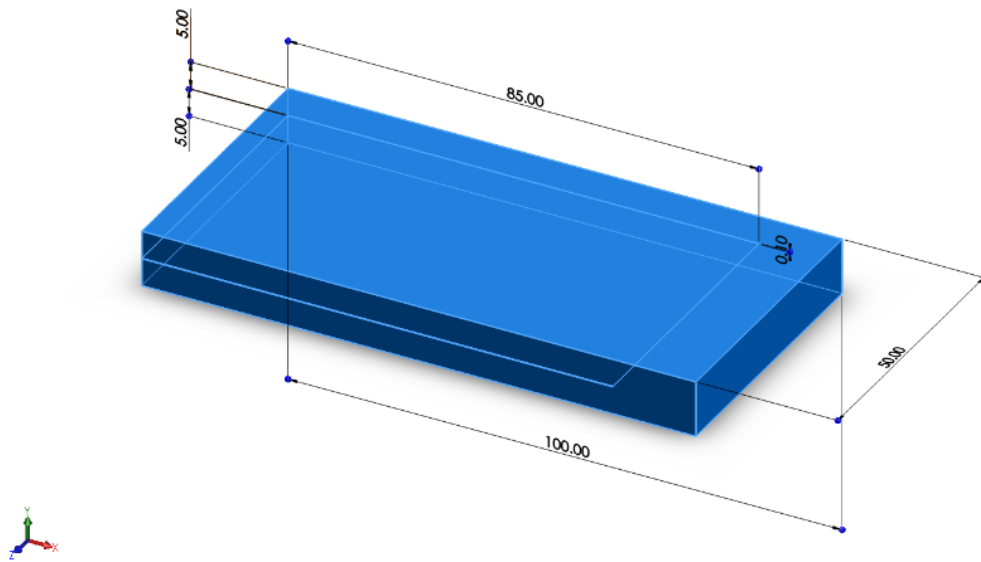


**Figure 3.1.** Physical model with dimension (cm)

##### 3.1.1.1. Geometry and Boundary Conditions

Fig. 3.1 demonstrates the numerical geometry and boundary state for dual-flow SAH mode of traditional dual-flow SAH. More information for PC was implemented in statistical models for dual-flow SAHs and inclined absorber plates to analyze the energy

balance of principal elements, such as (absorber plate, air stream within dual-flow SAHs, and glass ). Furthermore, it was demonstrated that the mass balance of the air stream according to previous literature turbulent flows range is characterized in the present work based on the Rayleigh number.

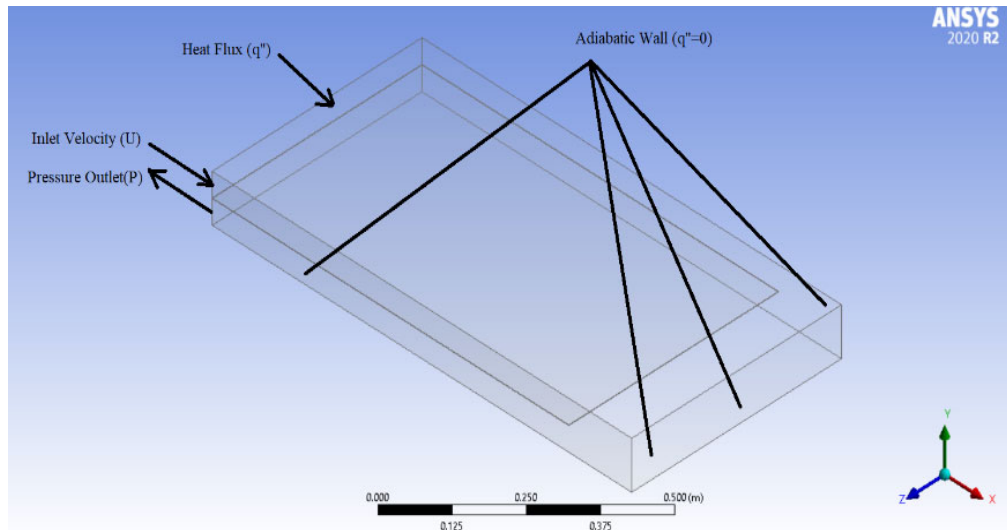


**Figure 3.2.** Boundary conditions

Figures below show the four types of the absorber plates for this study:

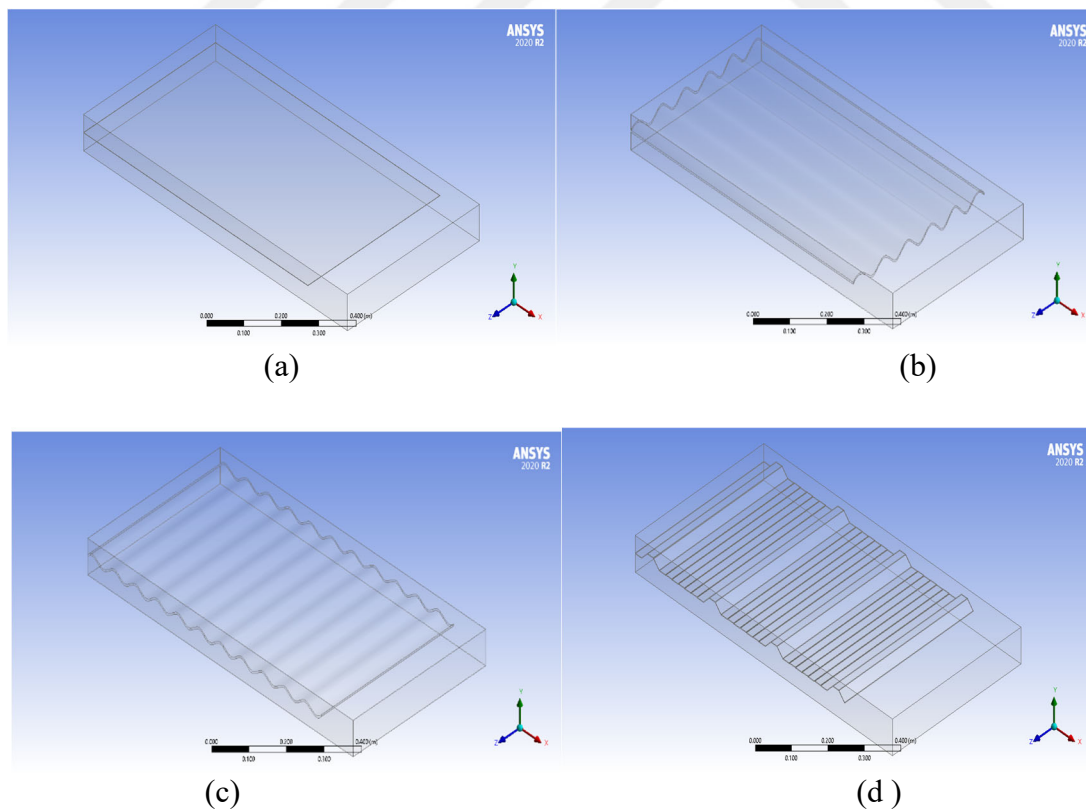


**Figure 3.3.** Types of absorber plates

(a) Flat, (b) U -corrugated parallel direction to airflow, (c) U -corrugated in anti-parallel direction, (d) Trapezoidal corrugated plate

### 3.1.1.2. Assumptions

To simplify the present numerical case, some of the following assumptions:

1. Steady-state incompressible airflow in the 3-D model.
2. Heat transfer by conduction in the absorber wall is neglected.
3. Three-dimensional conservation equations.
4. Airflow in the channel has been considered turbulent.
5. All characteristics are evaluated at an average temperature.

### 3.1.2. Governing equations

The conservation of mass, momentum, and energy equations (Navier-Stokes equation) are the equations that describe the flow of a fluid and heat. These equations describe turbulent and incompressible flow, taking the following forms (Churchill and Chu 1975b; Holman 2013).

Conservation of Mass

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0 \quad (3.1)$$

Conservation of Momentum

➤ x- direction (u- momentum)

$$\frac{\partial uu}{\partial x} + \frac{\partial vu}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial}{\partial x} \left[ \mu_{eff} \frac{\partial u}{\partial x} \right] + \frac{1}{\rho} \frac{\partial}{\partial y} \left[ \mu_{eff} \frac{\partial u}{\partial y} \right] + S_u \quad (3.2)$$

➤ y- direction (v-momentum)

$$\frac{\partial vu}{\partial x} + \frac{\partial vv}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{1}{\rho} \frac{\partial}{\partial x} \left[ \mu_{eff} \frac{\partial v}{\partial x} \right] + \frac{1}{\rho} \frac{\partial}{\partial y} \left[ \mu_{eff} \frac{\partial v}{\partial y} \right] - \frac{2}{3} \frac{\partial k}{\partial y} + S_v \quad (3.3)$$

➤ z- direction (w-momentum)

$$\rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + S_w \quad (3.4)$$

Energy equation

$$\frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} = \frac{1}{\rho} \frac{\partial}{\partial x} \left[ \Gamma_{eff} \frac{\partial T}{\partial x} \right] + \frac{1}{\rho} \frac{\partial}{\partial y} \left[ \Gamma_{eff} \frac{\partial T}{\partial y} \right] \quad (3.5)$$

The accepted procedure for a certain issue type, the required level of accuracy, the available resources for the computer, and the length of the simulation duration. Therefore, selecting the right model for the application necessitates having a thorough knowledge of

the potentials and constraints of different possibilities (John, 1996). The Large Eddy Simulation (*LES*), Reynolds Averaged Navier Stokes equations (*RANS*), and Direct Numerical Simulation (*DNS*) are the three major methods for computing turbulence (Moin and Mahesh, 1998). The effects of small-scale movements are represented in the *LES* approach, while large-scale motions are calculated directly. Compared to *DNS*, *LES* offers significant computational savings, albeit at the cost of modeling and a more complicated numerical approach (Zhou, 2006). Based on the notion that the flow field exhibits small local oscillations over time and can be handled using a time average, the *RANS* formulation was developed. For one and two-equation models. (*k in k-ε*), additional equations for transport for turbulent parameters are supplied (Moin and Mahesh, 1998). To compute the turbulent flow field in two-equation turbulence models, two extra governing equations must be solved. The majority of these models resolve a transport equation for kinetic energy in turbulent flow (*k*) and a different transport equation that enables the definition of a turbulent length scale. Some of these two equation models (low Reynolds number models) are valid close to the wall, whereas others are only valid beyond the inner region's boundary layer (high Reynolds number models). Standard two-equation models cannot reliably forecast flows with significant streamline curvature, unfavorable pressure gradients, flow separation, or system rotation. Typical two-equation models should be employed for flows around blades, rods, airfoils, etc. (Menter, 1994). The system of equations above, which comprises two transport equations for two turbulence parameters, namely the equation of turbulent dissipation rate ( $\epsilon$ ) and turbulent kinetic energy equation (*k*), is solved using the basic (*k*) turbulence model. These equations are stated as follows.:

Turbulent kinetic energy

$$\frac{\partial uk}{\partial x} + \frac{\partial vk}{\partial y} = \frac{1}{\rho} \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x} \right] + \frac{1}{\rho} \frac{\partial}{\partial y} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial y} \right] + \frac{1}{\rho} (G_k + G_b) - \epsilon \quad (3.6)$$

Dissipation rate ( $\epsilon$ )

$$\frac{\partial u\epsilon}{\partial x} + \frac{\partial v\epsilon}{\partial y} = \frac{1}{\rho} \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x} \right] + \frac{1}{\rho} \frac{\partial}{\partial y} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial y} \right] + C_1 \frac{\epsilon}{\rho k} (G_k + C_3 G_b) - C_2 \frac{\epsilon^2}{k} \quad (3.7)$$

Where:

$\mu_{eff}$  Effective viscosity coefficient

$$\mu_{eff} = \mu + \mu_t \quad (3.8)$$

$\Gamma_{eff}$  Effective diffusion coefficient

$$\Gamma_{eff} = \frac{\mu}{\rho_r} + \frac{\mu_t}{\sigma_t} \quad (3.9)$$

$\mu_t$  Turbulent viscosity

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (3.10)$$

$$S_u = -\frac{2}{3} \frac{\partial k}{\partial x} \quad (3.11)$$

$$S_v = g\beta(T_f - T_{in}) \quad (3.12)$$

Buoyancy in x – direction =  $\rho g \beta(T - T_{in})\sin\theta$

Buoyancy in y – direction =  $\rho g \beta(T - T_{in})\cos\theta$

$G_k$  kinetic energy generation by shear

$$G_k = \mu_t \left( 2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right] + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \right) \quad (3.13)$$

$G_b$  kinetic energy generation by buoyancy

$$G_b = \frac{\mu_t}{\sigma_t} \frac{\partial T}{\partial y} g\beta \quad (3.14)$$

Where “ $C_\mu$ ” is the value of an empirical constant for a flow with a large Reynolds number. The circulating fluid is air, which has a Prandtl number of (0.7) and creates a uniform heat flux on the area of the absorber plate.

**Table 3.1.** Values of constants in the ( $k$ - $\varepsilon$ ) models ( Sataloff et al 2007).

| $C_\mu$ | $C_1$ | $C_2$ | $C_3$ | $\sigma_\varepsilon$ | $\sigma_k$ |
|---------|-------|-------|-------|----------------------|------------|
| 0.09    | 1.44  | 1.92  | 1.0   | 1.3                  | 1.0        |

The existence of walls has a considerable impact on turbulent flows. Clearly, the mean velocity field is influenced by the no-slip criterion that must be achieved at the wall's surface. However, the wall's presence also changes the turbulence in non-trivial ways. Viscous damping lowers the tangential velocity fluctuations very near the wall, whereas kinematic blocking minimizes normal fluctuations. However, toward the outside

part of the near wall zone, the turbulence is significantly enhanced by creating turbulence kinetic energy caused by substantial gradients in mean velocity. The near-wall modeling has significant effects on the accuracy of mathematical solutions, in as much as walls are the primary cause of mean vorticity and turbulence. After all, the momentum and other scalar transfers are strongest at the near wall area where the solution parameters have substantial gradients. Therefore, an accurate depiction of the flow in the region near the wall determines reliable predictions of wall-bounded turbulent flows.

The  $k$ - $\varepsilon$  models, the *LES*, and the *RSM* models are mainly valid to turbulent core flows( i.e., flow in zones that are fairly far from walls). Therefore, it must be thought about how to adapt these models for use with wall-bounded flows. The Spalart-Allmaras and  $k$ - $\omega$  models were intended to be used across the boundary layer, providing that the near-wall mesh resolution is appropriate. Numerous investigations have revealed that the near-wall region may be largely separated into three layers. In the innermost layer, called the “viscous sublayer”, the flow is virtually laminar, and (molecular) viscosity dominates momentum and heat or mass transmission. In the outer layer, known as the fully turbulent layer, turbulence is a significant factor. Finally, there is an interim zone between the viscous sublayer and the completely turbulent layer, the effects of both turbulence and molecular viscosity are equally significant. The  $y^+$  value calculates the accuracy of the boundary layer thickness forecast,  $y^+$  is a parameter without dimensions that determines the distance from the first grid cell to the surface.

$$y^+ = \frac{\rho u_\tau y}{\mu} \quad (3.15)$$

Here  $u_\tau$  is the friction velocity defined as

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} \quad (3.16)$$

Typically, there are two techniques for modeling the near-wall region.

We need more than one equation because one equation is not enough to resolve the viscosity-affected inner region (buffer layer and viscous sublayer). Instead, "wall functions" are semi-empirical formulas that connect the viscosity-affected region between the fully turbulent region and the wall. The utilization of wall functions eliminates the requirement to alter turbulence models in order to take the wall into consideration. Another method involves changing the turbulence models so that the viscosity-affected

region, which involves the viscous sublayer, can be solved with a mesh all the way to the wall. This will be referred to as the "near-wall modeling" technique for the purpose of this discussion. However, the wall-function method is insufficient in cases where low-Reynold number effects are prevalent, and the assumptions underpinning the wall functions cease to be valid in such cases, near-wall models that are valid in the viscosity-affected zone and hence integrable all the way to the wall are required. ANSYS Fluent supports both the wall-function and near-wall modeling approaches.

According to the turbulent model, ANSYS Fluent provides three to four wall-function methods:

Standard Wall Functions

Non-Equilibrium Wall Functions

Enhanced Wall Functions (as a part of EWT)

User-Defined Wall Functions

The Standard Wall Functions will be used in this study to model the Near-Wall Treatments.

ANSYS Fluent's basic wall functions depend on the work of Launder and Spalding (Launder and Spalding 1974c) and are commonly utilized in industrial flows. They are the standard choice in ANSYS Fluent.

We took the following equations of momentum from Launder and Spalding 1974c.

Momentum;

The law of the wall for mean velocity yields

$$U^* = \frac{1}{k} \ln(Ey^*) \quad (3.17)$$

Where,

$$U^* = \frac{U_P C_\mu^{1/4} k_P^{1/2}}{\tau_w / \rho} \quad (3.18)$$

The dimensionless form of velocity,

$$U^* = \frac{\rho C_\mu^{1/4} k_P^{1/2} y_P}{\mu} \quad (3.19)$$

Here,  $k$  is von Kármán constant ( $= 0.4187$ ),  $E$  is the empirical constant ( $= 9.793$ ),  $U_P$  is the mean velocity of the fluid at the near-wall node P,  $k_P$  is turbulence kinetic energy

at the near-wall node P,  $y_P$  is the distance from point P to the wall, and  $\mu$  is the dynamic viscosity of the fluid.

The logarithmic law for mean velocity is known to be true for  $30 < y^* < 300$ . When  $y^*$  is greater than 11.225, ANSYS Fluent employs the log-law. The ANSYS Fluent uses the laminar stress-strain relationship when the mesh is such that  $y^* < 11.225$  at the wall-adjacent cells, which can be expressed as.

$$U^* = y^* \quad (3.20)$$

Energy equation;

Reynold's analogy between momentum and energy transmission yields an analogous logarithmic rule for mean temperature. The law of the wall for temperature used in ANSYS Fluent is composed of the two laws listed below, similar to the law of the wall for mean velocity, linear law for the thermal viscous sublayer or thermal conduction sublayer, where conduction is significant and logarithmic law for the turbulent zone, where turbulence effects predominate over conduction. The thickness of the thermal conduction layer is often different from the thickness of the (momentum) viscous sublayer and varies from fluid to fluid. For instance, the thickness of the momentum sublayer is substantially more than the thickness of the thermal sublayer for a high-Prandtl-number  $Pr_h$  fluid (such as oil). On the contrary, it is significantly bigger than the momentum sublayer thickness for fluids with low Prandtl number  $Pr_L$  (e.g., a liquid metal).

$$\frac{\delta}{\delta_T} = \sqrt{Pr} \quad (3.21)$$

The composite form of the law-of-the-wall used in ANSYS Fluent is as follows:

$$T^* = \frac{(T_w - T_P)\rho c_p k_P^{1/2}}{q'} = \begin{cases} Pr y^* + \frac{1}{2} \rho Pr \frac{C_\mu^{1/4} k_P^{1/2}}{q'} U_P^2 & (y^* < y_T^*) \\ Pr_t \left[ \frac{1}{k} \ln(E y^*) + P \right] & (y^* > y_T^*) \\ + \frac{1}{2} \rho \frac{C_\mu^{1/4} k_P^{1/2}}{q'} [Pr_t U_P^2 + (Pr - Pr_t) U_c^2] & \end{cases} \quad (3.22)$$

Where P is computed by using the formula given by Jayatilleke for the smooth walls (Jayatillaka, 1966):

$$P_{smooth} = 9.24 \left[ \left( \frac{Pr}{Pr_t} \right)^{3/4} - 1 \right] \left[ 1 + 0.28 e^{-0.007 Pr / Pr_t} \right] \quad (3.23)$$

For the rough walls, however, this function is modified as follows:

$$Pr_{rough} = 3.15Pr^{0.695} \left[ \frac{1}{E'} - \frac{1}{E} \right]^{0.359} + \left( \frac{E'}{E} \right)^{0.6} P \quad (3.24)$$

Where  $E'$  is the wall function constant modified for the rough walls, defined by  $E' = E/fr$ ,  $fr$  is the roughness function,  $k_P$  is turbulent kinetic energy at the first near-wall node  $P$ ,  $\rho$  is the density of the fluid,  $c_p$  is the specific heat of fluid,  $q'$  is wall heat flux,  $T_P$  is the temperature at the first near-wall node  $P$ ,  $T_w$  is the temperature at the wall,  $Pr$  is molecular Prandtl number ( $\mu c_p/k_f$ ),  $Pr_t$  is turbulent Prandtl number (0.85 at the wall),  $A$  is Van Driest constant ( $= 26$ ),  $U_c$  = mean velocity, and the magnitude at  $y^* = y^*_T$

#### Turbulence Equations

In the  $k$ - $\varepsilon$  models and the RSM (if the option to derive wall boundary conditions from the  $k$  equation is enabled), the  $k$  equation is solved all over the whole domain, including the wall-adjacent cells. The boundary condition for  $k$  imposed at the wall is:

$$\frac{\partial k}{\partial n} \quad (3.25)$$

Where  $n$  is the local coordinate normal to the wall, the generation of kinetic energy  $G_k$  and its dissipation rate,  $\varepsilon$ , at the wall-adjacent cells, which are the source terms in the  $k$  equation, are estimated using the local equilibrium hypothesis. Under this assumption, the generation of  $k$  and its dissipation rate are expected to be identical in the wall-adjacent control volume. Thus, the generation of  $k$  is based on the logarithmic rule and may be calculated as follows:

$$G_k = \tau_w \frac{\partial U}{\partial y} = \tau_w \frac{\tau_w}{k \rho k_P^{1/2} y_P} \quad (3.26)$$

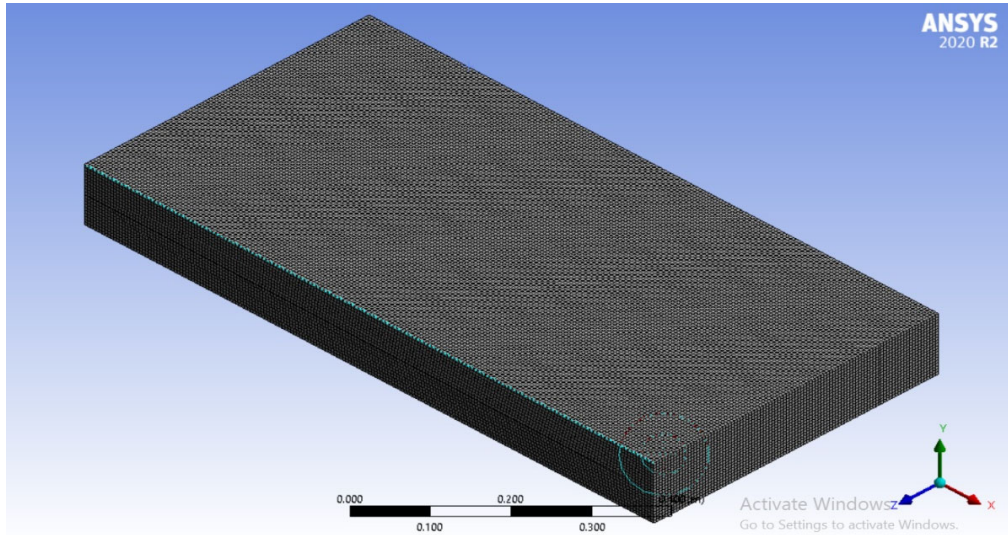
And  $\varepsilon$  is computed from:

$$\varepsilon_P = \frac{C_\mu^{3/4} k_P^{3/2}}{k y_P} \quad (3.27)$$

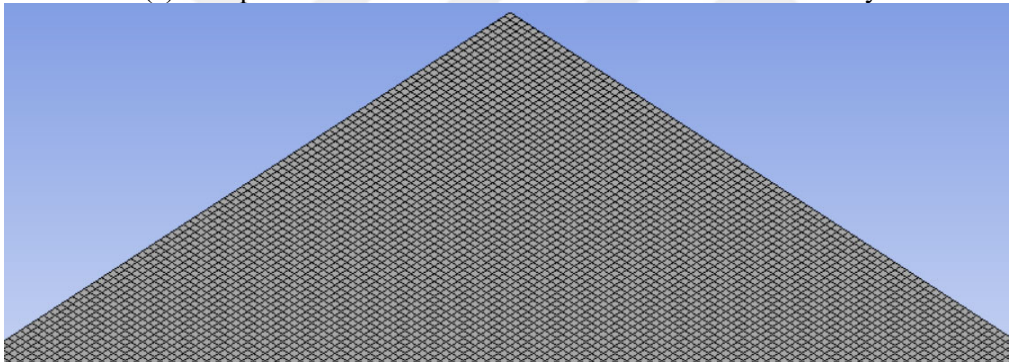
### 3.1.3. Grid generation (Meshing)

The forced heat transfer studied parameters in heated dual-flow solar air heater for various Reynolds number along the top channel was determined in this study by utilizing finite-volume grids, it was constructed along the whole geometrical domain. The SOLIDWORKS 2018 software (Planchard 2023) was used to simplify the construction of each of these geometry and mesh generation in (ANSYS Fluent Workbench 2020 R2) Ansys Fluent 2020 R1-Theory Guide was used to develop mesh files (Ansys Fluent 2020

R1-). Also, the tetrahedral mesh was employed in order to model the air space by 3251251 nodes in the x, y, and z directions. A section of the mesh of dual-flow solar air heater was presented in Fig.3.4 and 3.5.

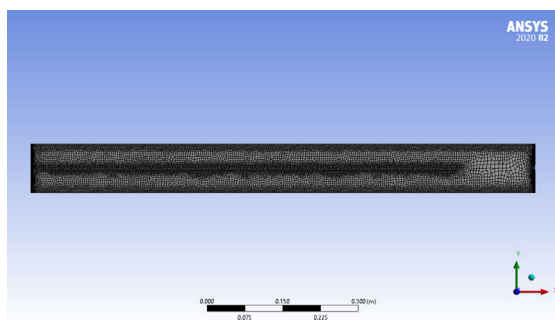


(a) Computational domain mesh of the dual-flow SAH cavity

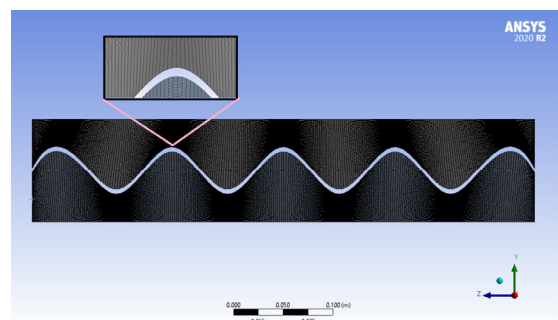


(b) zoom in on the right upper corner of computational domain mesh of the dual-flow SAH cavity

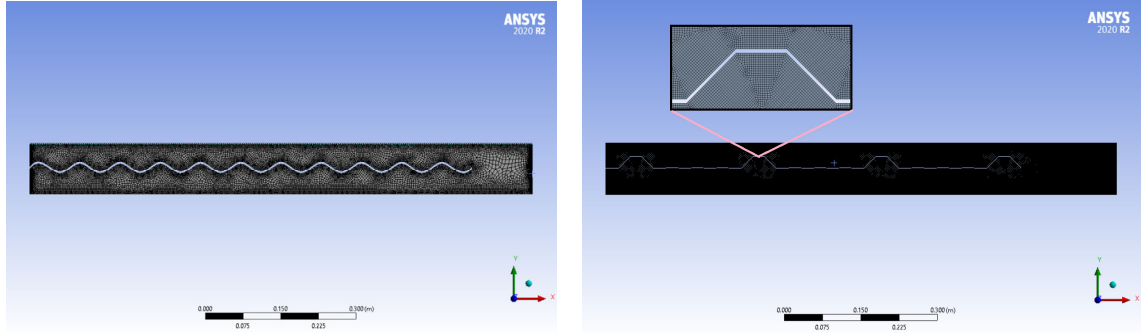
**Figure 3.4.** Computational domain mesh of the dual-flow SAH cavity model



(a) Flat absorber plate.



(b) U -corrugated plate parallel direction.



(c) U -corrugated plate anti-parallel direction. (d) Trapezoidal corrugated plate.  
**Figure 3.5.** Computational domain mesh of the four types of dual-flow SAH cavity model

### 3.1.4. Numerical solution

The computational domain's three-dimensional mesh was uploaded to the (ANSYS Fluent Workbench 2020 R2) software. This software employed the SIMPLE algorithm for linking the inlet and outlet pressure boundary conditions. The model is stopped when each simulation's energy, momentum, and mass are assessed over the course; residuals drop below  $10^{-7}$ . In addition, the momentum and pressure under relaxation factors were changed at 0.70 and 0.30, respectively, to increase the model's convergence rate, but the energy and density were retained at the standard values.

### 3.2. Mesh Independence Test

For the grid independence analysis of 3-D simulations, four meshes (coarse, medium, fine, and finer) were assessed, with their characteristics being summarized in Table 3.2. A block strategy for each loop component is used with the mesh specifications evaluated here. The near-wall cell size is aimed at a  $y^+ < 1$  with a near-wall clustering of cells and an expansion towards the central region (ratio = 1.06). A mesh sensitivity study compared the number of nodes with the output temperature profile computed and drawn. These results, from four different grids, are shown in Fig. 3.6. The mesh with a size of 1946385 finite volumes was chosen for the subsequent simulations because this grid control volume was considered sufficiently fine in terms of accuracy and computational cost for further comparisons.

**Table 3.2.** The properties of all the 2-D meshes considered for the dual-flow SAH cavity

| No. | Mesh type | Nodes    | Element  | T <sub>out</sub> |
|-----|-----------|----------|----------|------------------|
| 1.  | Coarse    | 797239.3 | 748405.6 | 311.223 K        |
| 2.  | Medium    | 1245686  | 1169383  | 312.446 K        |
| 3.  | Fine      | 1946385  | 1827162  | 313.205 K        |
| 4.  | Finer     | 2141024  | 2009878  | 313.213 K        |

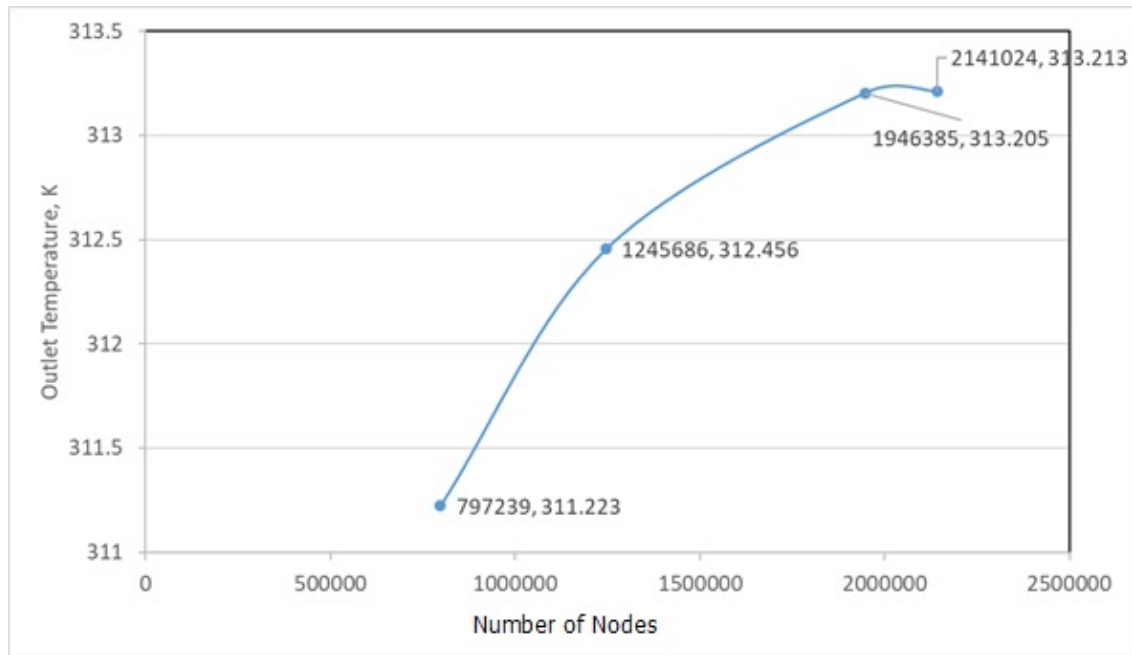


**Figure 3.6.** Grid independence analysis of 3-D simulations

### 3.2.1. Pre processing in CFD

For 3-D computations at the RANS *k-epsilon* turbulence model, the thermal energy transfer equations are solved and compared against a turbulent solution. The space discretization of the convective schemes in the momentum and energy equation is handled by the second upwind scheme with the "slope-test" turned on and flux reconstruction to account for any cells that are not totally orthogonal for the situations. The upwind scheme is used to discretize the turbulent quantities' convective terms (*k-epsilon*), and a convergence criterion of  $10 \times 10^{-6}$  is applied to all transport equations (*continuity, momentum, and energy equations*) that were solved. However, its impact is presumed to be small and is not modeled here because it was seen that the convergence process was unaffected significantly as the simulation progressed. At each sweep (or iteration level) in the SIMPLEC algorithm, pressures and velocities are guessed (or obtained from the previous iteration) to solve the momentum and energy equations. The numerical solution flow chart, as shown in Fig. 3.7.

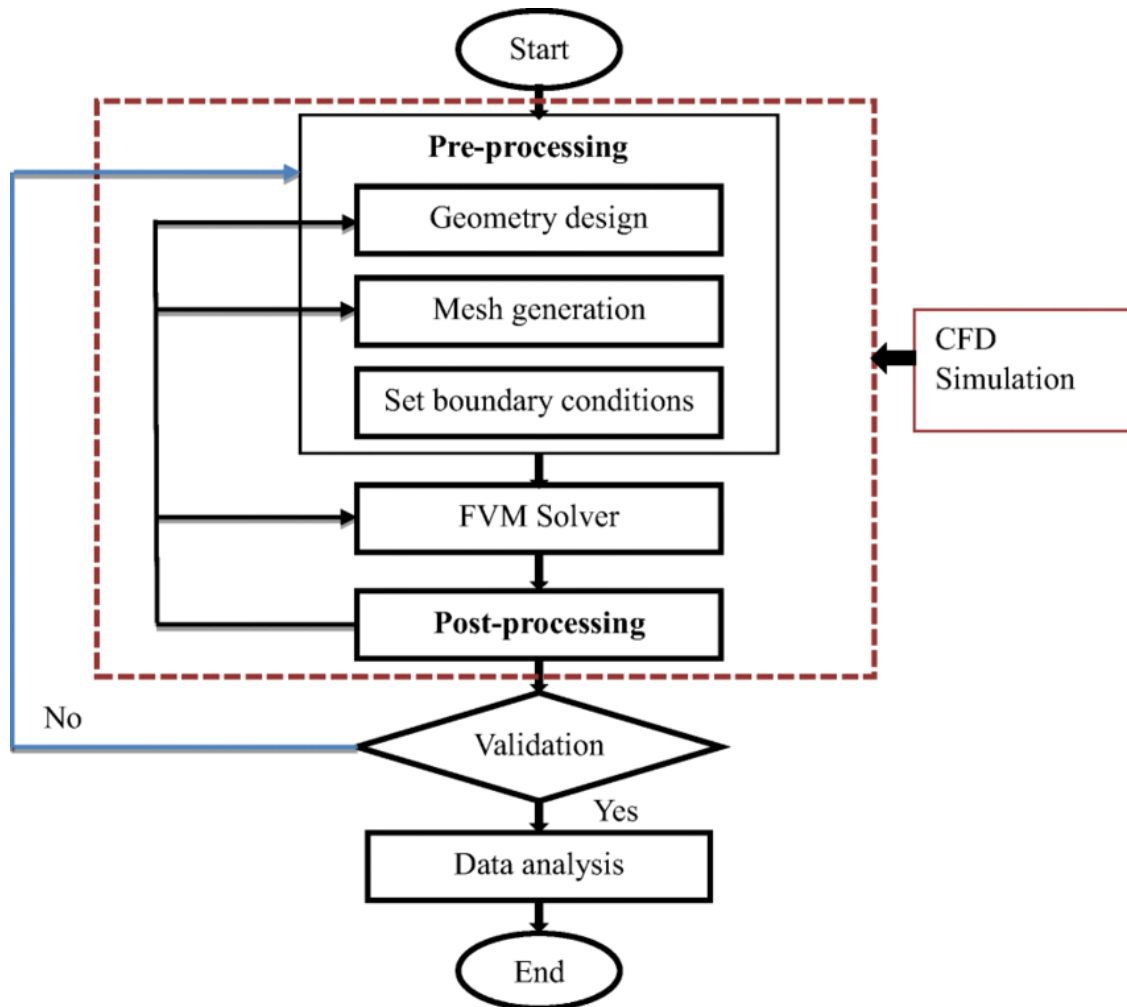


**Figure 3.7.** Flowchart diagram of numerical modeling using ANSYS Fluent

### 3.2.2. Numerical setup

Figs. 3.8-3.12 show the geometry generation, mesh generation, solution setup, solution iteration, and solution results.

We clicked on geometry to import the geometry we designed using the SOLIDWORKS 2018 software; after that, we clicked on the mesh to generate the mesh. After that, we clicked on the setup from general; we chose the type pressure-based, velocity formation is absolute, time is steady, and the gravity is -9.81 at the y-axis, and at the end, we ran the calculation.

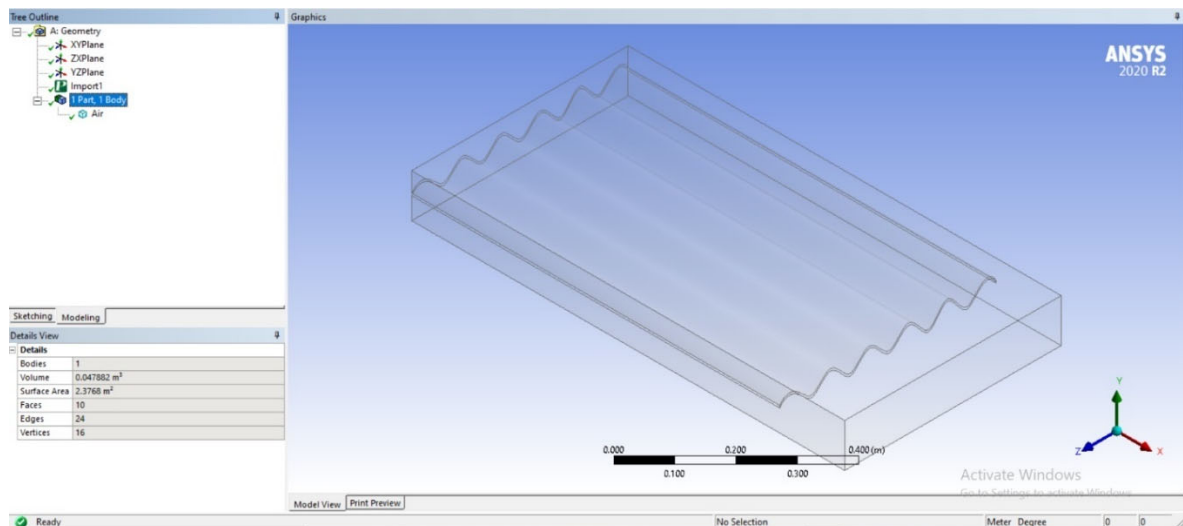


Figure 3.8. Step-1 Geometry generation

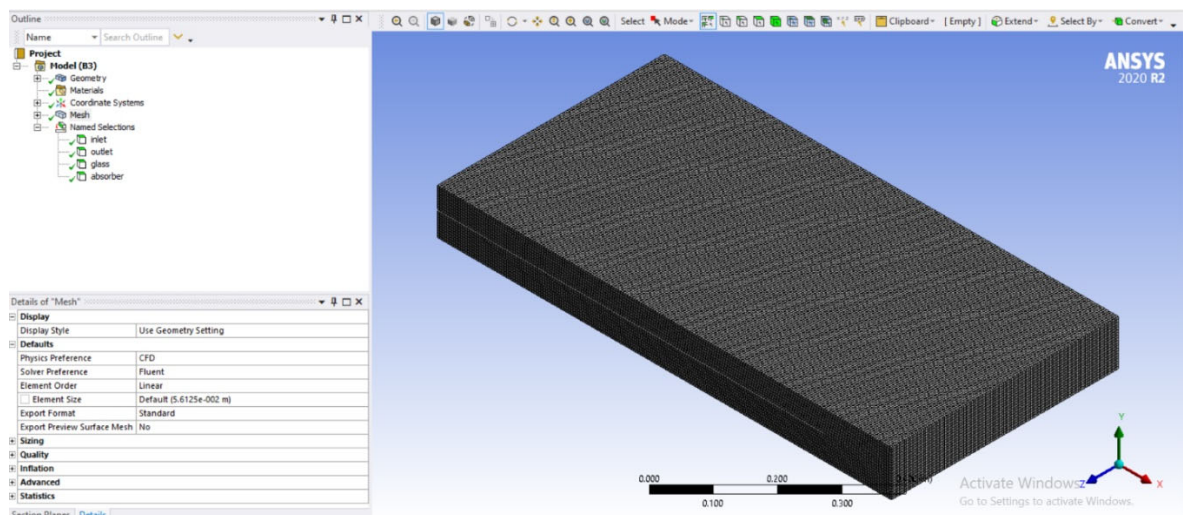


Figure 3.9. Step-2 Mesh generation

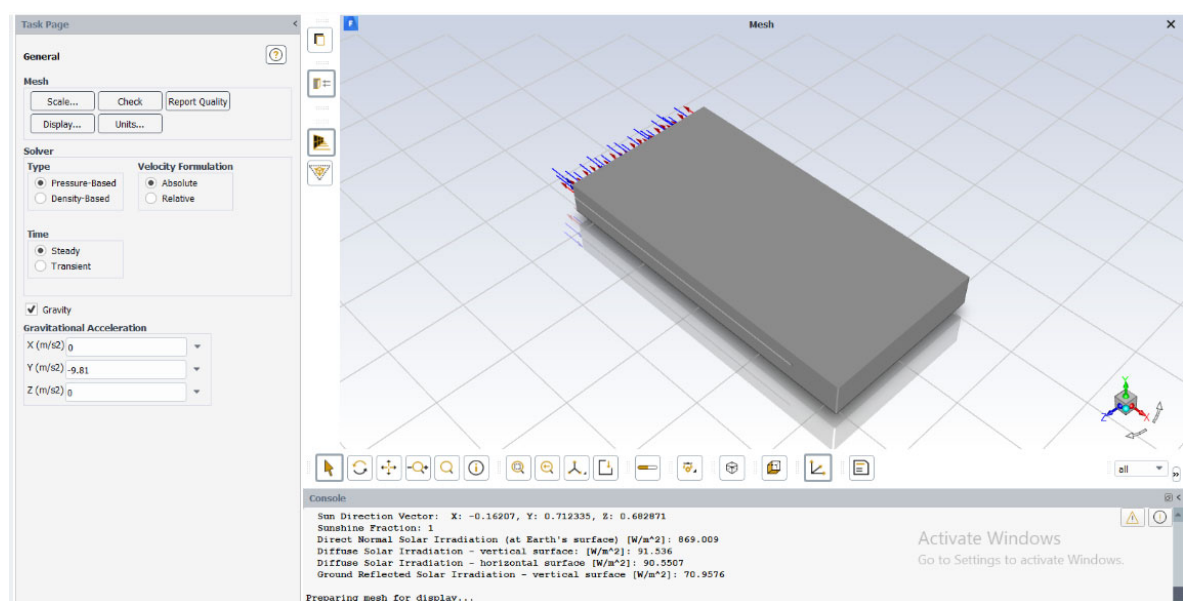


Figure 3.10. Step-3 Solution setup

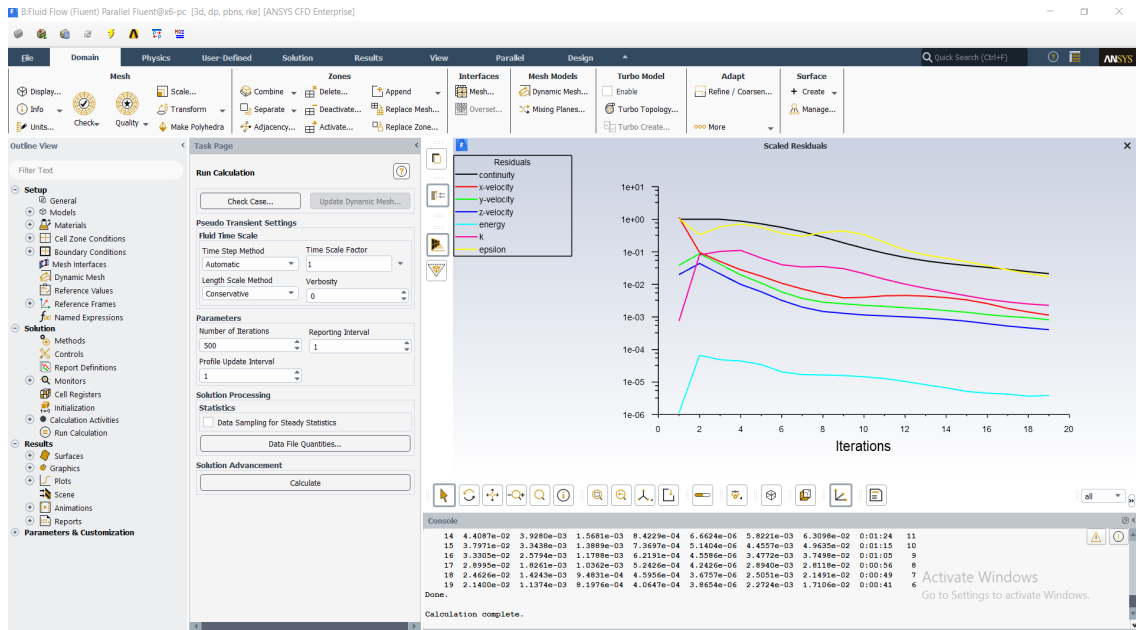


**Figure 3.11. Step-4 Iteration for solution**

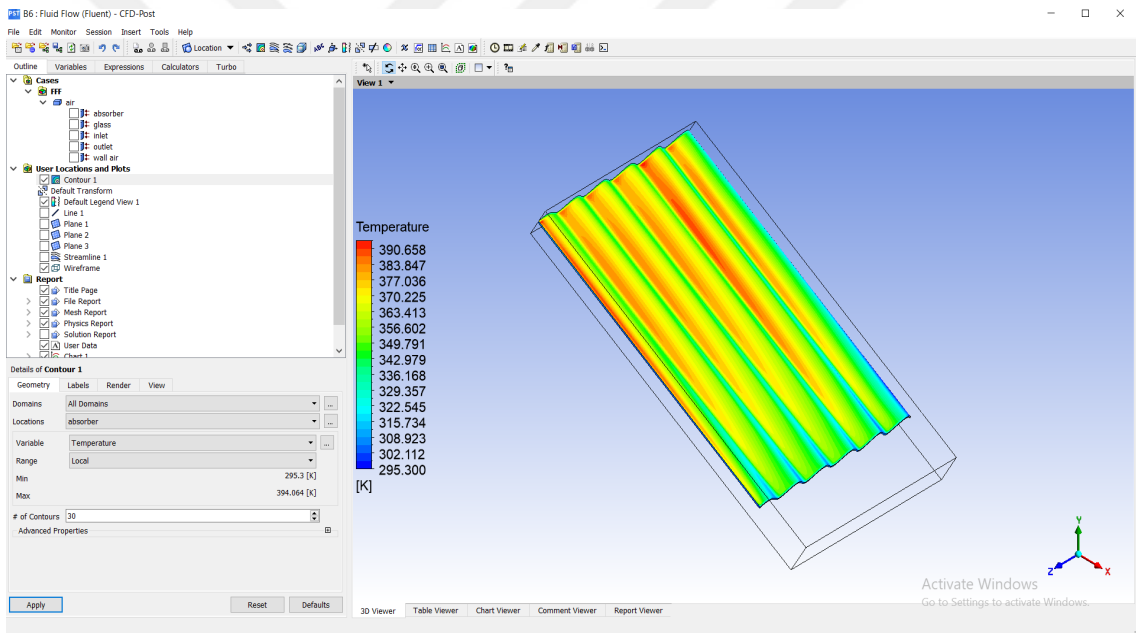


**Figure 3.12. Step-5 Solution results**

Fluent Launcher lets us choose the version of ANSYS Fluent that was used based on our geometry and on our processing capabilities, as shown in Fig. 3.13. The dimension is 3-D, and from the option, because the smallest relative variations are important to us, we chose double precision to improve the handling of the mathematical method and solver element. We selected display mesh after reading. It enables us to have the mesh displayed automatically when the mesh or case file has been read.

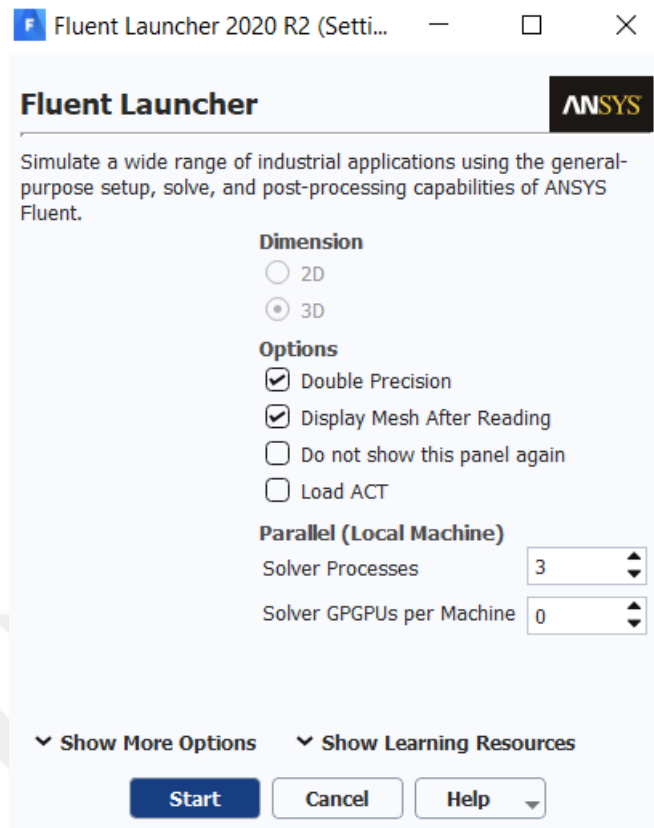


**Figure 3.13.** Launching ANSYS Fluent

We picked a solver and specified physical models, material parameters, and zone conditions for our simulation utilizing the Physics ribbon tab. Retain the default choice of the steady pressure-based solver in the Solver group box of the Physics ribbon tab. Since we have incompressible flows and a low value for velocity in the absolute domain, we chose pressure-based, velocity formation is absolute, and time is steady. Also, we enabled gravity because of its effects on the flow. We chose a value of -9.81 at the y-axis, and at the end, we ran the calculation. Set up models utilizing the Models group box of the Physics ribbon tab for the CFD simulation. Activate the energy equation to enable heat transfer. In the Physics ribbon tab, enable Energy (Models group box). Moreover, our flow is turbulent. We enabled the k-epsilon and also selected realizable because it's faster and more correct, as shown in Fig. 3.14.

**Viscous Model**

**Model**

- ☐ Inviscid
- ☐ Laminar
- ☐ Spalart-Allmaras (1 eqn)
- ☒ k-epsilon (2 eqn)
- ☐ k-omega (2 eqn)
- ☐ Transition k-kl-omega (3 eqn)
- ☐ Transition SST (4 eqn)
- ☐ Reynolds Stress (7 eqn)
- ☐ Scale-Adaptive Simulation (SAS)
- ☐ Detached Eddy Simulation (DES)
- ☐ Large Eddy Simulation (LES)

**k-epsilon Model**

- ☐ Standard
- ☐ RNG
- ☒ Realizable

**Near-Wall Treatment**

- ☒ Standard Wall Functions
- ☐ Scalable Wall Functions
- ☐ Non-Equilibrium Wall Functions
- ☐ Enhanced Wall Treatment
- ☐ Menter-Lechner
- ☐ User-Defined Wall Functions

**Options**

Buoyancy Effects: Only Turbulence Production

- ☐ Viscous Heating
- ☐ Curvature Correction
- ☐ Production Limiter

**Model Constants**

C2-Epsilon: 1.9

TKE Prandtl Number: 1

TDR Prandtl Number: 1.2

Energy Prandtl Number: 0.85

Wall Prandtl Number: 0.85

**User-Defined Functions**

Turbulent Viscosity: none

**Prandtl Numbers**

TKE Prandtl Number: none

TDR Prandtl Number: none

Energy Prandtl Number: none

Wall Prandtl Number: none

OK Cancel Help

**Figure 3.14.** Standard solve pressure

Enable radiation (Rosseland, solar loading). We chose Rosseland since we chose pressure-based solve before. In the solar load, we selected solar ray racing for predicting the direct illuminating source of energy resulting from incident solar radiation, and we enabled the use of direction computed from the solar calculator in the sun direction vector. As shown in Fig. 3.15.



Utilizing the Materials group box of the Physics ribbon tab, set up the materials for the CFD simulation. Utilizing the Create/Edit Materials dialog box, create a new material called water. In the Physics ribbon tab, click Create/Edit (Materials group box). As shown in Fig. 3.17. We chose the fluid as air, and the properties are the density is incompressible ideal gas, specific heat is constant 1006.43 kg/m<sup>3</sup>, thermal conductivity is constant 0.0242 W/m.K, viscosity is constant 1.7894e<sup>-05</sup> kg/m.s, molecular weight is constant 28.966 kg/kmol, absorption coefficient constant 0, scattering coefficient constant 0, scattering phase function is isotropic, and the refractive index is constant 1.

**Create/Edit Materials**

Name:

Material Type:

Chemical Formula:

Fluent Fluid Materials:

Mixture:

Order Materials by: ☒ Name ☐ Chemical Formula

Fluent Database...  
GRANTA MDS Database...  
User-Defined Database...

**Properties**

Density (kg/m3):

Cp (Specific Heat) (J/kg-K):

Thermal Conductivity (W/m-K):

Viscosity (kg/m-s):

Molecular Weight (kg/kmol):

Absorption Coefficient (1/m):

Scattering Coefficient (1/m):

Scattering Phase Function:

Refractive Index:

**Figure 3.17.** Materials properties

The setup of the boundary conditions for the inlets, outlets, and walls for CFD analysis utilizing the Zones group box of the Physics ribbon tab. In the physics tab, pick boundaries (Zones group box).

This brings up the task page for boundary conditions, where the boundaries established in our simulation appear in the Zone selection list. Bring up the Velocity Inlet

dialog box by double-clicking cold-inlet. Keep the standard Magnitude setting typical to the Boundary from the Velocity. From the Specification in the Turbulence group box, select Hydraulic Diameter and Intensity.

Inlet boundary conditions, we selected the velocity specification method is magnitude normal to the boundary, to enable us to provide a Velocity Magnitude normal to the boundary. The reference frame is absolute since our fluid flow in most case not rotating, and the velocity magnitude is 0.5 m/s, the supersonic/initial gauge pressure is 0, the specification method is intensity and viscosity ratio in order to define our turbulent boundary conditions, turbulent intensity is 5% mean the velocity of turbulent fluctuation is 5% of the mean velocity, and also the turbulent viscosity ratio is 10 reasonable value for case that we have as illustrated in Fig. 3.18.

**Figure 3.18.** Inlet boundary condition

The pressure outlet, since only when the flow is subsonic, is the given static pressure employed. The given pressure will no longer be utilized. For that, the backflow reference frame is absolute. The gauge pressure is 0, the pressure profile multiplier is 1, the backflow direction specification method is normal to the boundary, the backflow pressure specification is total pressure, the specification method is intensity and viscosity ratio, the backflow turbulent intensity is 5%, and the backflow turbulent viscosity ratio is 10 as illustrated in Fig. 3.19.

**Pressure Outlet**

Zone Name  
outlet

Momentum Thermal Radiation Species DPM Multiphase Potential UDS

Backflow Reference Frame: Absolute

Gauge Pressure (pascal): 0

Pressure Profile Multiplier: 1

Backflow Direction Specification Method: Normal to Boundary

Backflow Pressure Specification: Total Pressure

☐ Prevent Reverse Flow

☐ Radial Equilibrium Pressure Distribution

☐ Average Pressure Specification

☐ Target Mass Flow Rate

**Turbulence**

Specification Method: Intensity and Viscosity Ratio

Backflow Turbulent Intensity (%): 5

Backflow Turbulent Viscosity Ratio: 10

Apply Close Help

**Figure 3.19.** Outlet boundary condition

For absorber wall boundary conditions, the zone name is absorber, the adjacent cell zone is air, radiation, the BC type is opaque, and the solar boundary condition we enabled the participates in solar ray tracing, the absorptivity of the direct visible is 0.9, and the direct IR is 0.9. For glass wall boundary conditions, the adjacent cell zone is air and radiation, the BC type is semi-transparent, and we enabled participation in solar ray tracing for the solar boundary condition. For absorptivity, we chose the direct visible is 0.1, the direct IR is 0.1, and the diffuse hemispherical is 0.1. Also, for transmissivity, we chose the direct visible is 0.9, the direct IR is 0.9, and the diffuse hemispherical is 0.9, as illustrated in Fig. 3.20. For other wall boundary conditions, the zone name is wall-air, the adjacent cell zone is air, radiation, the BC type is opaque, the absorptivity of the direct visible is 0.8, and the direct IR is 0.8.

Wall

Zone Name  
glass

Adjacent Cell Zone  
air

Momentum Thermal **Radiation** Species DPM Multiphase UDS Potential Structure

BC Type  
semi-transparent

Solar Boundary Conditions

☒ Participates in Solar Ray Tracing

| Absorptivity          |     | Transmissivity        |     |
|-----------------------|-----|-----------------------|-----|
| Direct Visible        | 0.1 | Direct Visible        | 0.9 |
| Direct IR             | 0.1 | Direct IR             | 0.9 |
| Diffuse Hemispherical | 0.1 | Diffuse Hemispherical | 0.9 |

Apply Close Help

**Figure 3.20.** Glass Wall Boundary Condition

In the next steps, the Solution ribbon tab is used to set up and execute the calculation. Additionally, execute solution-related tasks using the task pages mentioned below in the Solution tree branch. Choose a solver scheme. In the Solution ribbon tab, we chose Methods (Solution group box), as shown in Fig. 3.21.

The scheme is coupled for the solution methods we selected for pressure velocity coupling because this solver has some benefits. Furthermore, steady-state flows it is more resilient and efficient. For spatial discretization, the gradient is least squares cell-based since the tetrahedral mesh has been employed, the pressure and the momentum are selected second-order and second-order upwind, respectively, for more accuracy, the turbulent kinetic energy is first-order upwind, and the specific dissipation rate is first order upwind. Furthermore, we selected pseudo transient to get the steady state solution and warped-face gradient correction. Any mesh with polyhedral components should have this option enabled by default. This operation fixes gradient inaccuracies caused by the polyhedral.

**Solution Methods**

**Pressure-Velocity Coupling**

Scheme  
Coupled

**Spatial Discretization**

Gradient  
Least Squares Cell Based

Pressure  
Second Order

Momentum  
Second Order Upwind

Turbulent Kinetic Energy  
First Order Upwind

Specific Dissipation Rate  
First Order Upwind

Energy

Transient Formulation  
[Dropdown]

☐ Non-Iterative Time Advancement

☐ Frozen Flux Formulation

☒ Pseudo Transient

☒ Warped-Face Gradient Correction

☐ High Order Term Relaxation Options...

Structure Transient Formulation  
[Dropdown]

Default

**Figure 3.21.** Solution methods

During the calculation, enable the plotting of residuals. In the Solution ribbon tab, choose Residuals 10-6 to ensure the correct solution. (Reports group box) as shown in Fig. 3.22.

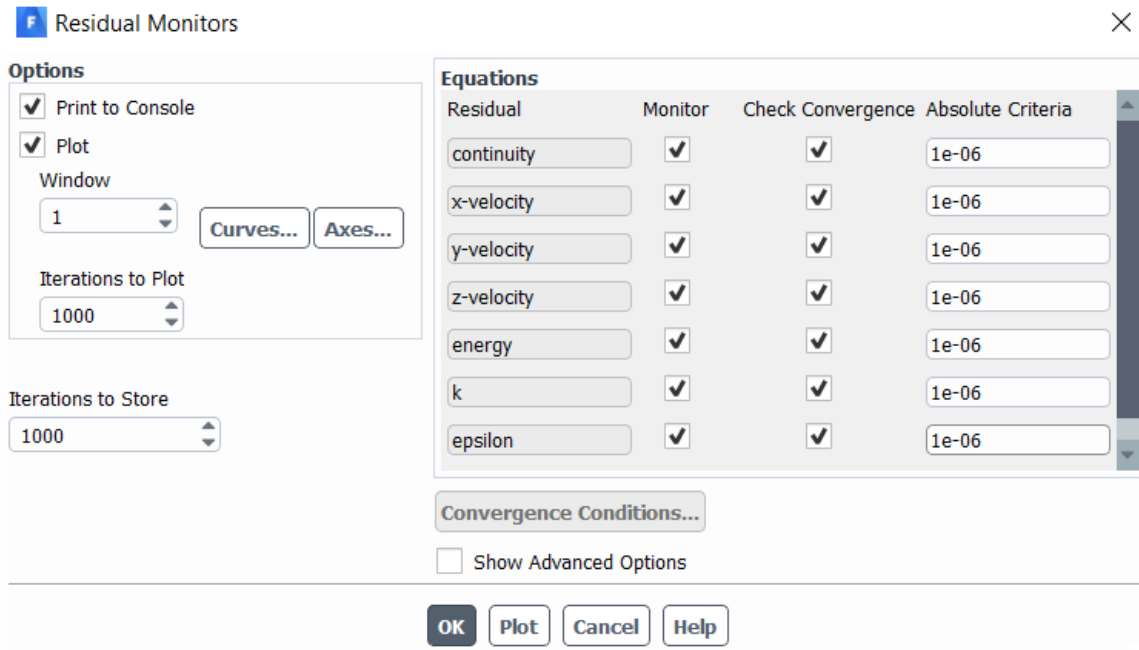


**Figure 3.22.** Residual monitors

We used the Initialization group box of the Solution ribbon tab to initiate the flow field. We selected standard initialization for the solution initialization methods, and the reference frame is relative to the cell zone for initial values. We selected the gauge pressure as 0, X velocity as 0, Y velocity as 0, Z velocity as 0, turbulent kinetic energy as  $1 \text{ m}^2/\text{s}^2$ , and the turbulent dissipation rate as  $1 \text{ m}^2/\text{s}^3$ . To start the calculation, the solver requests 250 iterations on the Solution ribbon tab (Run Calculation group box). For the run calculation, we selected the time advancement is fixed, the method is user-specified, for the parameters we selected the number of times is 120, the time step size is 5, the max iterations/time step is 250, the reporting interval is 1, and the profile update interval is 1.

### 3.3. Experimental Work

Full details of the experimental setup are presented in this section. The dual-flow SAHs with different types of plate collectors were designed and used in dimensions. The dual-flow SAHs were tested on different days in April 2022, and these were the 2<sup>nd</sup>, 3<sup>rd</sup>, 6<sup>th</sup>, 18<sup>th</sup>–20<sup>th</sup>, 24<sup>th</sup>, 27<sup>th</sup>, 28<sup>th</sup>, 30<sup>th</sup>, and in May 2022, the 31<sup>st</sup>.

The present study was designed to examine the effects of various flow rates, inlet air temperatures, and solar irradiation levels.

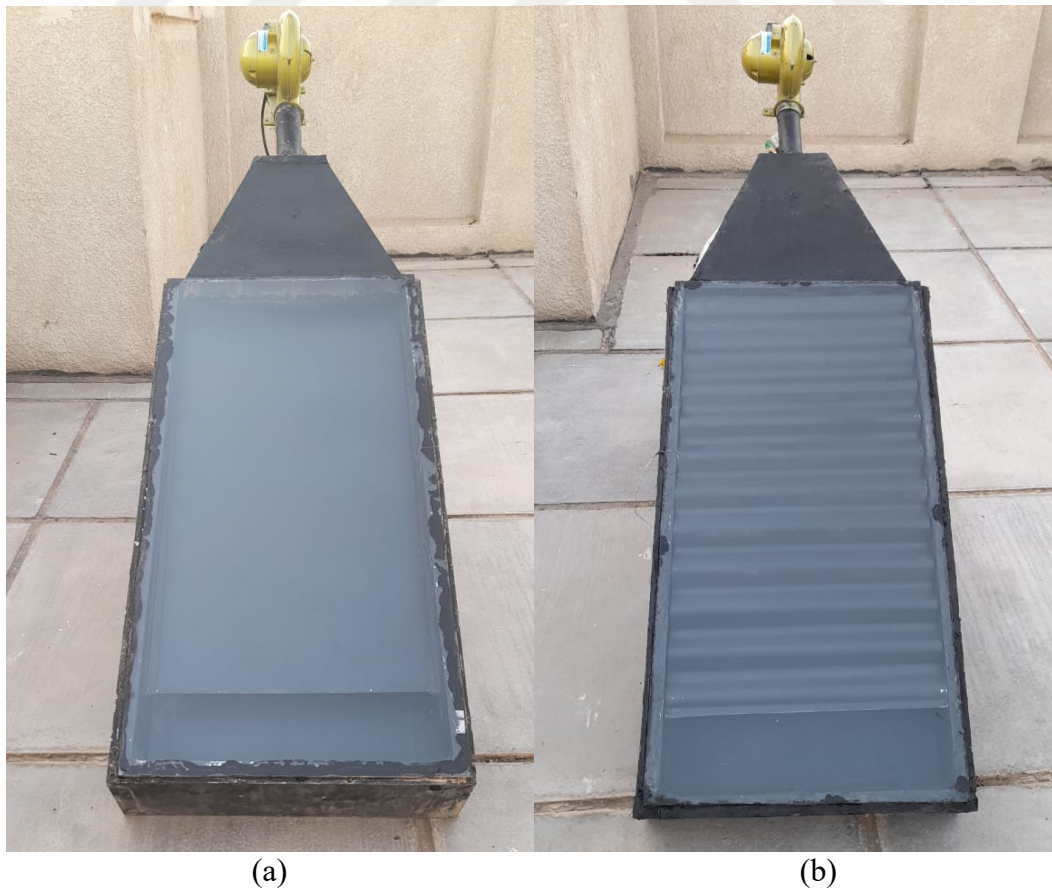
#### 3.3.1. Experimental setup

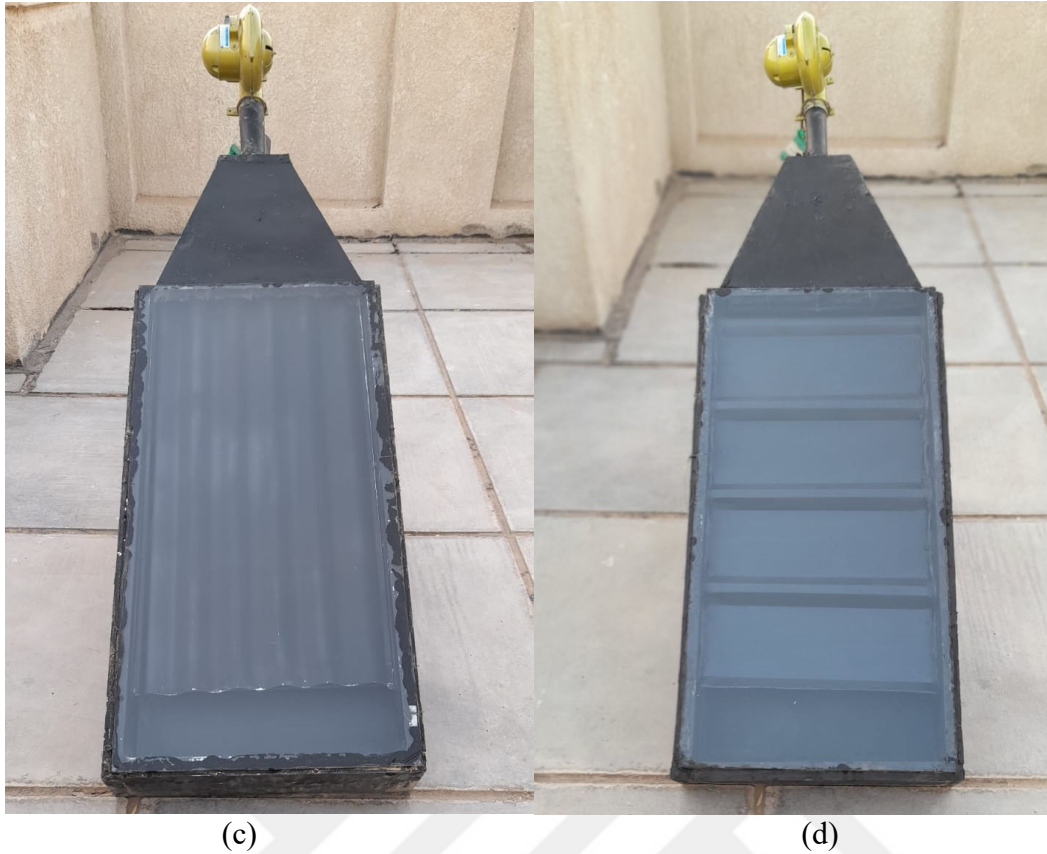
We developed and built two models of counter-flow dual-flow solar air heaters (dual-flow SAH) with comparable dimensions and different absorber plates using locally

accessible materials to conduct thermal efficiency. The completed dual-flow SAHs are shown in Fig. 3.23.

We installed the dual-flow SAH in Baghdad, Iraq (33.3° Latitude) on the south side (surface azimuth angle zero due south) with a tilt angle of 30° degrees from horizontal. A sketch of the cross-section experimental set-up of dual-flow SAH is illustrated in Fig. 3.24. In the opposite direction, air flows over and below the absorber plate.

The structure of the dual-flow SAH is rectangular (100 cm) in length (50 cm) in width, and its thickness is 15 cm, with 5 cm of glass wool insulation on the bottom wall and 3 cm of glass wool insulation on the side walls. The inlet and the exit of the collector are trapezoidal shapes, and the length was equal to or more than  $2.5\sqrt{W*H}$ , where W is the width, and H is the height. In the present work rig, the length of the entry section was 35 cm to allow the air to develop flow fully, and the upper base and lower base were (44 cm and 14 cm), respectively. The inlet is a single-hole circular duct (5 cm) in diameter. The fan was located at the upper section of the SAH to force air inside the collector, as shown in Fig. 3.25.





(c) (d)

**Figure 3.23.** Photo for the dual-flow SAHs with different absorber plates  
 (a) Flat plate, (b) U -corrugated plate parallel direction to airflow, (c) U -corrugated plate anti-parallel direction, (d) Trapezoidal corrugated plate

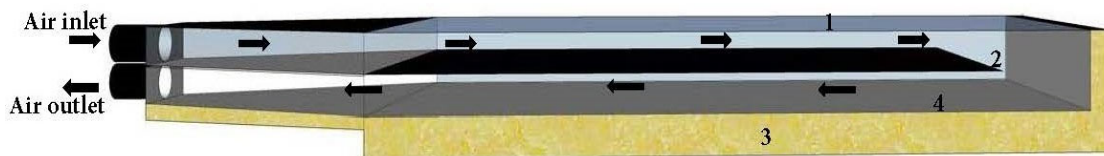


**Figure 3.24.** Schematic of a dual-flow SAH  
 (1. Glass, 2. Absorber plate, 3. Glass wool 4. Bottom plate)

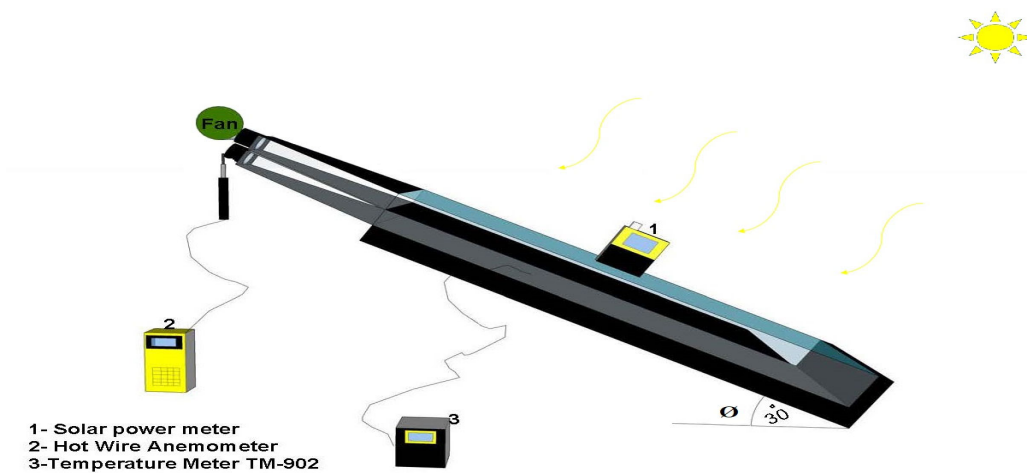


**Figure 3.25.** Experimental set-up of dual-flow SAH

### 3.3.2. Preparation and manufacturing

First, the dimensions and sizes of the collector were chosen based on past studies so that they could be compared with other researchers. The physical parameters properties of the collector components are in Table 3.3.

**Table 3.3.** SAH's Physical properties.

|                                                 | Thermal conductivity<br>( $k$ ) W/m.K | Density<br>( $\rho$ ) kg/m <sup>3</sup> | Specific Heat<br>( $C_p$ ) J/kg.K | Absorptivity | Emissivity<br>( $\epsilon$ ) | Ref                    |
|-------------------------------------------------|---------------------------------------|-----------------------------------------|-----------------------------------|--------------|------------------------------|------------------------|
| Flat plate<br>(Aluminum)                        | 217                                   | 2707                                    | 887                               | 0.94         | 0.09                         | Kumar A, et al (2019). |
| U - corrugated<br>plate<br>(Galvanized<br>iron) | 204.2                                 | 7870                                    | 896                               | 0.91         | 0.8                          |                        |
| Glass wool                                      | 0.0372                                | 200                                     | 670                               | -            | -                            |                        |
| Glass                                           | 0.8                                   | 2500                                    | 840                               | 0.05         | 0.8                          | Ovando et al. (2010).  |

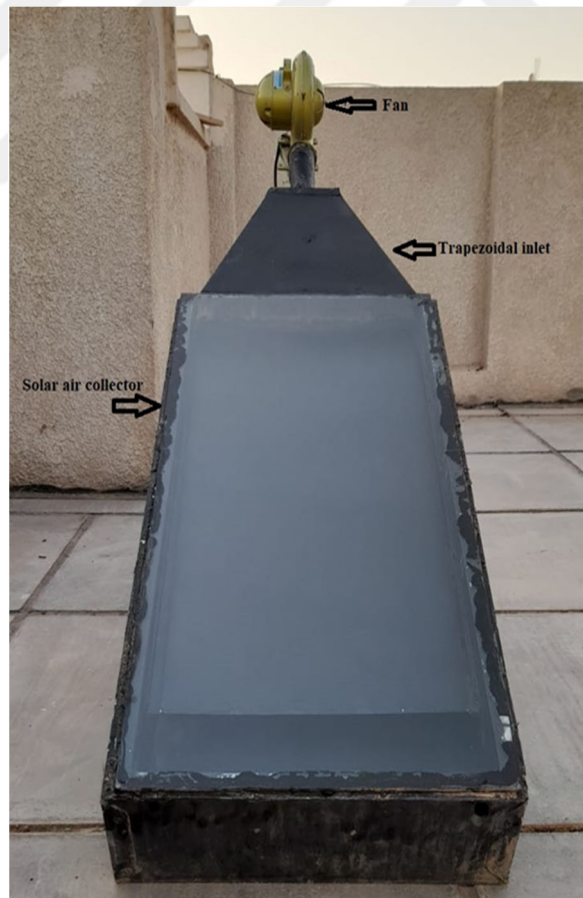


**Figure 3.26.** The manufactured air solar collector

The dual-flow SAH structure is the container that structurally holds the collector assembly together. The structure must be structurally sound, waterproof, and fireproof.

We used an aluminum plate and held it together with a tong and also painted it with black mat paint as indicated in Fig .3.27.



**Figure 3.27.** Manufacturing dual-flow SAH structure

Furthermore, it is capable of being mechanically linked to a substructure to construct a rigorous collector structure material, which in the present study is made of aluminum with a thickness of 0.7 mm, as indicated in Fig. 3.28.



**Figure 3.28.** Dual-flow SAH structure

The dual-flow SAH structure, which is the major portion of the collector, is tied to a conic duct having three pieces to maintain the uniformity of inlet and outlet airflow. The top base and lower base of the heater created for the experimental setup were 44 cm and 14 cm, respectively, long to allow for fully developed airflow. The inlet was a 5 cm-

in diameter circular duct connected to a centrifugal fan that was fixed in the upper section, as indicated in Fig. 3.29.



**Figure 3.29.** Vanes of collector

The absorber flat plate utilized in this experiment was made from aluminum with a thickness of 0.7 mm. In addition, all three other types of corrugated absorbent plates utilized in this study were galvanized iron with a thickness of 1 mm. The dimensions of the absorbent plate were 85 cm  $\times$  44 cm, and the spray technique was used for painting it with a thin layer of matt black color to enable the metal substrate's emission properties to result in a high overall selectivity or efficiency while maintaining high absorbance.

The absorbent plate installed (10 cm) from the SAH base will lead to a split inside the SAH into upper and lower channels, as well as an empty zone with a length of (12cm) to force air exit from the SAH and change the flow from the upper to the lower channel. As indicated in Fig. 3.30.

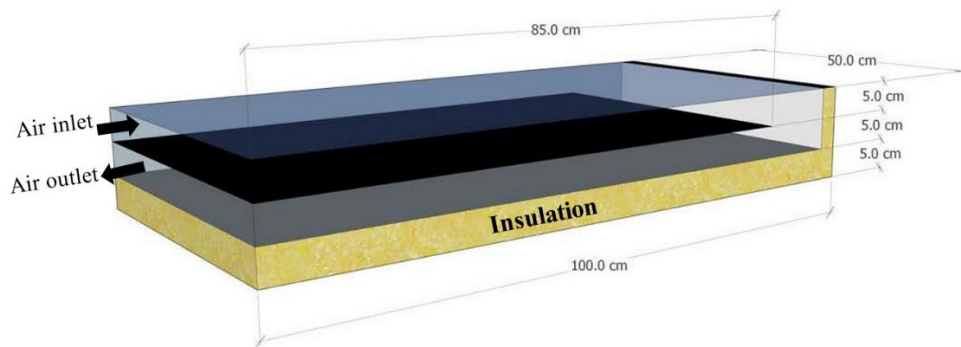


**Figure 3.30.** The absorber plate at 10 cm away from the SAH base

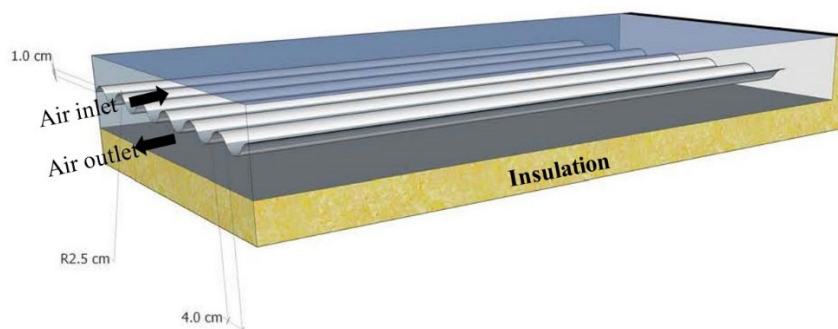
It is a significant part because air flows over and below it and can affect heat transfer and function as a heat exchanger in SAH by converting radiant energy into thermal energy.

The following are four types of absorbers that were used in the study to compare the thermal efficiency of SAH.

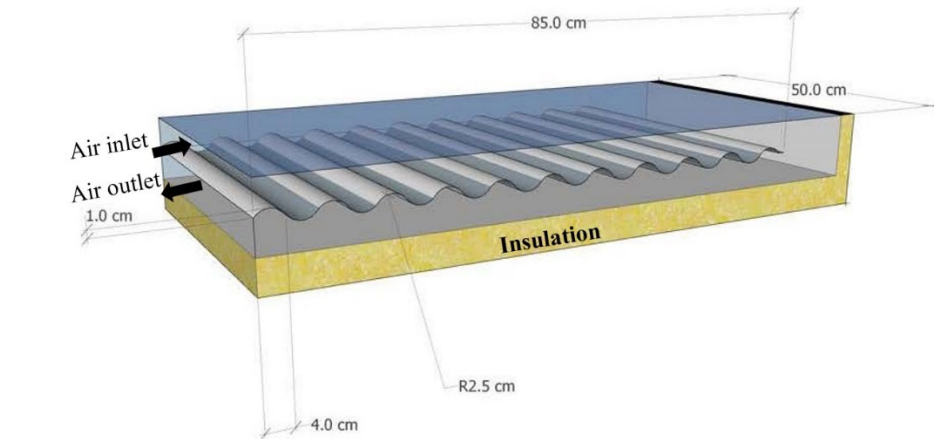
- The first model is a flat plate without corrugated, and this model will be taken as a reference one as indicated in Fig. 3.31.a.
- The second model is u-corrugated plate. Utilized in a parallel direction to airflow as shown in Fig 3.31.b.
- The third model is a u-corrugated plate. Utilized in anti-parallel direction to airflow as shown in Fig 3.31.c
- The fourth model is a trapezoidal corrugated plate. Utilized in anti-parallel direction to airflow as indicated in Fig 3.31.d. In addition, Fig 3.32. shows the dimensions of this type.



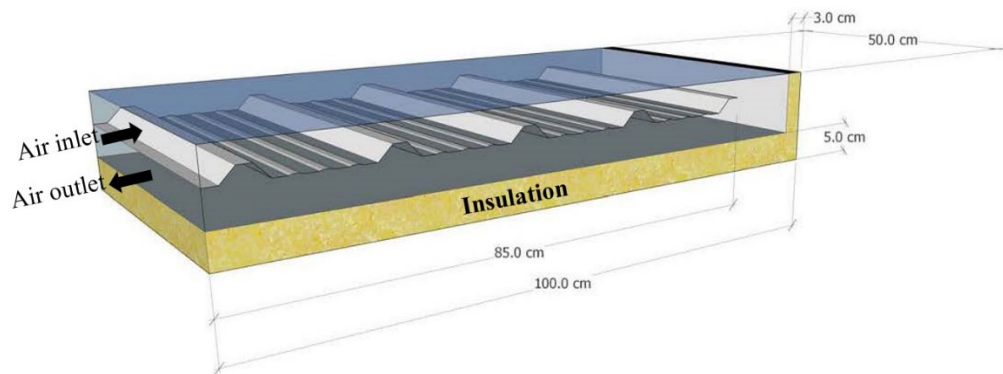
(a) Type I - Flat absorber plate



(b) Type II – U-corrugated plate utilized in a parallel direction to airflow



(c) Type III – U-corrugated plate utilized in an anti-parallel direction to airflow



(d) Type IV- Trapezoidal corrugated plate utilized in an anti-parallel direction to airflow

**Figure 3.31.** Four types of absorber plates

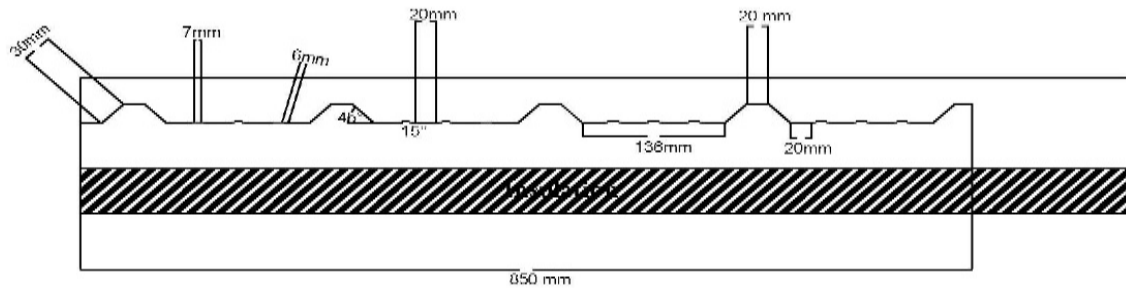


**Figure 3.32.** Trapezoidal corrugated plate dimensions

The spray technique was utilized for painting the absorber plates with black matt paint and then exposed to sunlight to evaporate the solvents and increase adhesion. The effectiveness of any solar collector is heavily reliant on its absorber's capacity to convert solar irradiance into heat by employing a coating with low thermal emittance and a high solar absorptance.

Aluminum was used to make the bottom plate, which had a thickness (0.7 mm). The size of the bottom plate was (97 cm × 44 cm), and the spray technique for painting it with a thin layer of matt black color enabled the metal substrate's emission properties to

result in a high overall selectivity or efficiency and keep high absorbance as shown in Fig 3.35. The Aluminum plate was used to construct a bottom plate to move air over it. It has a thermal conductivity of ( $k= 217 \text{ W/m}\cdot\text{K}$ ) at temperature =  $100^\circ\text{C}$ , an absorptivity of 0.94 with a transmissivity of 0.09 (Abdullah et al., 2018).

Glass covers are commonly used to glaze SAH because they may transmit up to 90% of the ambient shortwave solar irradiance. The transparency cover reduces radiation wastage from the SAH because the glass is translucent to short-wave solar irradiance but almost opaque to long-wave thermal irradiance released by the absorbent plate (greenhouse effect), acting as a solar radiation catcher. It uses a conventional 4 mm thick glass for the cover (100 cm length x 50 cm width).

SAH casings have to be properly insulated to reduce heat loss from the collector's sides and back. The insulation is comprised of glass wool and can tolerate temperatures of up to  $200^\circ\text{C}$ . It's commonly utilized in solar collectors. The thickness of the back insulation is 5 cm, while the thickness of the edge insulation is 3 cm, as indicated in Fig. 3.33.



**Figure 3.33.** Insulation of Collector

The SAH was connected to a centrifugal fan blower of the radial types as indicated in Fig. 3.34. Table 3.4 lists the fan's specifications as noted on the fan plate.

**Table 3.4.** Specification of fan blower.

| Size | Voltage | Cycles | Power | Current | Rotation | Flow rate                 |
|------|---------|--------|-------|---------|----------|---------------------------|
| (in) | (V)     | (Hz)   | (W)   | (Amps)  | (rpm)    | ( $\text{m}^3/\text{h}$ ) |
| 2"   | 220     | 50     | 150   | 1.0     | 3000     | 192                       |



**Figure 3.34.** Centrifugal fan blower

Furthermore, an SSR-10VA solid state relay with a rheostat of 500 ohms was utilized to adjust the flow rate of the mass as indicated in Fig. 3.35.

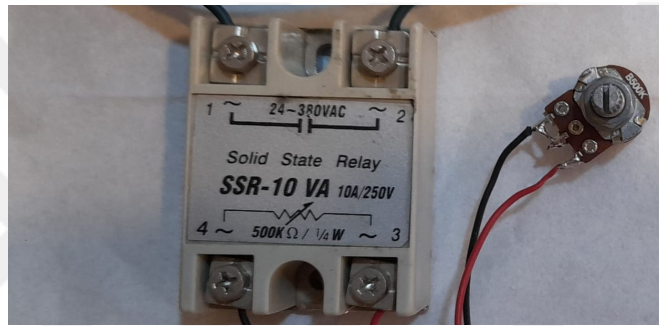


**Figure 3.35.** SSR-10VA solid state relay with a rheostat

### 3.3.3. Measurement devices

The solar meter, Model: TES 1333, was utilized to measure the solar radiation, as illustrated in Fig. 3.36. Every step of the time from sunrise to sunset was recorded, and the data was then written and entered into a computer (Excel application) so that the solar radiation data could be readily managed and manipulated.



**Figure 3.36.** Solar power meter (TES)

The velocity of the fan is measured with a Hot Wire Anemometer model GM8903, as illustrated in Fig. 3.37. It was mounted on the outlet of the collector. The range of this

instrument is (0-30m/s) and its accuracy is ( $\pm 3\% \pm 0.1$ ). In this study, four-speed were utilized (0.5, 1, 1.5, 2,) m/s.



**Figure 3.37.** Hot Wire Anemometer GM8903

K-type thermocouples we utilized to measure the temperature within the test rig. It is connected to a twelve thermostat type TM-902C (-50 °C – 1300 °C) as indicated in Figs. 3.38 and 3.39 are used to read temperatures by suitably attaching the Thermistors to the absorber plate to decrease contact resistance. Calibration of a temperature meter and thermocouples in Appendix [A](#).



**Figure 3.38.** Thermocouple of type K



**Figure 3.39.** Temperature Meter TM-902C (-50C-1300 °C)

We used in this study, a digital thermometer TPM-10 as shown in Fig. 3.40, was used to measure the ambient air temperature, it has a range of -50 °C to 110 °C and temperature accuracy is  $\pm 1$  °C.

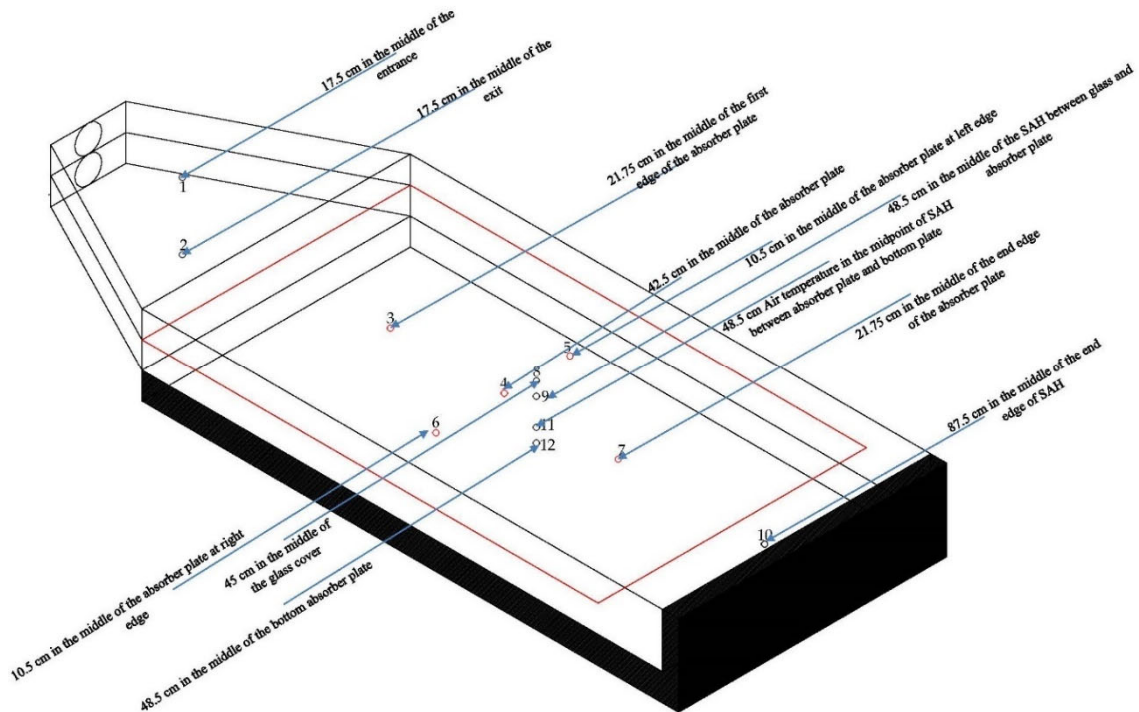


**Figure 3.40.** Digital thermometer TPM-10

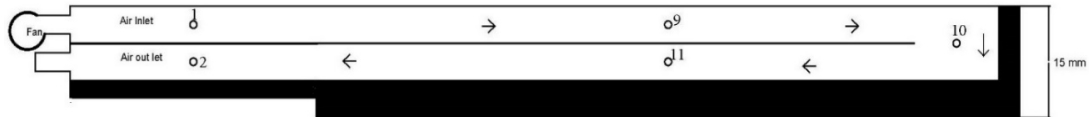
The measuring methods listed below must be followed in order to acquire data from the testing experiment:

- Measurements of temperature.
- Measurements of solar radiation.
- Measurements of air flow.

The temperature distribution was determined by measuring the temperature in the SAH. Thirteen sensors were employed for this purpose and installed in various areas within the collection and outside (environmental) of SAH. Whereas some are directly on the heated surface - on the plate - others were employed to measure the temperature of air in and out of the SAH. As indicated in Figs. 3.4.



(a) General sensor arrangements for the air



(b) Cross-sectional sensor arrangements for the air  
**Figure 3.41.** Sensor arrangements

The temperature will be measured as following in Table 3.5.

**Table 3.5.** Temperature readings and sensor arrangements

| Measurement location                        | Number of points | Sensor No.                                                                                  |
|---------------------------------------------|------------------|---------------------------------------------------------------------------------------------|
| Inlet air temperature                       | One point        | Tc <sub>1</sub>                                                                             |
| Outlet air temperature                      | One point        | Tc <sub>2</sub>                                                                             |
| Temperature of the plate                    | Five points      | Tc <sub>3</sub> , Tc <sub>4</sub> , Tc <sub>5</sub> , Tc <sub>6</sub> , and Tc <sub>7</sub> |
| Temperature of the glass                    | One point        | Tc <sub>8</sub>                                                                             |
| Temperature of the bottom Plate             | One point        | Tc <sub>12</sub>                                                                            |
| Temperature of the air inside the collector | Three point      | Tc <sub>9</sub> , Tc <sub>10</sub> , and Tc <sub>11</sub>                                   |
| Temperature of ambient                      | One point        | Tc <sub>12</sub>                                                                            |



**Figure 3.42.** Arrangement the fixing of thermocouples

### 3.3.4. Data reduction

The mathematical equations of the thermal balance of the dual-flow SAH are (Yousef and Adam, 2008b).

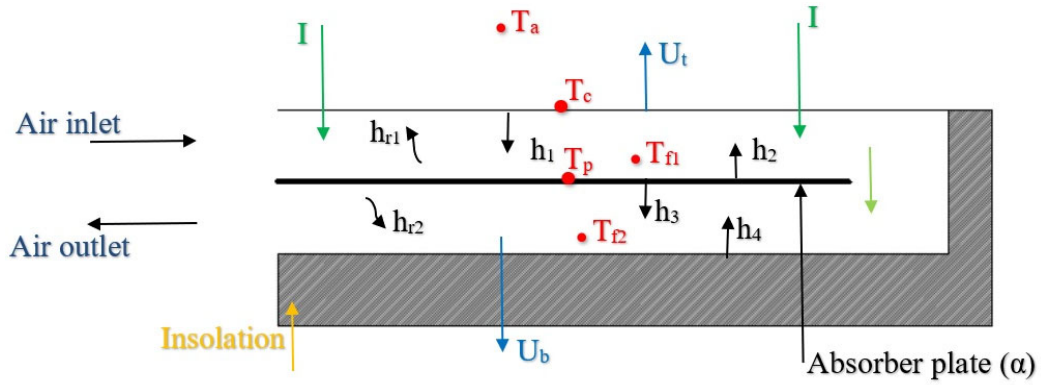


**Figure 3.43.** Dual-flow SAH schematic illustration

For the collector cover

$$h_1(T_{f1} - T_c) + h_{r1}(T_p - T_c) = U_t (T_c - T_a) \quad (3.28)$$

For the upper stream

$$h_2(T_p - T_{f1}) = \left(\frac{m \cdot C_p}{w}\right) \left(\frac{dT_{f1}}{dx}\right) + h_1(T_{f1} - T_c) \quad (3.29)$$

For absorber plate

$$I\tau\alpha = h_{r1}(T_p - T_c) + h_2(T_p - T_{f1}) + h_3(T_p - T_{f2}) + h_{r2}(T_p - T_r) \quad (3.30)$$

For the lower stream

$$h_3(T_p - T_{f2}) = \left(\frac{m \cdot C_p}{w}\right) \left(\frac{dT_{f1}}{dx}\right) + h_4(T_{f2} - T_r) \quad (3.31)$$

For the bottom plate

$$h_4(T_{f2} - T_r) + h_{r2}(T_p - T_r) = U_b (T_r - T_a) \quad (3.32)$$

Here,  $h_3$  is the convection heat transfer coefficient from plate to stream in the bottom passage, expressed in  $W/m^2K$ ,  $h_4$  is the coefficient of convection heat transfer from the stream in the lower passage to the bottom plate, expressed in  $W/m^2K$ ,  $h_{r2}$  is the irradiance heat transfer coefficient from the absorbent plate to the bottom plate, expressed in  $W/m^2K$ , and  $T_r$  is bottom temperature, expressed in  $K$ .

The ratio of energy gained to total absorbed solar irradiation is known as thermal efficiency. We used the equations from this ref (Abdullah et al., 2018).

$$\eta = \frac{Q_u}{A_c \cdot I} \quad (3.33)$$

Here  $A_c$  is collector absorber area ( $m^2$ ), and  $I$  is the incident solar energy ( $W/m^2$ ).

The energy gained is given by

$$Q_u = \dot{m} \cdot C_p \cdot (T_{out} - T_{in}) \quad (3.34)$$

Here  $C_{pa}$  is the specific heat capacity of air ( $kJ / kg \cdot ^\circ C$ ), and  $(T_{out} - T_{in})$  is input and outlet air temperatures ( $^\circ C$ )

Air mass flow rate

$$\dot{m} = \rho_a \cdot V_a \cdot A_{duct} \quad (3.35)$$

We used air's physical characteristics are expected to fluctuate linearly with temperature and are regulated by the following relationships in Table 3.6 below:

**Table 3.6.** Air's physical propartiese in this study

| Parameters           | Equations                                        | Reference                   |
|----------------------|--------------------------------------------------|-----------------------------|
| Specific heat        | $C_p = 1.0057 + 0.000066(T - 27)$                | (Rasham and Alaskari 2018). |
| Density              | $\rho = 1.1774 - 0.00359(T - 27)$                |                             |
| Thermal conductivity | $k = 0.02624 - 0.0000758(T - 27)$                |                             |
| Viscosity            | $\mu = [1.983 - 0.00184(T - 27)] \times 10^{-5}$ |                             |

The following equation is used to calculate the SAH duct's air flow velocity

$$V = \frac{\dot{m}}{\rho WH} \quad (3.36)$$

The Reynold number and hydraulic diameter are written as

$$Re = \frac{\dot{m} \cdot D_h}{A_c \cdot \mu} \quad (3.37)$$

$$D_h = \frac{4w \cdot d}{2(w+d)} \quad (3.38)$$

Here,  $w$  is the collector width, and  $m$  and  $d$  are the channel dimensions ( $m$ ).

The following equation is calculated h value

$$h = \frac{Q}{A_p(T_p - T_f)} \quad (3.39)$$

The Nu is then determined using the h and the following equation

$$Nu = \frac{hD_h}{k} \quad (3.40)$$

The pressure drop ( $P$ ) measurements recorded over the length of the test section are used to calculate the friction factor as follows

$$f = \frac{2\Delta P D_h}{4\rho LV^2} \quad (3.41)$$

In all honesty, the pressure drop will also rise if a corrugated absorber plate is used in place of a flat absorber plate. Thus, it is crucial to concurrently calculate the rise in heat transfer and pressure drop. The following equation may be used to determine the enhancement of Nu:

$$TEF = \frac{Nu_w/Nu_p}{(f_w/f_p)^{0.33}} \quad (3.42)$$

Absorber plate temperature is given by

$$T_a = \frac{T_3+T_4+T_5+T_6+T_7}{5} \quad (3.43)$$

### 3.3.5. Uncertainty analysis

Uncertainty can be divided into two groups—direct measurement ( $\delta T$ ,  $\delta P$ ,  $\delta I$ , and  $\delta U$ ) and indirect measurement ( $\delta A_c$ ,  $\delta m$ ,  $\delta p$ , and  $\delta \eta$ ). If a parameter is computed using certain measured quantities, then uncertainty in the measurement of ‘y’ was given as in (Acir et al., 2019), where  $\delta x_1$ ,  $\delta x_2$ ,  $\delta x_3$ , . . .  $\delta x_n$  were the possible errors in measurements of  $x_1$ ,  $x_2$ ,  $x_3$ , . . .  $x_n$ .  $\delta y$  is known as the absolute uncertainty.

$$\delta y = \left[ \left( \frac{\partial y}{\partial x_1} \delta x_1 \right)^2 + \left( \frac{\partial y}{\partial x_2} \delta x_2 \right)^2 + \left( \frac{\partial y}{\partial x_3} \delta x_3 \right)^2 + \dots \left( \frac{\partial y}{\partial x_n} \delta x_n \right)^2 \right] \quad (3.44)$$

where,  $\delta x_1$ ,  $\delta x_2$ ,  $\delta x_3$ , . . .  $\delta x_n$  were the possible errors in measurements of  $x_1$ ,  $x_2$ ,  $x_3$ , . . .  $x_n$ .  $\delta y$  is known as absolute uncertainty.

**Table 3.7.** Uncertainty specifications

| Parameter                       | Unit             | Uncertainty ( $\delta$ ) |
|---------------------------------|------------------|--------------------------|
| Inlet temperature of collector  | °C               | ±0.12                    |
| outlet temperature of collector | °C               | ±0.12                    |
| Absorber temperature            | °C               | ±0.12                    |
| Ambient temperature             | °C               | ±0.12                    |
| Air velocity                    | m/s              | ±0.04                    |
| Time                            | min              | ±0.11                    |
| Solar radiation                 | W/m <sup>2</sup> | ±1.33                    |

In this study, the uncertainty values for the derivative parameters (rate of heat transfer,  $h$ ,  $Re$ , friction factor,  $Nu$ , and  $\eta$ ) were estimated using Eqns. (3.45)-(3.50), with the calculated values given in Table 3.7.

$$u_Q = \sqrt{\left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta cp}{cp}\right)^2 + \left(\frac{\Delta T}{T}\right)^2} \quad (3.45)$$

$$u_h = \sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta T_{LMTD}}{T_{LMTD}}\right)^2} \quad (3.46)$$

$$u_{Re} = \sqrt{\left(\frac{\Delta \rho}{\rho}\right)^2 + \left(\frac{\Delta u}{u}\right)^2 + \left(\frac{\Delta \mu}{\mu}\right)^2 + \left(\frac{\Delta D_h}{D_h}\right)^2} \quad (3.47)$$

$$u_f = \sqrt{\left(\frac{\Delta \Delta p}{\Delta p}\right)^2 + \left(\frac{\Delta \rho}{\rho}\right)^2 + \left(\frac{\Delta u}{u}\right)^2 + \left(\frac{\Delta D_h}{D_h}\right)^2 + \left(\frac{\Delta L}{L}\right)^2} \quad (3.48)$$

$$u_{Nu} = \sqrt{\left(\frac{\Delta h}{\Delta h}\right)^2 + \left(\frac{\Delta D_h}{D_h}\right)^2 + \left(\frac{\Delta k}{k}\right)^2} \quad (3.49)$$

$$u_\eta = \sqrt{\left(\frac{\Delta Q}{\Delta Q}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \quad (3.50)$$

## 4. RESULT AND DISCUSSIONS

The results of the recorded data and numerical examination were analyzed and described. These results investigate the impact of solar irradiation and air flow rates on the forced convection turbulence flow performance in the dual-flow SAH for four different absorber plates. Furthermore, a comparison of theoretical results and experimental results is validated. Finally, a comparison of the current mathematical model to earlier investigations is provided.

### 4.1. The Major Variables of the Subject Investigation

In this investigation, the ambient air temperature and solar irradiance were variable according to weather conditions. The tests were done on different days in April and May 2022 in Baghdad, Iraq.

The first test lasted four days (30 April, 03, 02, and 06 May) from 7:30 am to 5 pm. The second test lasted four days (18, 19, 20, and 24 May) from 7:30 am to 5 pm. The third test lasted four days (27, 28, 30, and 31 May) from 7:30 am to 5 pm. The readings were collected and categorized as follows in Table 4.1.

**Table 4.1.** Variables of the present study.

| Variables                 | Description                                                                                                                                                                                                                    |
|---------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Types of absorbent plates | a. Flat plate absorber plate.<br>b. U -corrugated plate parallel direction to airflow.<br>c. U -corrugated plate anti-parallel direction to airflow.<br>d. Trapezoidal corrugated plate in anti-parallel direction to airflow. |
| Air mass flow rate        | a. 0.0011 kg/s.<br>b. 0.0023 kg/s.<br>c. 0.0034 kg/s.<br>d. 0.0046 kg/s.                                                                                                                                                       |
| Solar irradiance          | Different values of solar radiation from 50 W/m <sup>2</sup> to 895 W/m <sup>2</sup> depending on the weather and day times.                                                                                                   |

The primary components of the SAH in the experiments conducted are glass covering, absorbent surfaces, two airflow channels, and a bottom plate. Thermocouples measure the temperatures of these SAH parts and the airflow in the dual-flow. The heat transmission from the heated upper and bottom absorbent plates of the dual-flow SAH to the moving air is enhanced thermally because of the double region of heat convection in two channels along the absorber plate.

## 4.2. Experimental Investigation Results

This section compares the conventional flat plate SAH to different types of SAH and illustrates the effect of utilizing four different mass flow rate values. The experimental results are investigated for the four cases of the dual-flow SAH in an outdoor environment. Every 30 minutes, the measurements of flow rate, solar irradiance, ambient, entrance and output air temperatures, absorbent plate temperature at several predetermined points, and air temperature within the SAH are recorded as detailed below;

### 4.2.1. Absorber flat plate and other types

Fig. 4.1 illustrates the variation in mean absorbent plate temperature, input air temperature, and output air temperature ( $T_{ap}$  and  $T_{out}$ ), respectively, over daytime at a flow rate of mass of 0.0011 kg/s. It can be noticed that the maximum value occurs at noon ( $T_{ap} = 98.76\text{ }^{\circ}\text{C}$ ,  $T_{in} = 33\text{ }^{\circ}\text{C}$  and  $T_{out} = 79.7\text{ }^{\circ}\text{C}$ ). It is clear that the mean absorbent plate temperature is higher than the outlet air temperature during the day. This results from the heat transmission resistance between the flat plate surface and the flowing air stream. The difference between these two values is frequently negligible for liquid heating collectors, but it may be important for SAHs, as observed in this work. Furthermore, Fig. 4.2 showed that the maximum absorbent plate temperature was at noon  $99\text{ }^{\circ}\text{C}$  for u-corrugated plate anti-parallel to airflow type at a flow rate of mass is 0.0046 kg/s while it was  $99.48^{\circ}\text{C}$ ,  $78.34^{\circ}\text{C}$ , and  $71.78\text{ }^{\circ}\text{C}$  for trapezoidal corrugated plate anti-parallel to airflow, u-corrugated plate parallel to airflow, and a flat plate at the same mass flow rate, respectively.

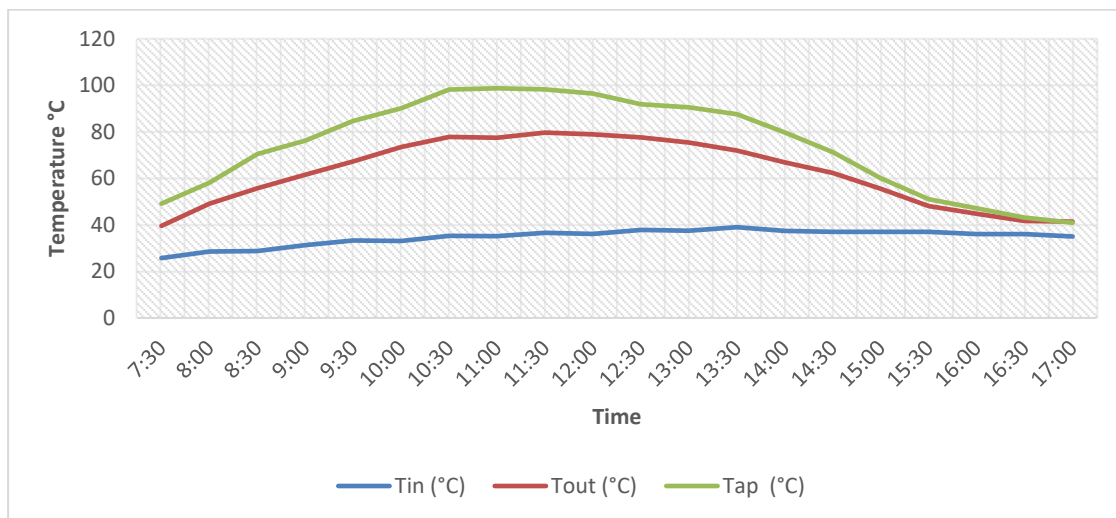


**Figure 4.1.** Variations in temperature vs time plot [ Test at 30-04-2022 ]

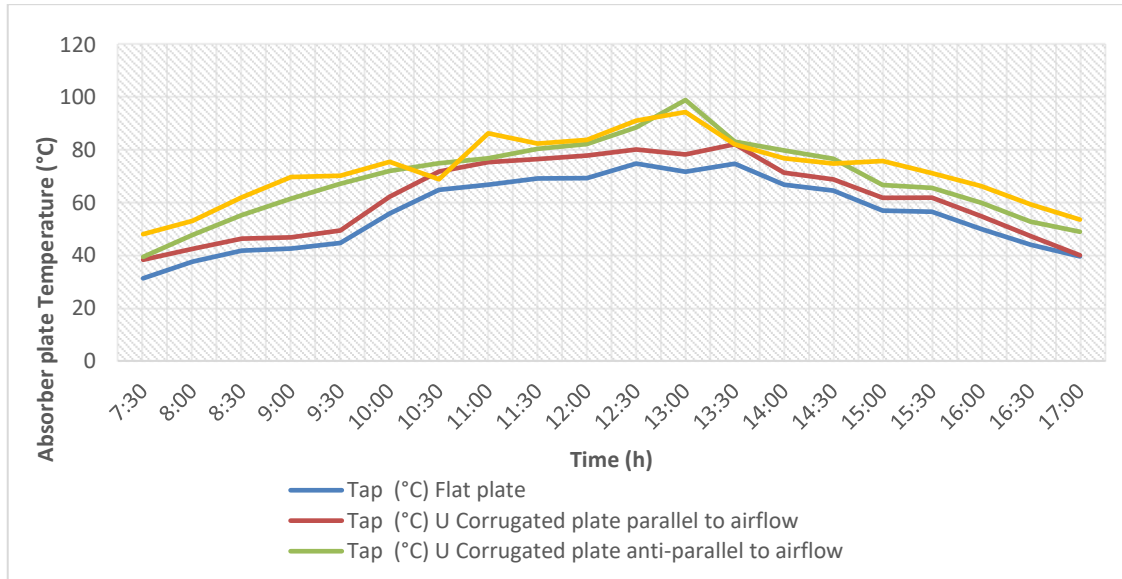


**Figure 4.2.** Absorber plate temperature for four types of dual-flow SAH at a flow rate of mass 0.0046 kg/s

The following figures illustrate the changes in hourly solar irradiance during the daytime for four types of SAH, and it can be observed that these figures have the same pattern of behavior when they reach their highest value at noon as expected. The solar irradiance increased from sunrise until noon when it peaked, and then gradually fell until evening. Fig. 4.3 illustrates the hourly fluctuation in solar irradiance for the flat plate dual-flow SAH with flow rates of mass from 0.0011 kg/s to 0.0046 kg/s. The maximum solar irradiance value  $I$  during 11:00 am and 1:00 pm was 884.3 W/m<sup>2</sup>.

The hourly efficiency ( $\eta$ ) at varied flow rates of mass of 0.0011 kg/s, 0.0023 kg/s, 0.0034 kg/s and 0.0046 kg/s is illustrated in Figs. 4.4.

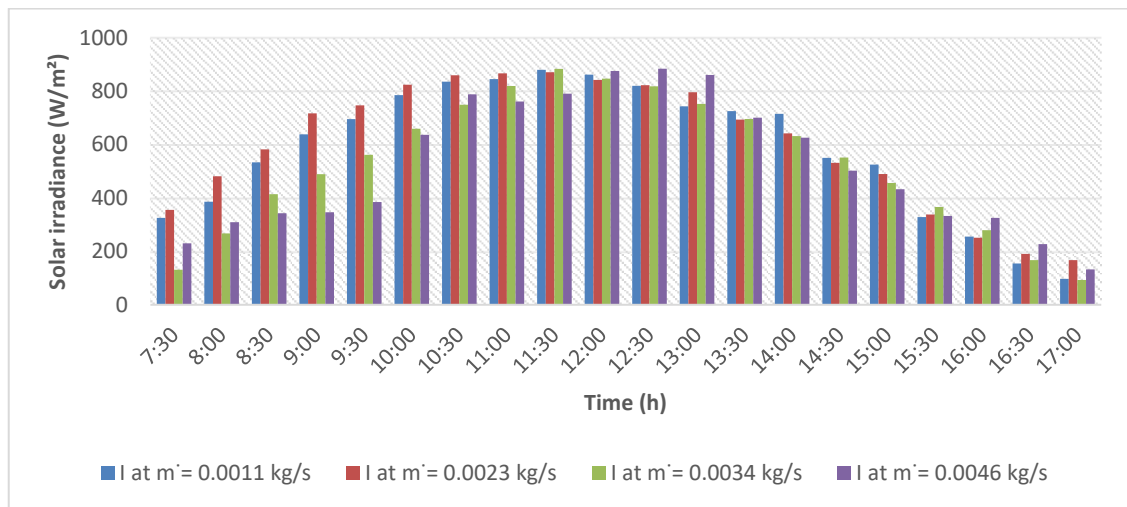


**Figure 4.3.** Hourly fluctuation in solar irradiance for the flat plate

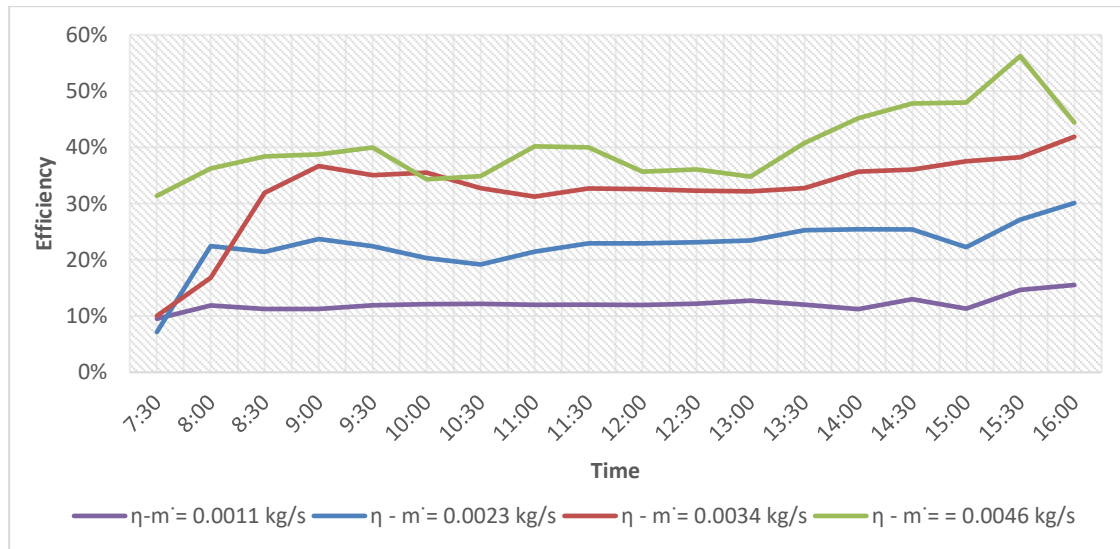


**Figure 4.4.** The hourly efficiency ( $\eta$ ) for flat plate dual-flow SAH

According to the value of plate temperature indicated in Fig. 4.1, the efficiency ( $\eta$ ) started with a modest. Then, it improved somewhat over the daytime until reaching the maximum value at the end of the day. Fig. 4.5 illustrates the hourly solar irradiance value  $I$  for a u-corrugated plate in a parallel direction. This type of dual-flow SAH with the flow rates of mass at 0.0011 kg/s to 0.0046 kg/s. The maximum solar irradiance value  $I$  during 11:00 am and 1:00 pm was 895 W/m<sup>2</sup>. The hourly efficiency ( $\eta$ ) at varied flow rates of mass 0.0011 kg/s, 0.0023 kg/s, 0.0034 kg/s, and 0.0046 kg/s for u-corrugated plate in a parallel direction dual-flow SAH are illustrated in Figs. 4.6.

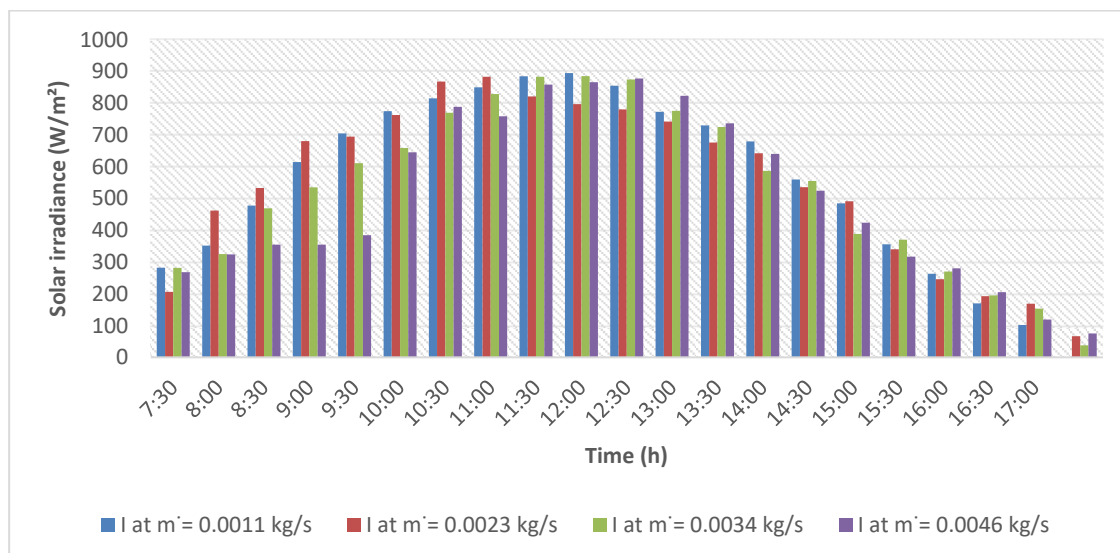


**Figure 4.5.** Hourly solar irradiance value for u -corrugated plate in a parallel direction dual-flow SAH

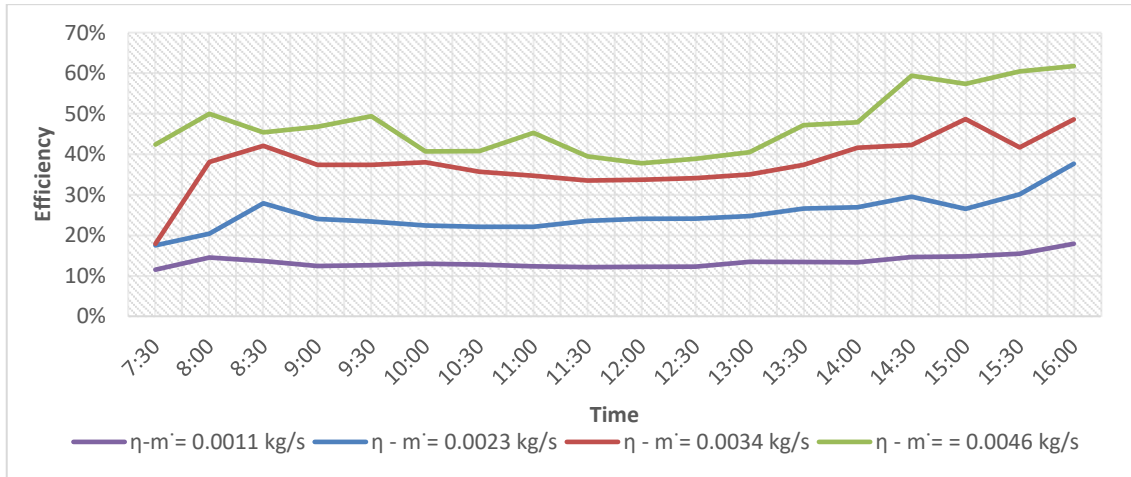


**Figure 4.6.** The hourly efficiency ( $\eta$ ) for u-corrugated plate parallel to airflow dual-flow SAH

The collector efficiency of the u-corrugated plate in a parallel direction is higher than that of a flat plate, as illustrated in Fig. 4.4 because corrugation improves the area of the surface and heat transfer coefficient while also extending the airflow pathway by establishing new airflow channels within the corrugation. Fig. 4.7 illustrates the hourly solar irradiance value  $I$  for trapezoidal corrugated plate anti-parallel direction dual-flow SAH with flow rates of mass from 0.0011 kg/s to 0.0046 kg/s. The maximum solar irradiance value  $I$  during 11:00 am and 1:00 pm was 860.6 W/m<sup>2</sup>. The hourly efficiency ( $\eta$ ) at varied flow rates of mass of 0.0011 kg/s, 0.0023 kg/s, 0.0034 kg/s, and 0.0046 kg/s for trapezoidal corrugated plate anti-parallel to airflow dual-flow SAH are illustrated in Figs. 4.8.

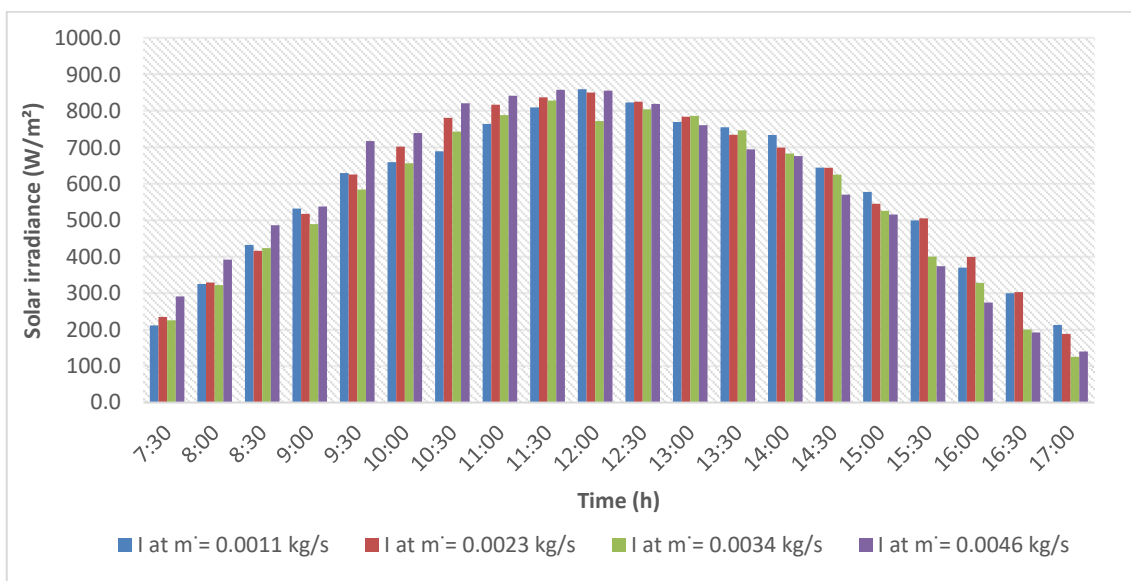


**Figure 4.7.** Hourly solar irradiance value for trapezoidal corrugated plate anti-parallel direction dual-flow SAH

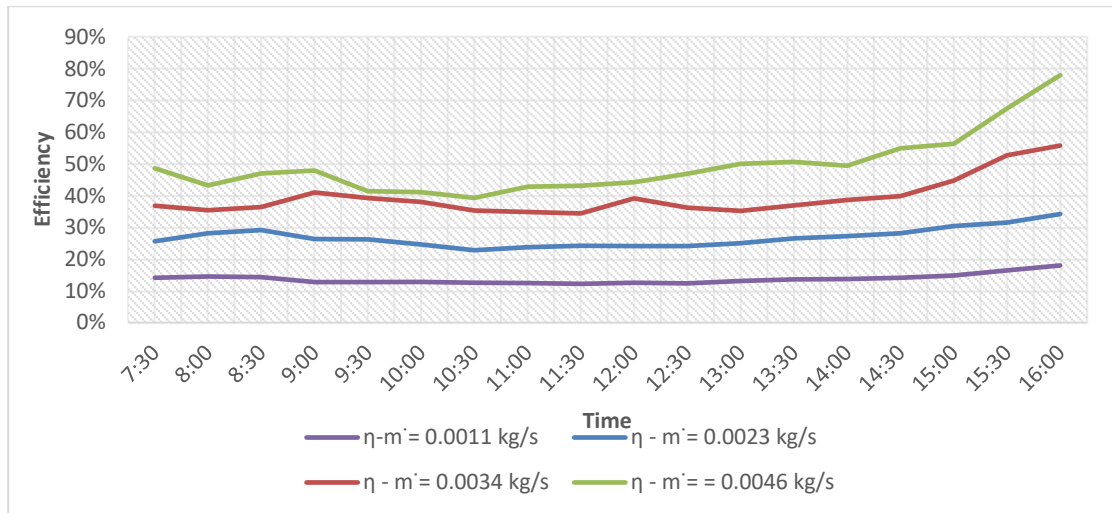


**Figure 4.8.** The hourly efficiency ( $\eta$ ) for trapezoidal corrugated plate anti-parallel to airflow dual-flow SAH

In the parallel direction of flow, trapezoidal corrugated was more efficient than flat plate and u-corrugated plate, as shown by the comparison in Figs 4.5 between flat plate and both types of u-corrugated plate and trapezoidal corrugated plate. This is because the air flowing all over the trapezoidal corrugated absorbent plate creates turbulent conditions that improve the convective heat transfer coefficient; for that, this study utilized a u-corrugated plate anti-parallel to airflow to compare the thermal performance.

Fig. 4.9 illustrates the hourly solar irradiance value  $I$  for u -corrugated plate anti-parallel to airflow dual-flow SAH with flow rates of mass from 0.0011 kg/s to 0.0046 kg/s. The maximum solar irradiance value  $I$  during 11:00 and 1:00 pm was 845.4 W/m<sup>2</sup>.

The hourly efficiency ( $\eta$ ) at varied flow rates of mass of 0.0011 kg/s, 0.0023 kg/s, 0.0034 kg/s and 0.0046 kg/s for u -corrugated plate anti-parallel to airflow dual-flow SAH are illustrated in Figs. 4.10.

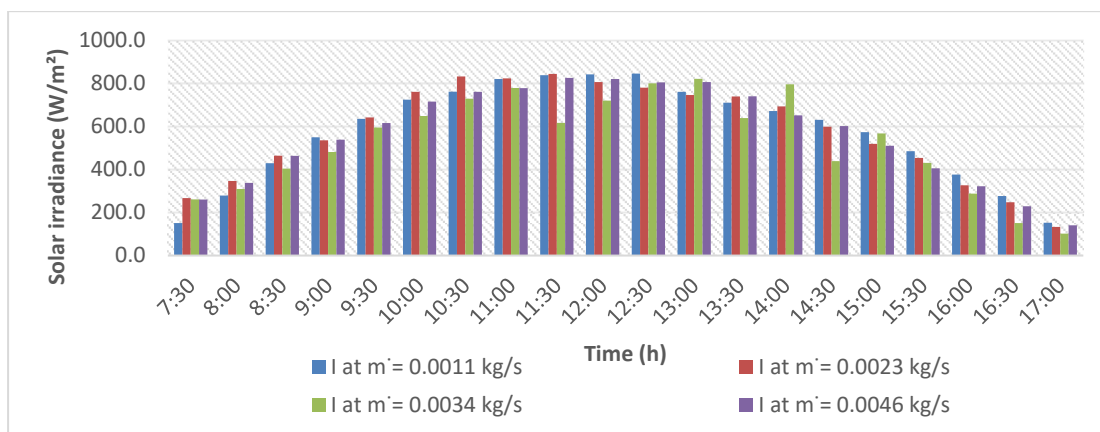


**Figure 4.9.** Hourly solar irradiance value for u -corrugated plate anti-parallel to airflow dual-flow SAH

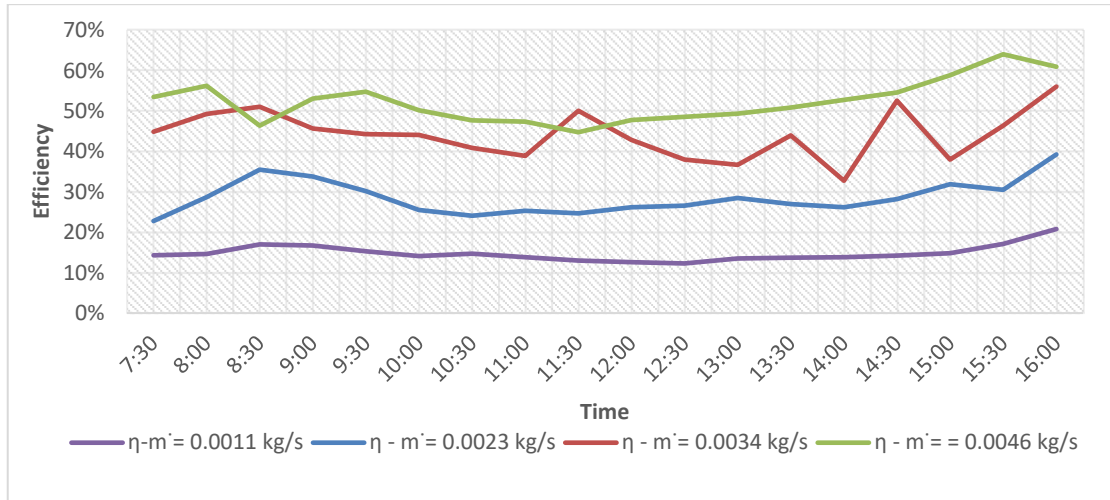


**Figure 4.10.** The hourly efficiency ( $\eta$ ) for u -corrugated plate anti-parallel to airflow dual-flow SAH

The efficiency of the u-corrugated plate anti-parallel to airflow was higher than that of flat plate and the other two types, as illustrated by the comparison in Figs 4.6 between u-corrugated plate anti-parallel to airflow and the other three types of absorbent plate. This is due to the air moving across the u-corrugated plate anti-parallel to airflow, creating more turbulence along the plate, which enhances the convective heat transfer coefficient and increases the transfer of heat between the absorbent plate and the air moving over and below the absorbent plate, so hence increasing the thermal efficiency of dual-flow SAH.

#### 4.2.2. Temperature Differences ( $\Delta T$ ) Between the Outlet and Inlet Air Temperatures

Figs. 4.11 - 4.14 illustrate the differences in temperature (average output temperature - input temperature) with the time of day for four types of dual-flow SAH with flow rates of mass of 0.0011 kg/s to 0.00446 kg/s. For all flow rates of mass, the temperature difference ( $\Delta T = T_{\text{out}} - T_{\text{in}}$ ) peaked from sunrise until noon, then gradually fell from 1:00 pm to the end of the day at 5:00 pm, in a comparable way to solar irradiance.  $\Delta T$  climbed to its highest point during noon and then fell at the end of the day for all curves (comparable to solar irradiance). Furthermore, at the same flow rate of mass,  $\Delta T$  was greater for the u-corrugated plate anti-parallel to airflow dual-flow SAH than for the other types of dual-flow SAH. In the case of the u-corrugated plate anti-parallel to airflow dual-flow SAH, the airflow creates more vortex along the plate, which caused  $\Delta T$  to enhance. Fig. 4.11 demonstrates the temperature difference ( $\Delta T = T_{\text{out}} - T_{\text{in}}$ ) with a time of day for flat plate dual-flow SAH at four values of mass flow rates  $\Delta T$  max values were

47.4 °C, 43 °C, 41.7 °C, and 34.4 °C, respectively. Fig. 4.12 demonstrates the temperature difference for u-corrugated plate parallel to airflow dual-flow SAH at four values of mass flow rates  $\Delta T$  max values were 48.2 °C, 43.9 °C, 43.2 °C, and 37.5 °C, respectively. Fig. 4.13 demonstrates the temperature difference for trapezoidal corrugated plate anti-parallel to airflow dual-flow SAH at four values of mass flow rates  $\Delta T$  max values were 48.5 °C, 44.1 °C, 43.5 °C, and 41.4 °C, respectively. Fig. 4.14 demonstrates the temperature difference for u-corrugated plate anti-parallel to airflow dual-flow SAH at four values of mass flow rates  $\Delta T$  max values were 51 °C, 45.7 °C, 44.5 °C, and 42.9 °C, respectively. The curves in these figures demonstrate an improvement in the daily difference of temperature of the u-corrugated plate parallel to airflow, trapezoidal corrugated plate anti-parallel to airflow, and u -corrugated plate anti-parallel to airflow dual-flow SAHs over flat dual-flow SAH at the same flow rate of mass. This increase can be due to the presence of corrugation, which increases the heat transfer area. Furthermore, the corrugation improves airflow over the absorbent plate, creates turbulence, as well as reducing dead zones in the SAH. The temperature differences u-corrugated plate anti-parallel to airflow (max turbulence) were higher than other types of dual-flow SAH, as shown by the comparison in Figs. 4.11 – 4.14. Furthermore, the flow rate of mass influences the output air temperature. As a result, the flow rate of mass and the outlet air temperature are inversely related. The differences in temperature decrease as the mass flow rate increases.

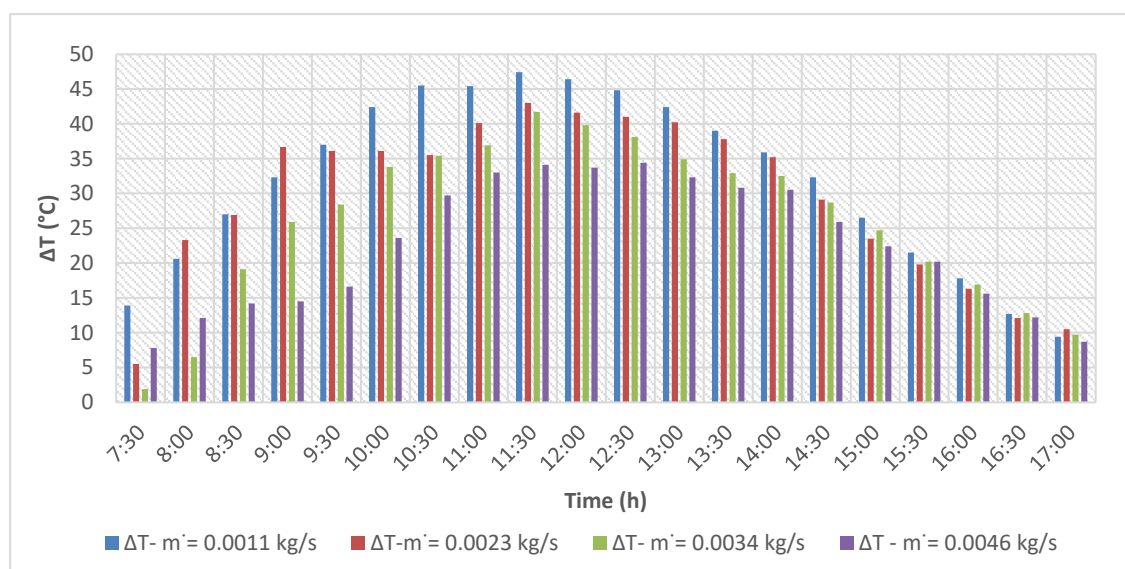


**Figure 4.11.** The difference of temperature with a time of day for flat plate dual-flow SAH

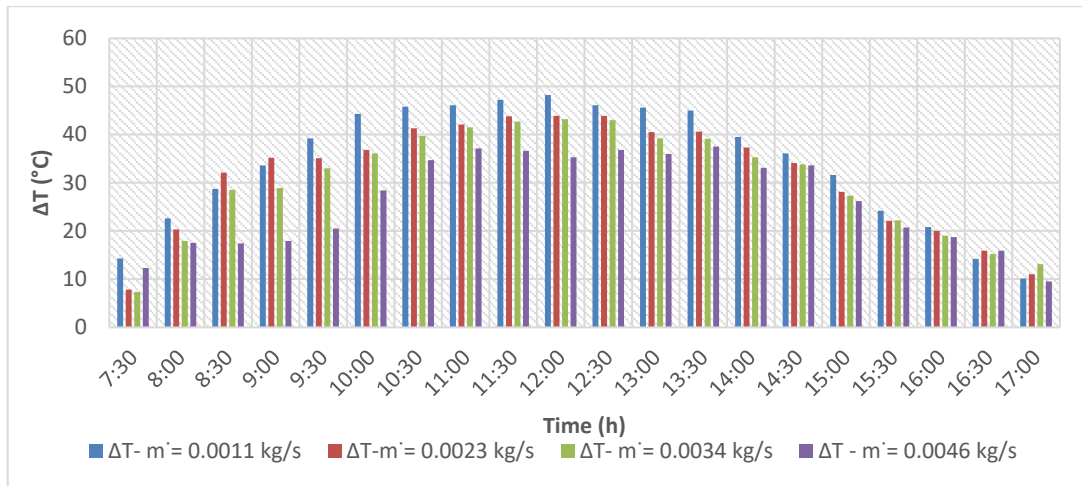


**Figure 4.12.** The difference of temperature with a time of day for u -corrugated plate parallel to airflow dual-flow SAH

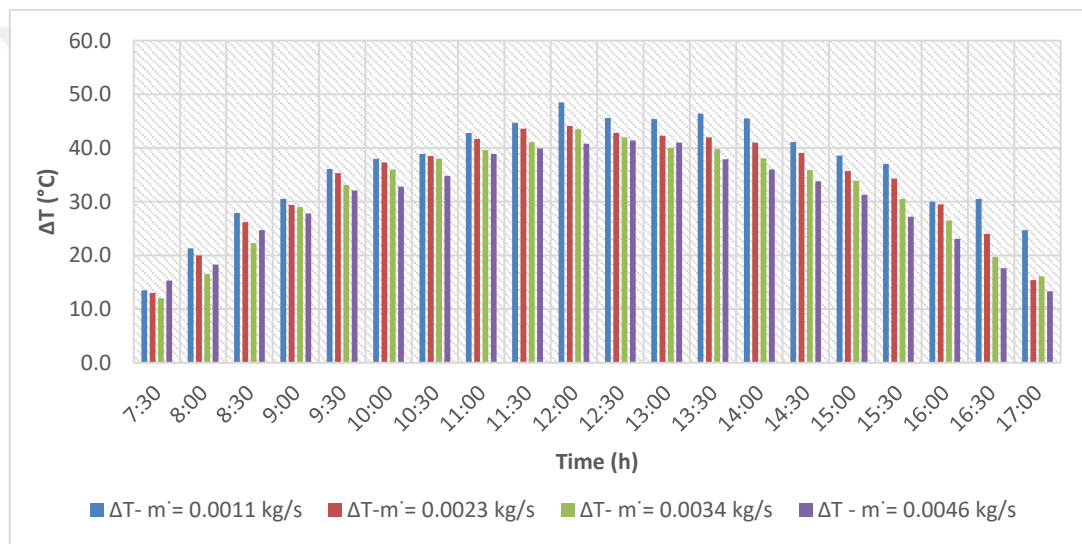


**Figure 4.13.** The difference of temperature with a time of day for trapezoidal corrugated plate anti-parallel to airflow dual-flow SAH

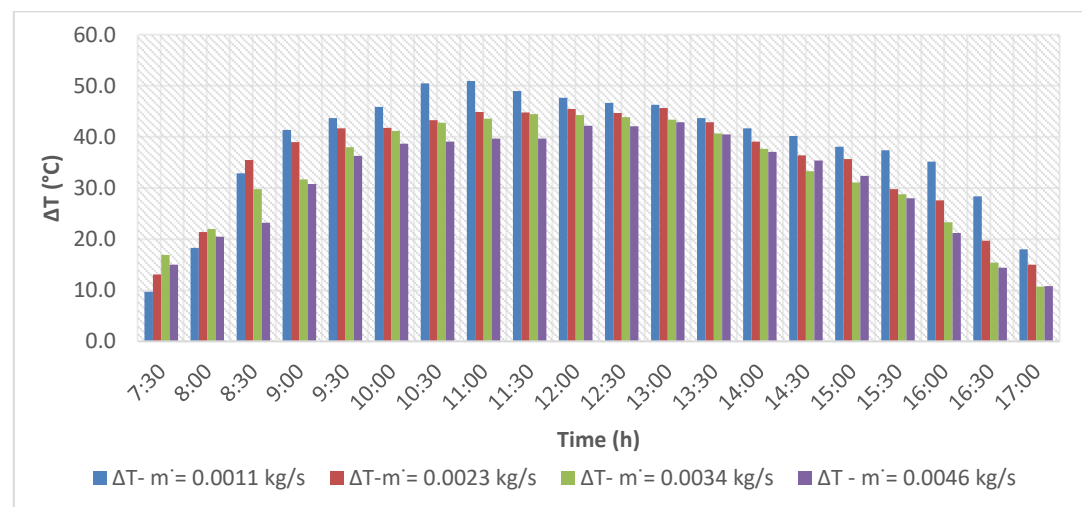


**Figure 4.14.** The difference of temperature with a time of day for u -corrugated plate anti-parallel to airflow dual-flow SAH

### 4.2.3. Energy Gained

Figs. 4.15 – 4.18 shows the energy gained  $Q_u$  variation with an hour of the day for four types of dual-flow SAH at four different mass flow rates. According to the results, the energy gained started from the lowest value and then increased until noon, when it peaked, and then gradually decreased until the evening. The curves exhibit the same pattern of behavior when they reach their maximum value at noon. Fig. 4.15 shows the energy gained variation with an hour of the day for flat plate dual-flow SAH; the maximum value of energy gained  $Q_u$  for this type was 159.51 W at noon with a flow rate of mass 0.0046 kg/s. Fig. 4.16 shows the energy gained variation with an hour of the day for u-corrugated plate parallel to airflow dual-flow SAH, and the maximum value of energy gained  $Q_u$  for this type was 173.88 W at noon with a flow rate of mass 0.0046 kg/s. Fig. 4.17 shows the energy gained variation with an hour of the day for trapezoidal corrugated plate anti-parallel to airflow dual-flow SAH. The maximum value of energy gained  $Q_u$  for this type was 192.34 W at noon with a flow rate of mass 0.0046 kg/s. Fig. 4.18 shows the energy gained variation with an hour of the day for u-corrugated plate anti-parallel to airflow dual-flow SAH, and the maximum value of energy gained  $Q_u$  for this type was 199.12 W at noon with a flow rate of mass 0.0046 kg/s. The quantity of energy gained mostly depends on the collector's thermal properties. By comparing the Figs. 4.15, 4.16, 4.17, and 4.18, it is obvious that the amount of the flow rate of mass directly relates to the amount of energy gained, i.e., as the flow rate of mass increases, the energy gained is increased too; this is because increased airflow rate results in lower operating temperatures for the SAH. Moreover, by comparing all four types of the dual-flow SAH in Fig. 4.19, the results indicate that the maximum energy gained was at noon 199.12 W for u-corrugated plate anti-parallel to airflow type at a flow rate of mass of 0.0046 kg/s while it was 192.34 W, 173.88 W, and 159.51 W for trapezoidal corrugated plate anti-parallel to airflow, u-corrugated plate parallel to airflow, and a flat plate at the same mass flow rate, respectively.

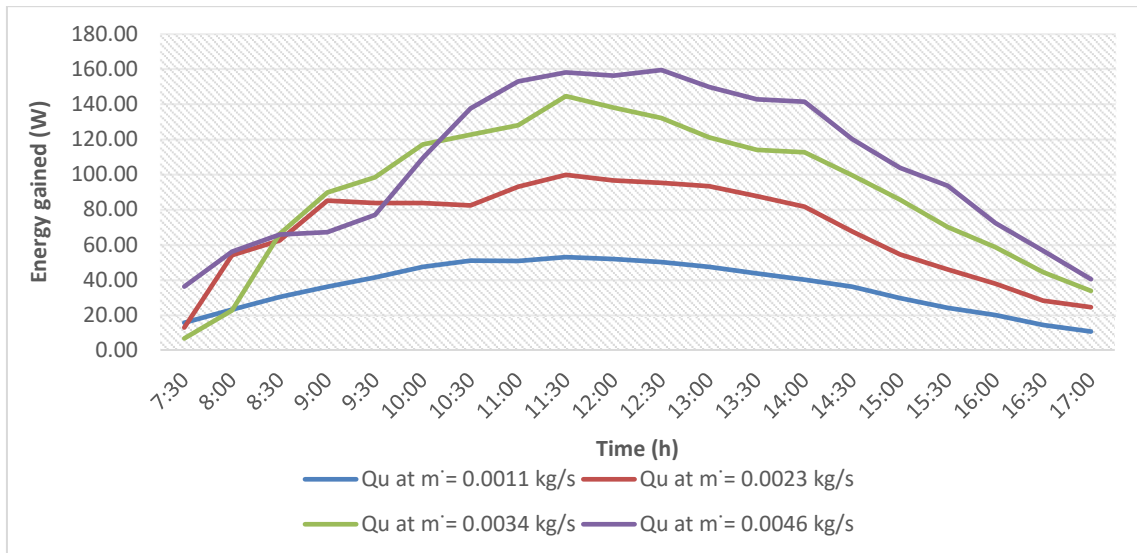


**Figure 4.15.** Energy gained with a time of day for flat plate dual-flow SAH

The energy obtained began at the lowest amount and then gradually climbed until midday, when it peaked, and then gradually fell until the evening. Furthermore, the maximum value of energy gained  $Q_u$  for this type was 159.51 W at noon with a flow rate of mass 0.0046 kg/s.

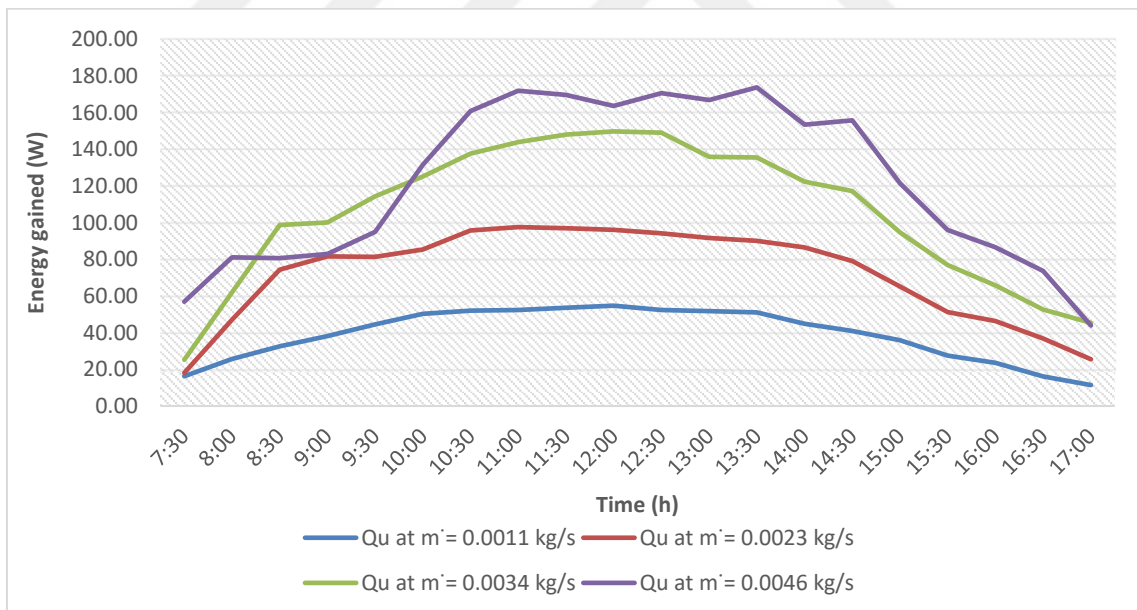


**Figure 4.16.** Energy gained with a time of day for u-corrugated plate parallel to airflow dual-flow SAH

This graph shows the maximum value of energy gained  $Q_u$  for this type was 173.88 W at noon with a flow rate of mass 0.0046 kg/s. It's greater than the flat plate type.

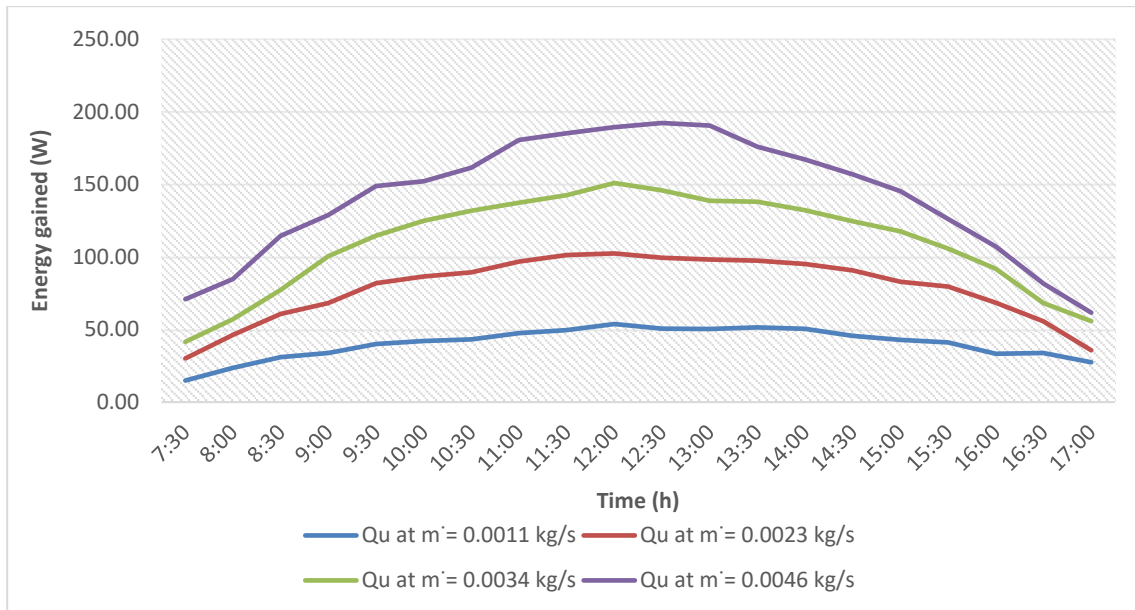


**Figure 4.17.** Energy gained with a time of day for trapezoidal corrugated plate anti-parallel to airflow dual-flow SAH

This graph shows the maximum value of energy gained  $Q_u$  for this type was 192.34 W at noon with a flow rate of mass 0.0046 kg/s. It's greater than the flat and u-corrugated plate parallel to airflow dual-flow SAH.

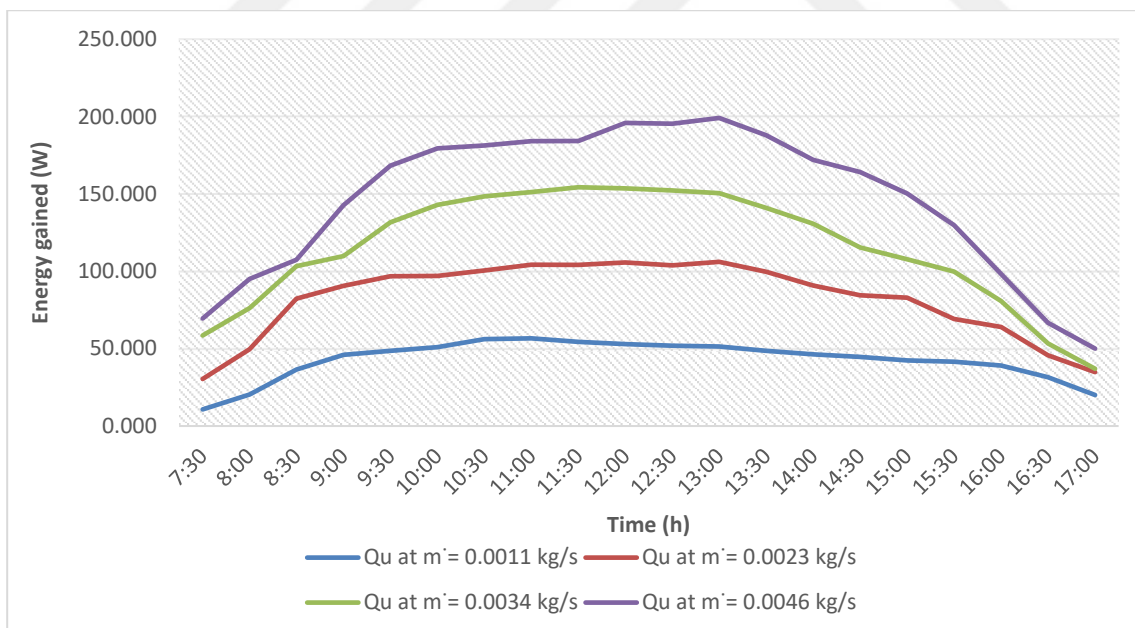


**Figure 4.18.** Energy gained with a time of day for u-corrugated plate anti-parallel to airflow dual-flow SAH

This graph shows that the maximum value of energy gained  $Q_u$  for u-corrugated plate anti-parallel to airflow dual-flow SAH was 199.12 W at noon with a flow rate of mass 0.0046 kg/s. It's greater than the other three types.

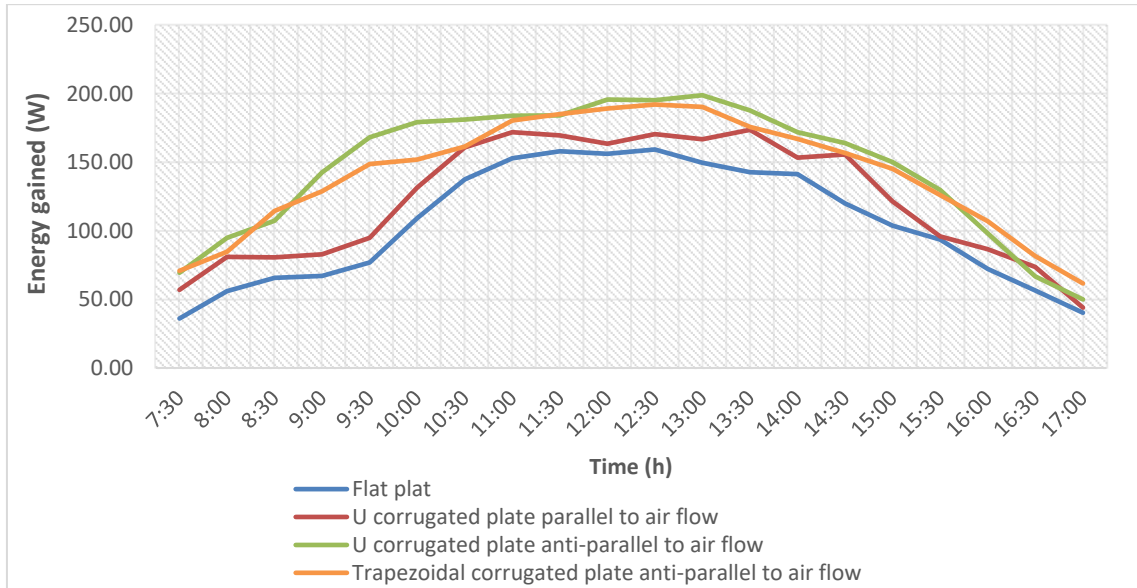


**Figure 4.19.** Comparing energy gained for four types of dual-flow SAH at a flow rate of mass of 0.0046 kg/s

The results indicate that the best type is the u-corrugated plate anti-parallel to airflow type with maximum energy gained at noon 199.12 W at a flow rate of mass of 0.0046 kg/s compared to other three types.

#### 4.2.4. Effect of mass flow rate on average efficiency

Fig. 4.20 illustrates the average efficiencies for the four types studied dual-flow SAH. Flat plate dual-flow SAH average efficiencies at four different values of the flow rate of mass from 0.0011 kg/s to 0.0046 kg/s were 12.94 %, 25.26 %, 37.05 %, and 42.80%, respectively. For the u-corrugated plate, parallel to airflow dual-flow SAH was 14.20 %, 27.55%, 41.09 %, and 51.33%, respectively. While for trapezoidal corrugated plate anti-parallel to airflow, dual-flow SAH was 14.67 %, 28.21 %, 45.94 %, and 54.38 %, respectively. And for u-corrugated plate anti-parallel to airflow, dual-flow SAH was 15.57 %, 31.22 %, 48.95 %, and 55.53 %, respectively. Compared to the traditional absorbent flat plate, the best absorbent plate was the anti-airflow u-corrugated plate, followed by the anti-parallel airflow trapezoidal plate, and finally u-corrugated plate parallel to the airflow. This enhancement of thermal efficiency is due to increasing turbulence, creating good airflow over the absorbent plate, and increasing the heat transfer area. The maximum average was 55.53 % for anti-parallel airflow u-corrugated plate.

Furthermore, the average efficiency increase for the studied four types of dual-flow SAHs as the flow rate of mass increases from 0.0011 kg/s to 0.0046 kg/s. It may also be explained that increasing the turbulence intensity is what caused the efficiency to

rise noticeably when the air mass flow rate was increased from 0.0011 kg/s to 0.0046 kg/s.

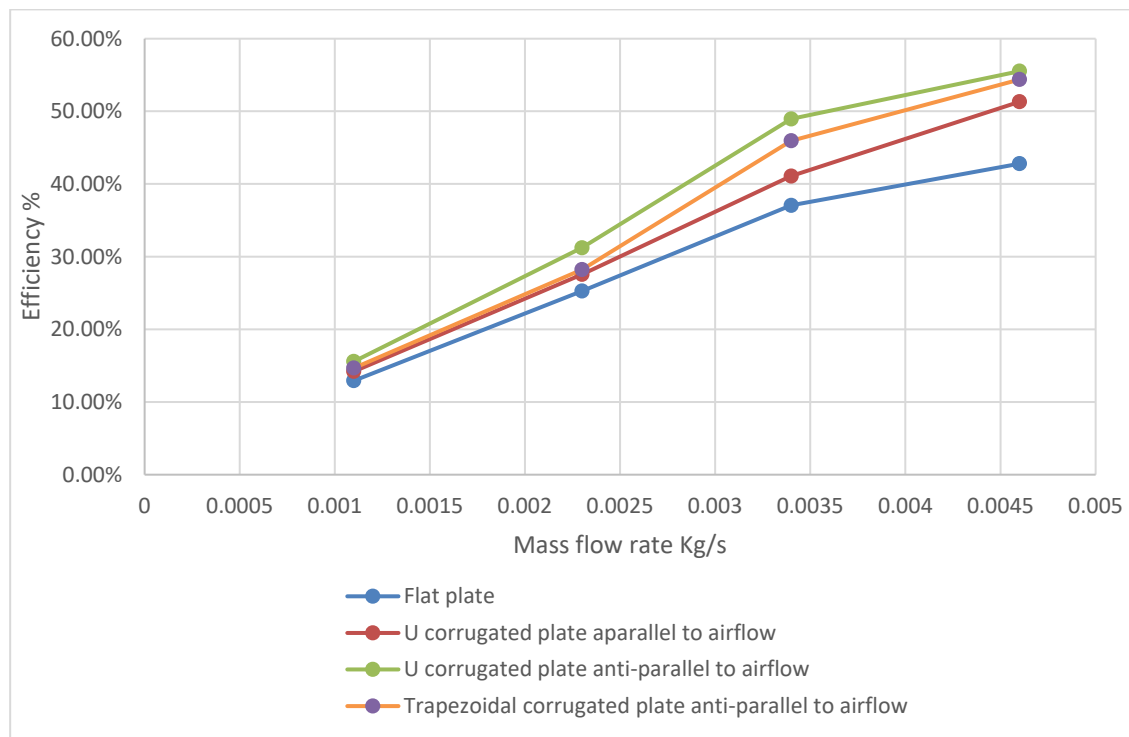


**Figure 4.20.** Average thermal efficiency vs mas flow rate

### 4.3. Numerical Results

#### 4.3.1. Flat plate absorbera and other types

In this numerical study, a flat plate absorber is used in the dual-flow SAH three times a day at 9:00 am, 12:00 pm, and 4:00 pm, and it employed two air mass flow rates of 0.0011 to 0.0046 kg/s as shown in Figs. 4.21 to 4.28. The numerical results were presented using pressure, temperature, velocity, and absorber temperature distribution 3D. Figs.4.21 and 4.22 plotted the pressure contours in the flat plate dual-flow SAH three times and four air mass flow rates. The results showed that increasing the air mass flow rate from 0.0011 kg/s to 0.0046 kg/s will lead to an increase in the pressure drop from 0.047 Pa to 0.157 Pa under the same condition on the day of 9:00 am, but it increased from 0.041 Pa to 0.150 Pa under the same condition of the day of 4:00 pm. Furthermore, at high mass flow rates, the maximum pressure region occurs in the top zone of the SAH. Figs. 4.23 and 4.24 presented the air temperature distribution under the impact of solar irradiation and the heat flux convection. The results demonstrated the greatest temperature located at the absorber wall, and it decreased with increasing the flow rate of the air mass, but it increased with increasing the time of day from 9:00 am to 12:00 pm.

Figs. 4.25 and 4.26 showed the impact of increasing the flow rate of air on the velocity contours in the flat plate dual-flow SAH for three times and four flow rates of mass. The results presented that the maximum velocity was located at the top channel of the SAH, and it increased with increasing the flow rate of the air mass. It increased with increasing the time of day from 9:00 am to 12:00 pm but decreased by increasing the time from 12:00 pm to 4:00 pm due to decreasing the solar radiation heat flux. Figs. 4.27 and 4.28 plotted the temperature 3D contours in the flat plate dual-flow SAH for three times and two air mass flow rates at three positions of the z-direction. The results demonstrated that the temperature on the flat plat absorber decreased gradually from the top input to the rear of the SAH.

The numerical simulation results and counters of the u-corrugated plate utilized in a parallel direction to airflow instead of the flat plate once are presented in Figs. 4.29 to 4.36. The pressure distribution results indicated that the u-corrugated plate utilized in a parallel direction to airflow increased from 0.150 Pa to 8.841 Pa at a flow rate of air  $\dot{m} = 0.0046$  kg/s and time 4:00 pm. Also, the maximum temperature decreased from 89.84 °C to 56.56 °C when using the u-corrugated plate utilized in a parallel direction to airflow at a flow rate of air  $\dot{m} = 0.0046$  kg/s and time 4:00 pm. But the maximum velocity in the case of a u-corrugated plate utilized in a parallel direction to airflow is found to be 3.422 m/s as compared with the maximum velocity of a flat plate of 0.463 m/s at air flow rate  $\dot{m} = 0.0046$  kg/s and time 4:00 pm due to increasing the momentum of the airflow because using the u-corrugated plate utilized in a parallel direction to airflow. Finally, the maximum absorber temperature was focused in the upper region of the u-corrugated plate utilized in a parallel direction to airflow, and it increased in the upper region of the u-corrugated plate utilized in a parallel direction to airflow because of the projection of the solar irradiation in these regions as compared with the flat plat absorber.

Figs. 4.37 to 4.44 plotted the pressure, velocity, and temperature contours for the model of the counter u-corrugated plate. Utilized in an anti-parallel direction to airflow three times and four types of flow rates of air. The pressure distribution results indicated that the u-corrugated plate utilized in an anti-parallel direction to airflow increased from 0.150 Pa to 25.664 Pa at a flow rate of air  $\dot{m} = 0.0046$  kg/s and time 4:00 pm. Also, the maximum temperature decreased from 89.84 °C to 55.15 °C when using the u-corrugated plate utilized in an anti-parallel direction to airflow at a flow rate of air  $\dot{m} = 0.0046$  kg/s and time 16:00. But the maximum velocity when using of u-corrugated plate utilized in anti-parallel direction to airflow is found 3.662 m/s as compared with the maximum

velocity of a flat plate of 0.463 m/s at a flow rate of air  $\dot{m} = 0.0046$  kg/s and time 4:00 pm due to increasing the momentum of the airflow because using the u-corrugated plate utilized in anti-parallel direction to airflow. Finally, the maximum absorber temperature was focused in all regions of the u-corrugated plate utilized in an anti-parallel direction to airflow at noon because of the projection of the solar irradiation in these regions in comparison to the flat plat absorber.

Figs. 4.45 to 4.52 illustrated the results of the pressure, velocity, and temperature contours for the model of trapezoidal plate absorber three times and four types of flow rates of air. The pressure distribution results indicated that the use of trapezoidal increased from 0.150 Pa to 18.466 Pa at a flow rate of air  $\dot{m} = 0.0046$  kg/s and time 4:00 pm. Also, the maximum temperature decreased from 89.84 °C to 55.81 °C when using the trapezoidal absorber plate at a flow rate of air  $\dot{m} = 0.0046$  kg/s and time 4:00 pm. But the maximum velocity when using a trapezoidal absorber plate is found to be 4.366 m/s as compared with the maximum velocity of a flat plate of 0.463 m/s at a flow rate of air  $\dot{m} = 0.0046$  kg/s and time 4:00 pm due to increasing the momentum of the airflow because using the trapezoidal absorber. Finally, the maximum absorber temperature was focused in all regions of the trapezoidal plate at noon because of the projection of the solar irradiation in these regions in comparison to the flat plat absorber.

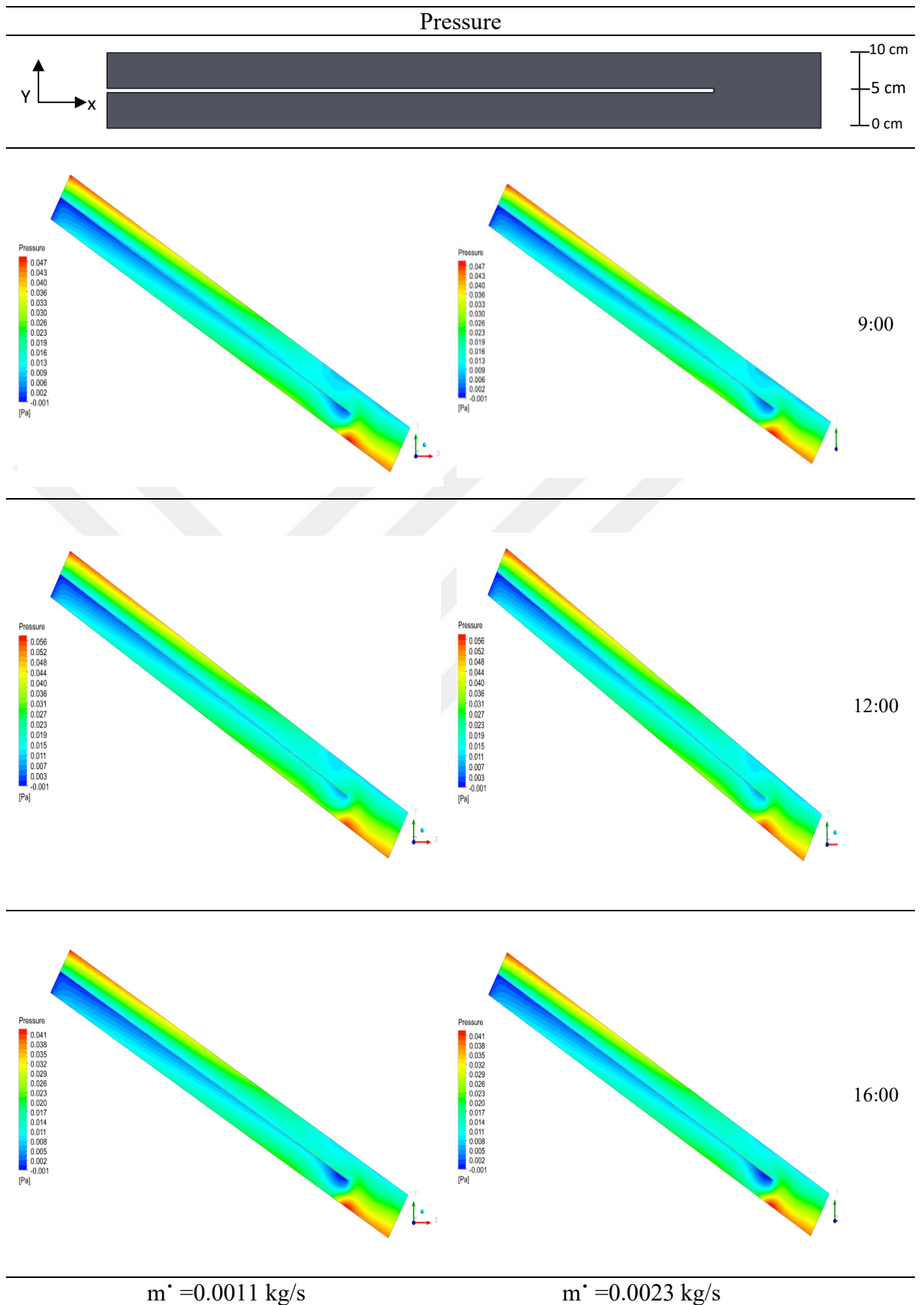


**Figure 4.21.** Pressure contours in the flat plate dual-flow SAH for three times and two flow rates of mass

# Pressure

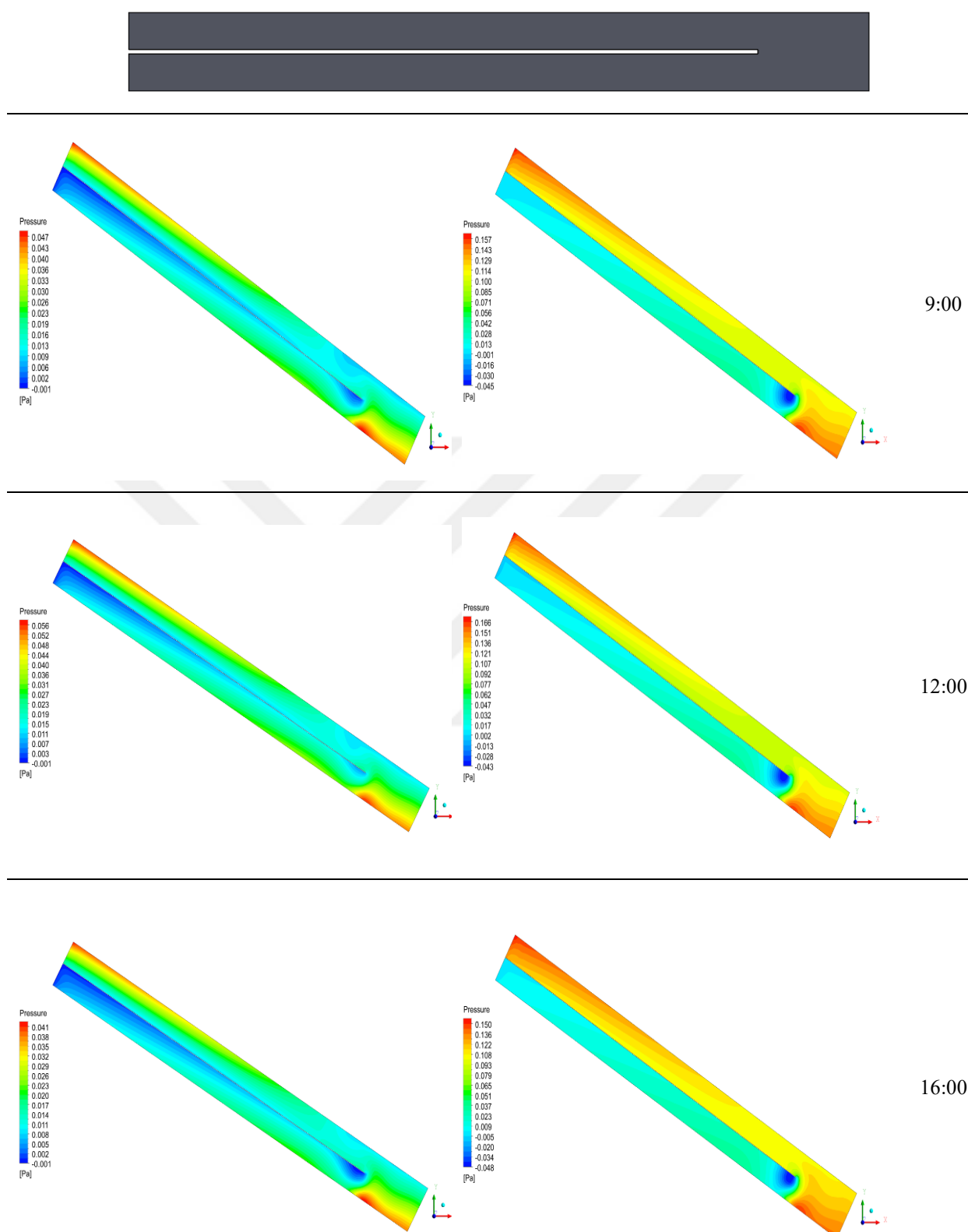


**Figure 4.22.** Pressure contours in the flat plate dual-flow SAH for three times and two flow rates of mass

## Temperatures

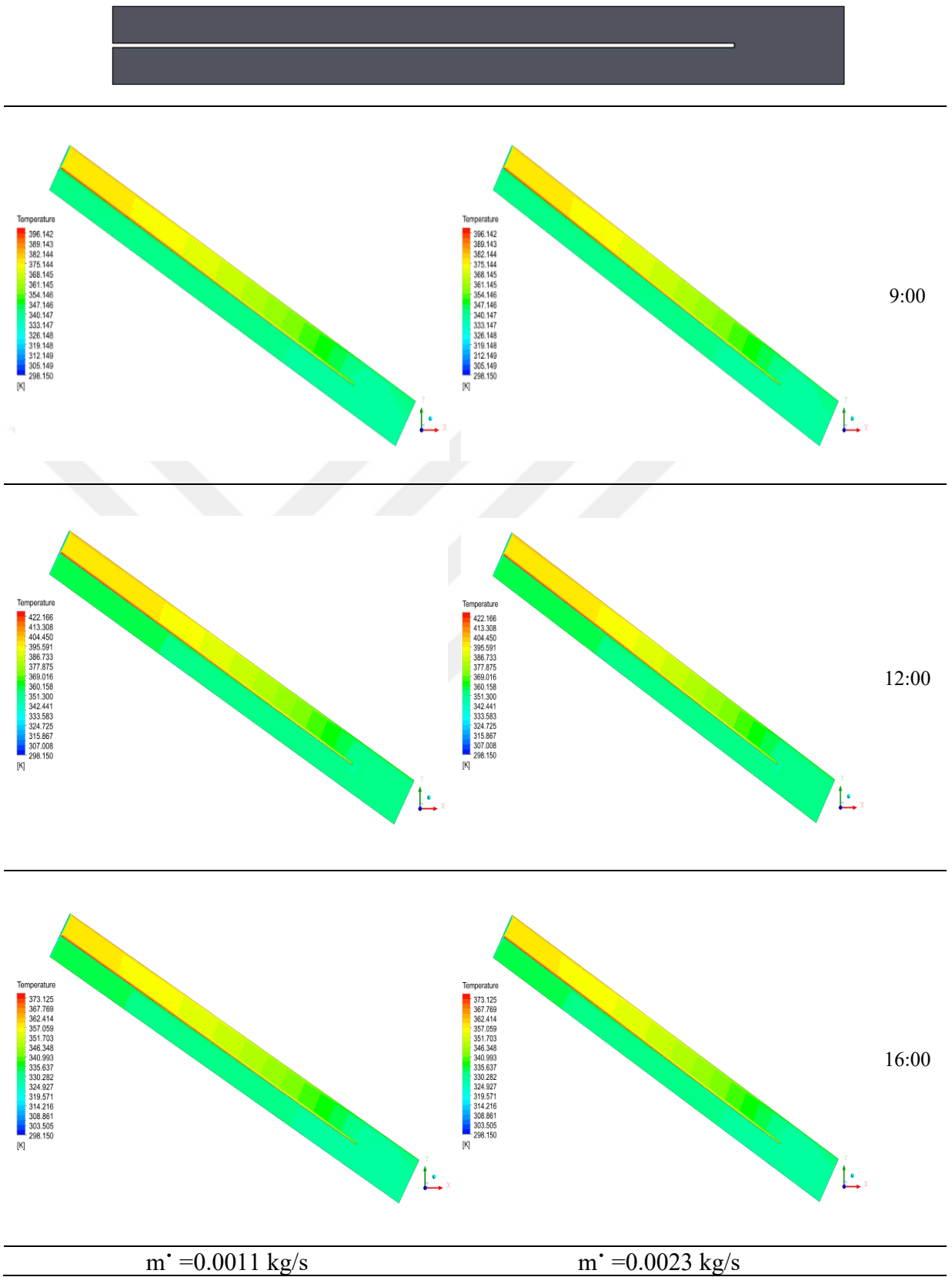


**Figure 4.23.** Temperature contours in the flat plate dual-flow SAH for three times and two flow rates of mass

## Temperatures

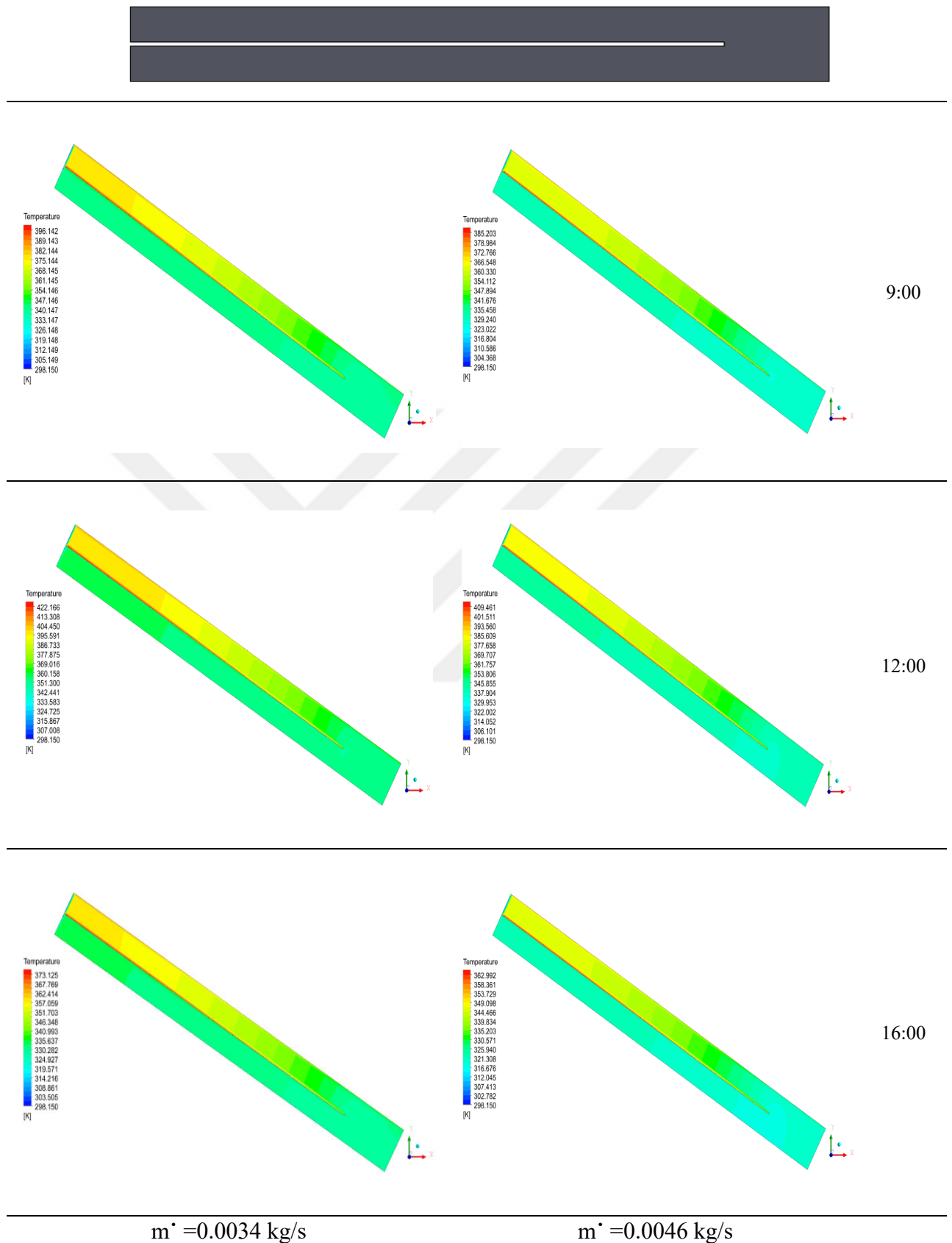
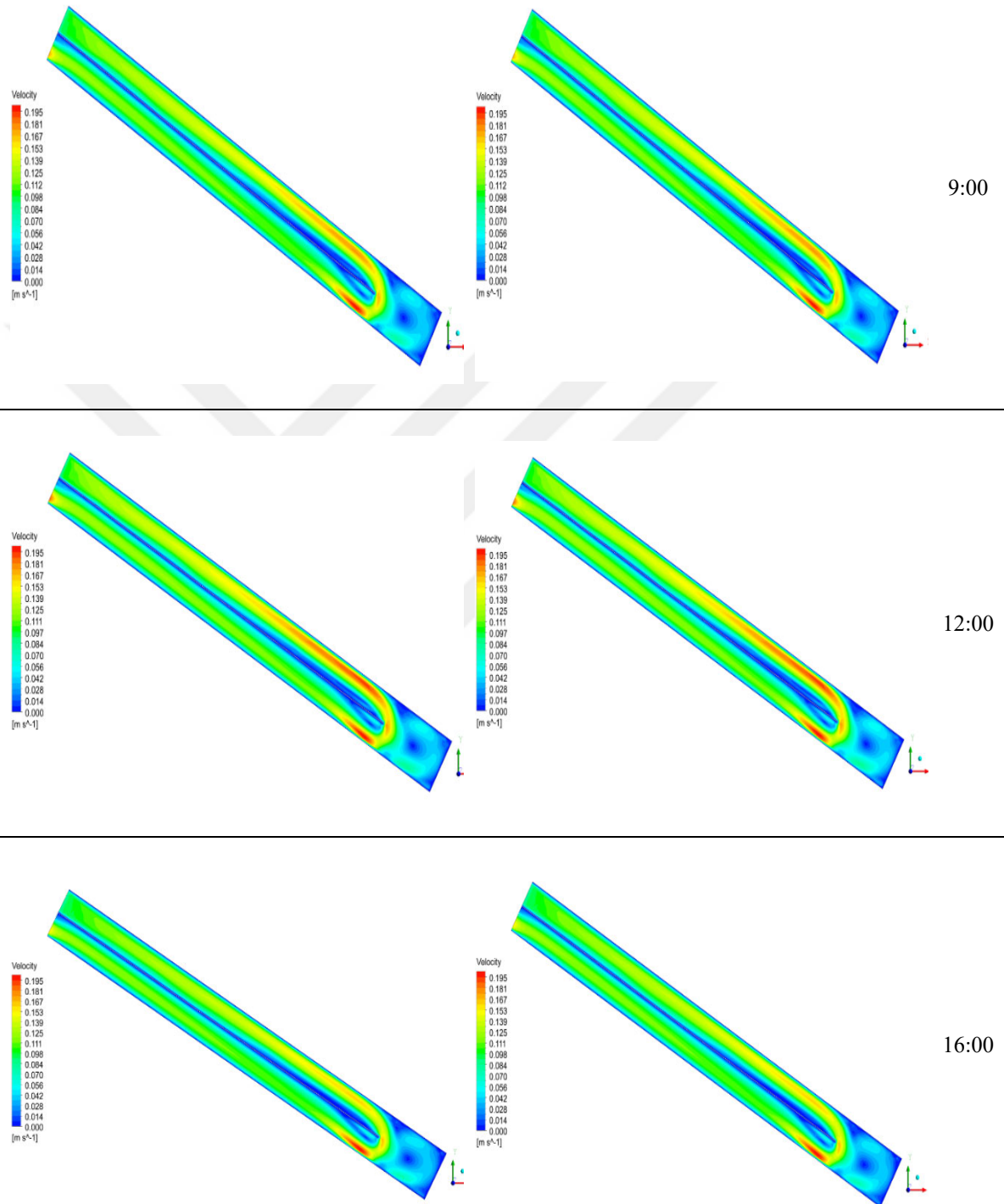


**Figure 4.24.** Temperature contours in the flat plate dual-flow SAH for three times and two flow rates of mass

## Velocity

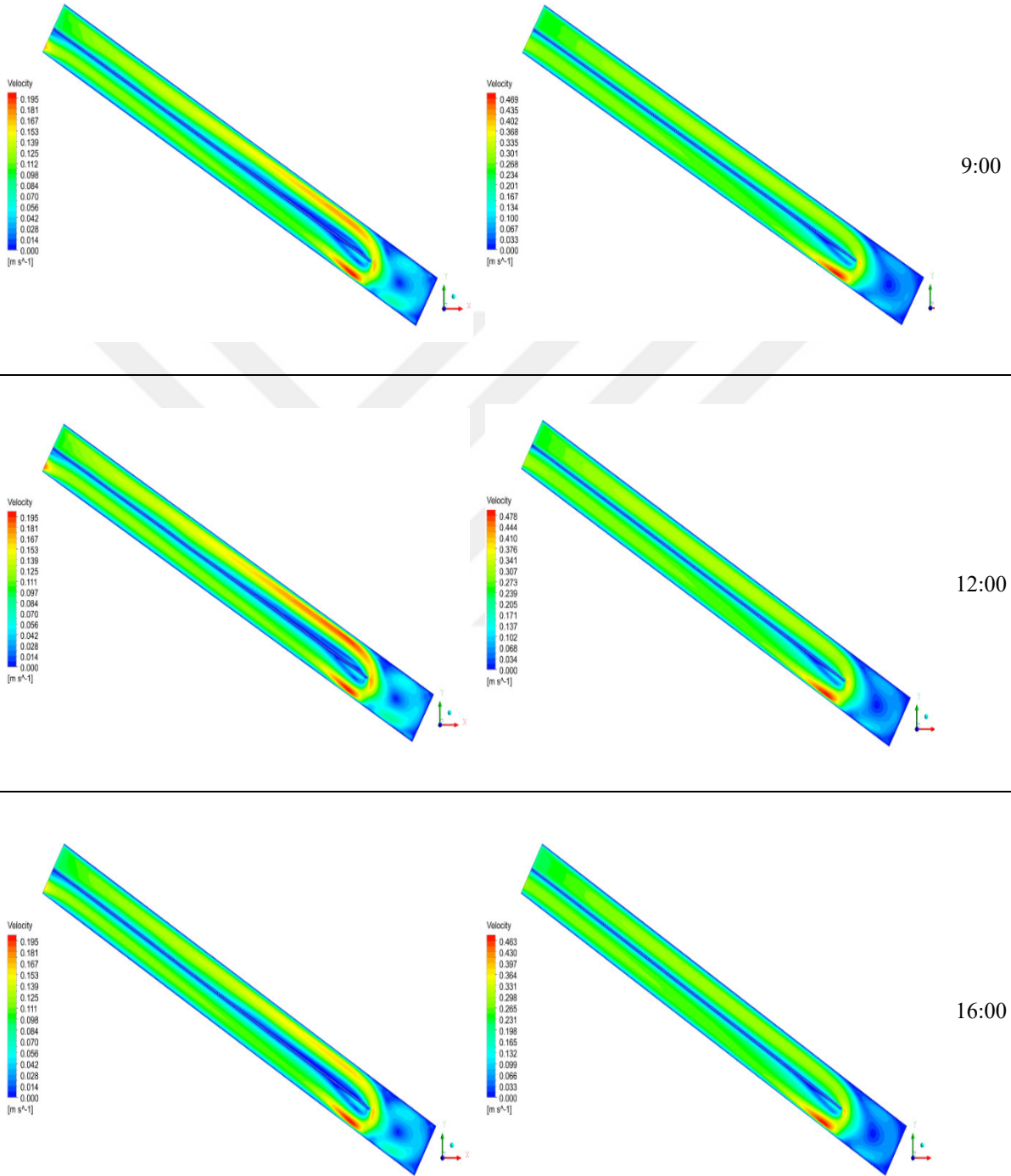


$\dot{m}^* = 0.0011 \text{ kg/s}$

$\dot{m}^* = 0.0023 \text{ kg/s}$

**Figure 4.25.** Velocity contours in the flat plate dual-flow SAH for three times and two flow rates of mass

## Velocity



$\dot{m} = 0.0034 \text{ kg/s}$

$\dot{m} = 0.0046 \text{ kg/s}$

**Figure 4.26.** Velocity contours in the flat plate dual-flow SAH for three times and two flow rates of mass

## Temperature 3D

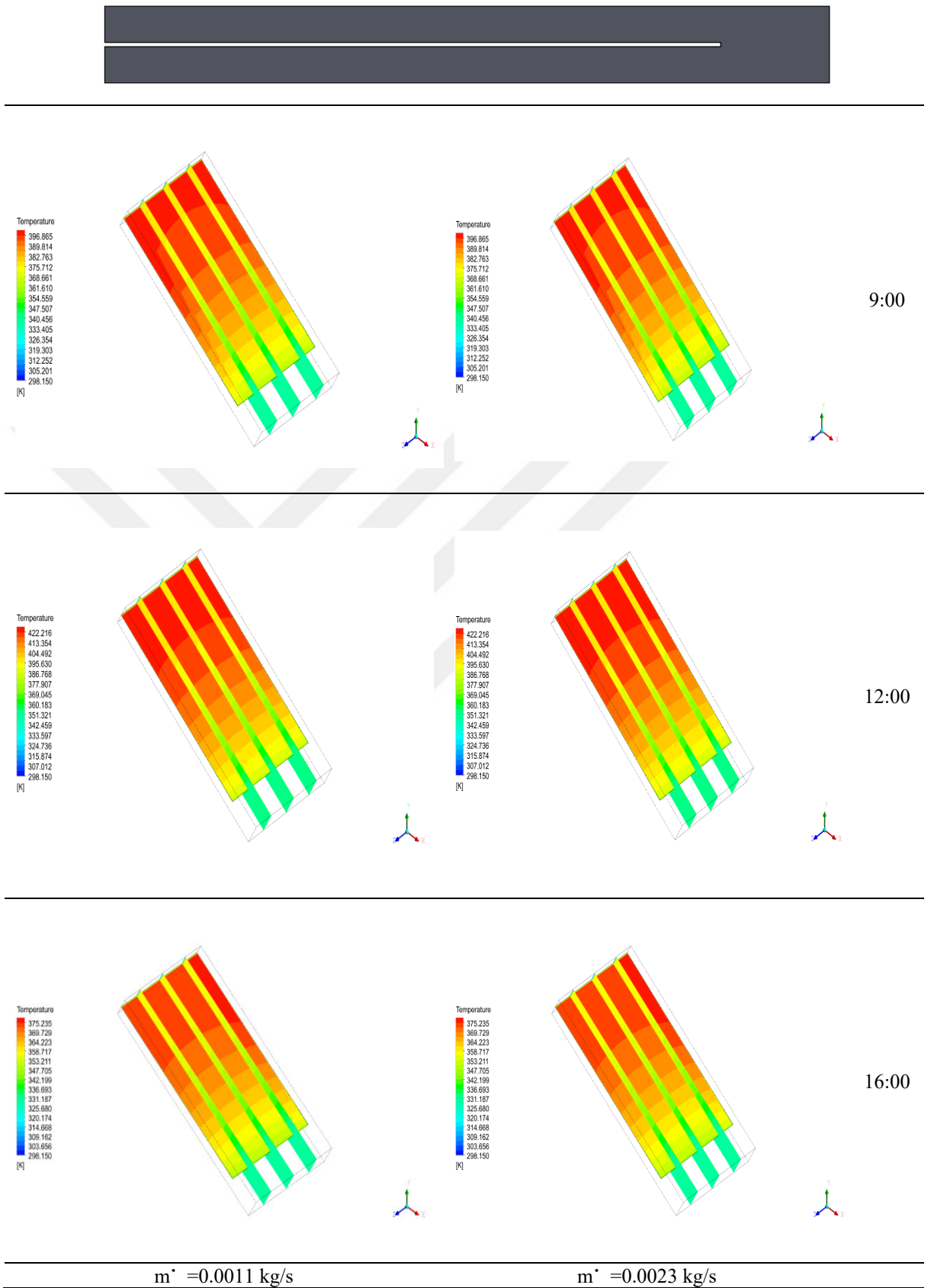
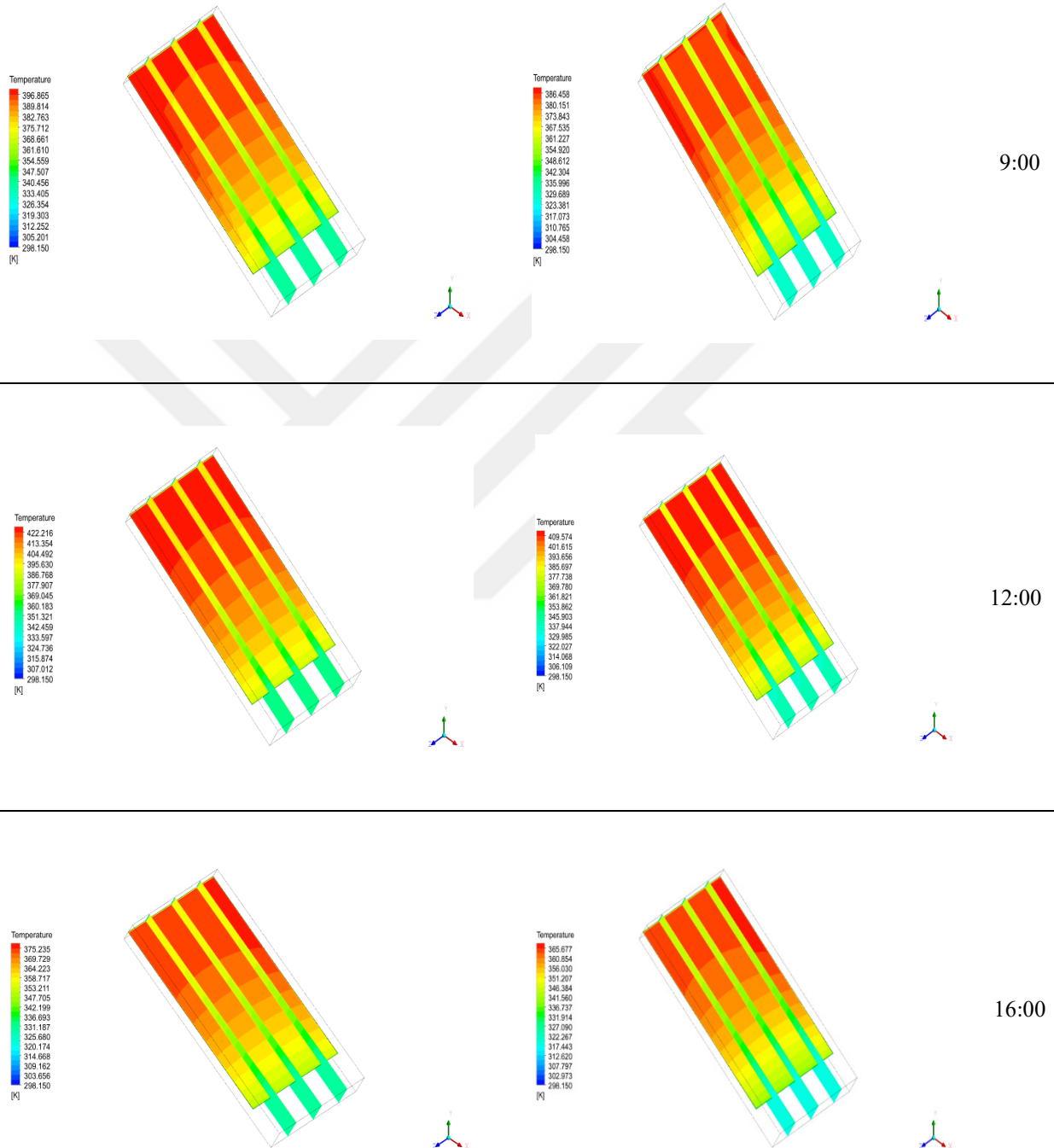


**Figure 4.27.** Absorber temperature 3D contours in the flat plate dual-flow SAH for three times and two flow rates of mass

## Temperature 3D



$\dot{m}^* = 0.0034 \text{ kg/s}$

$\dot{m}^* = 0.0046 \text{ kg/s}$

**Figure 4.28.** Absorber temperature 3D contours in the flat plate dual-flow SAH for three times and two flow rates of mass

# Pressure

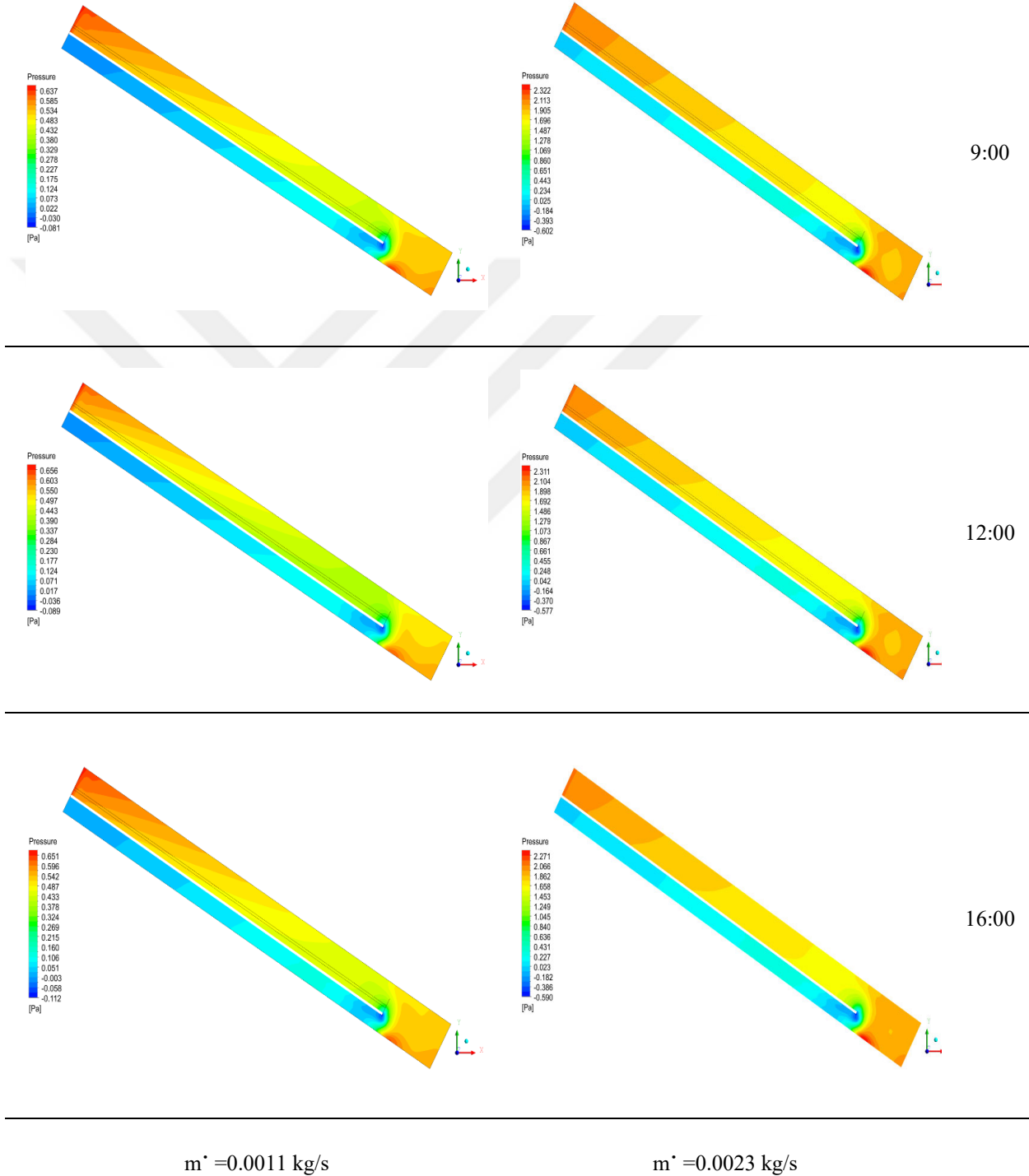
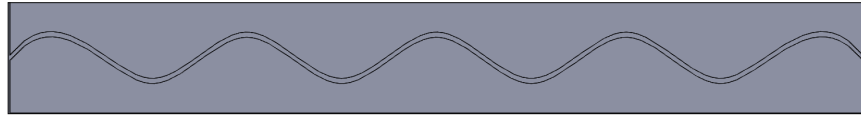


**Figure 4.29.** Pressure contours in the u -corrugated plate utilized in a parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

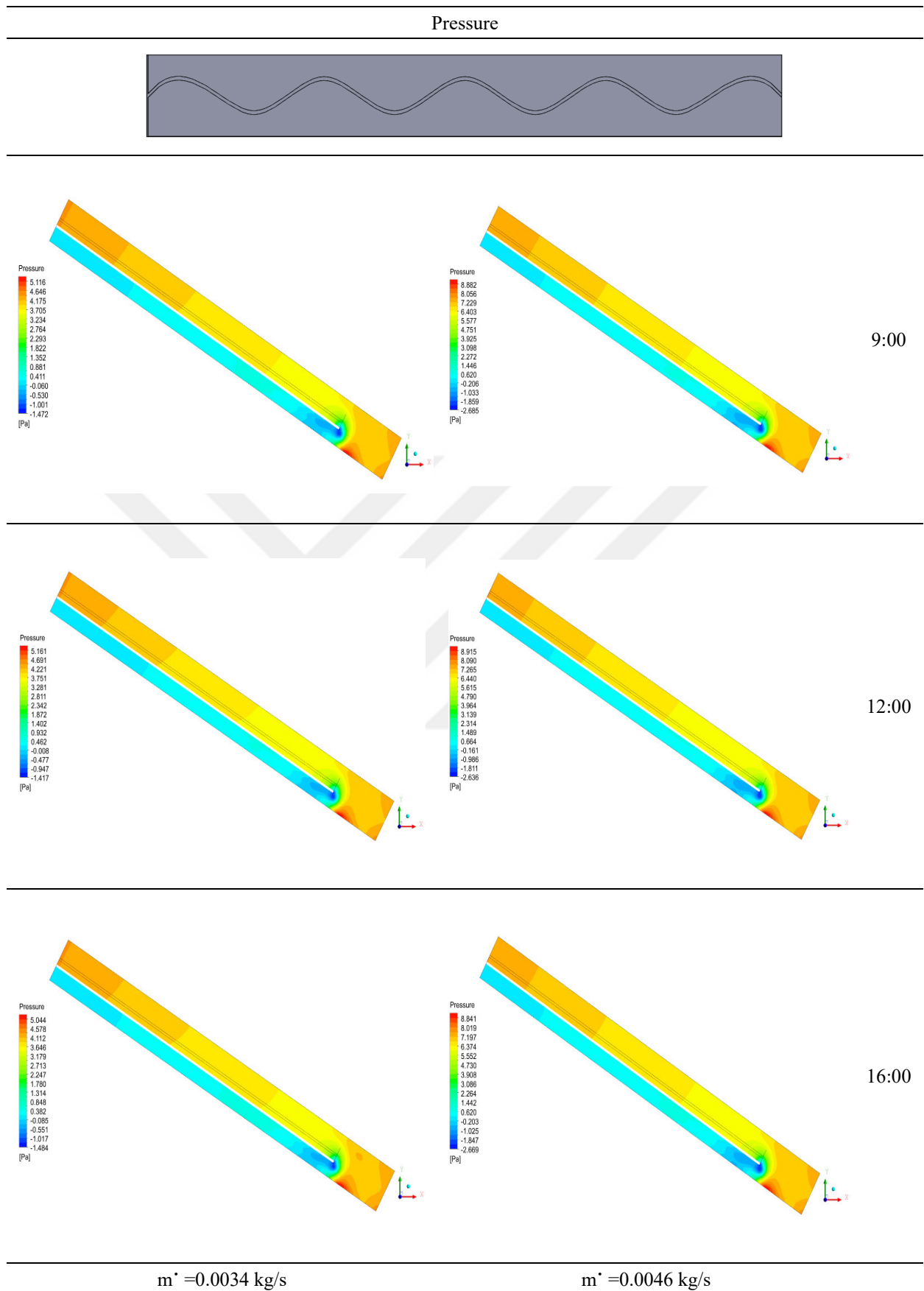
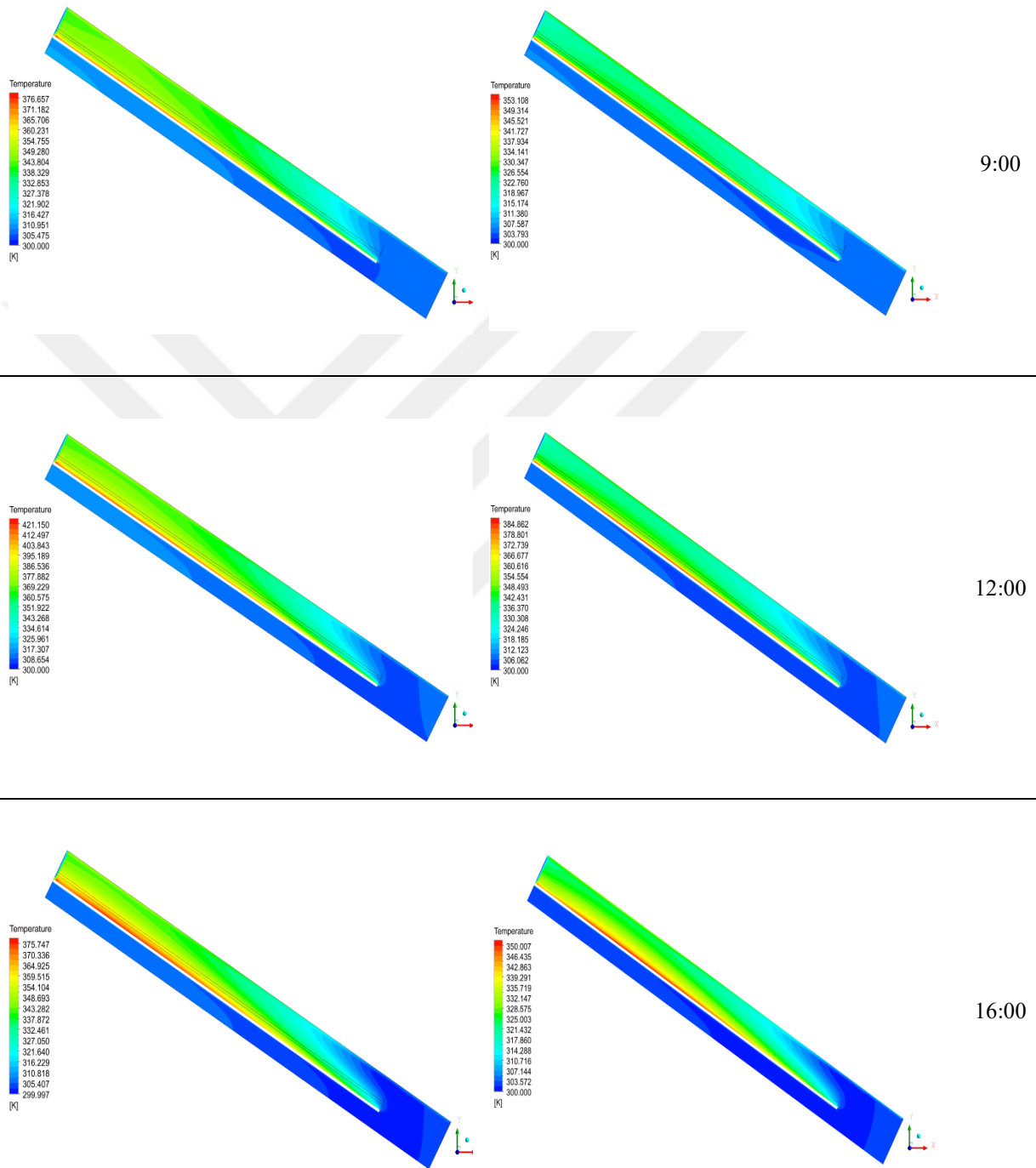
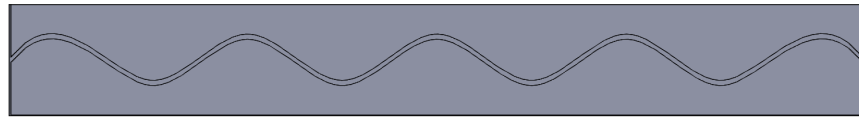


**Figure 4.30.** Pressure contours in the u -corrugated plate utilized in a parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

## Temperatures

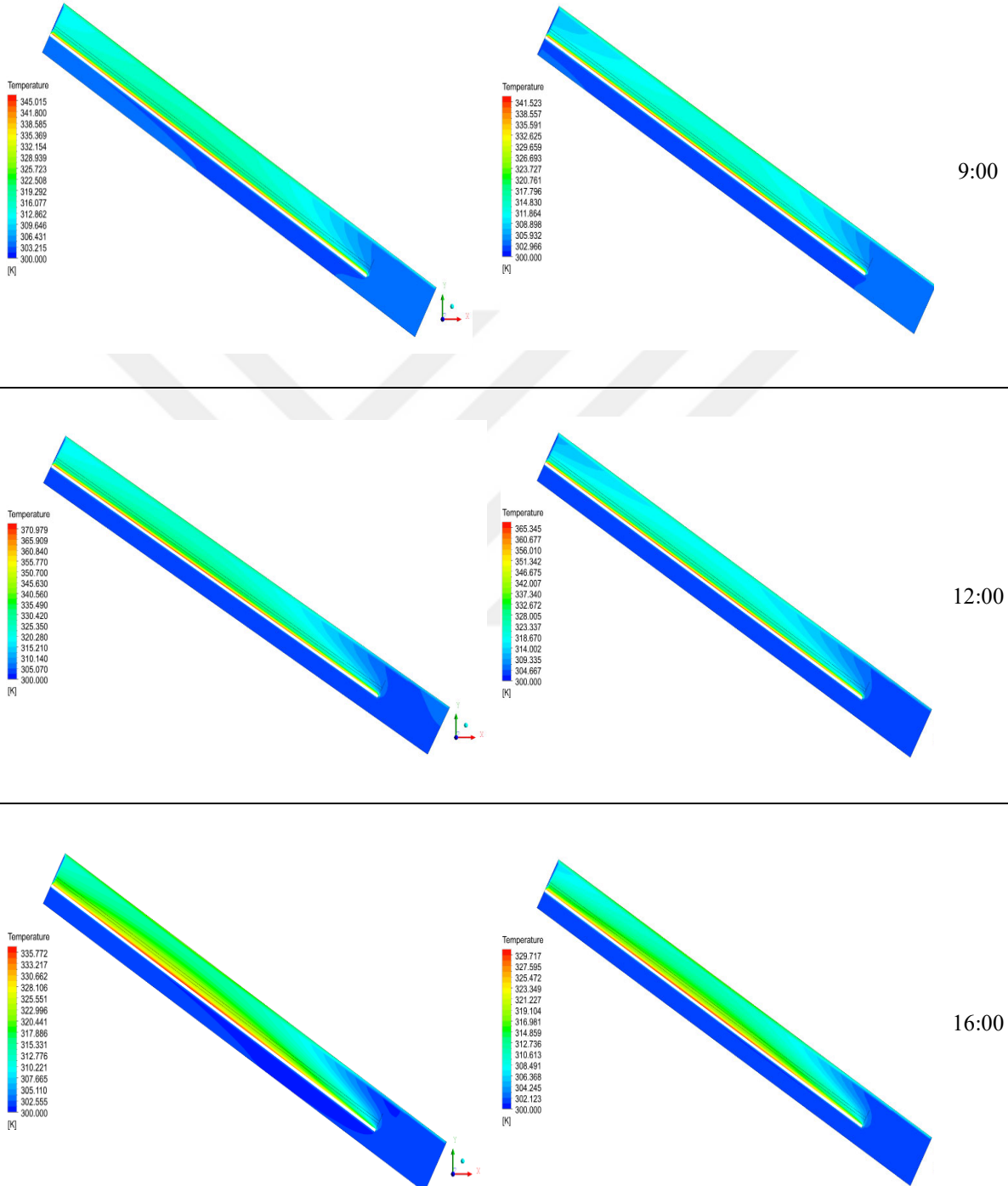
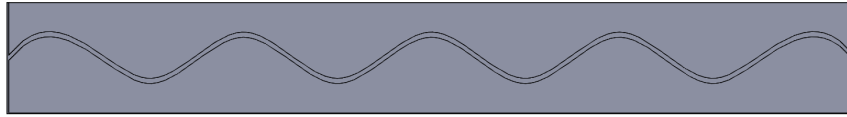


$\dot{m}^* = 0.0011 \text{ kg/s}$

$\dot{m}^* = 0.0023 \text{ kg/s}$

**Figure 4.31.** Temperature contours in the u -corrugated plate utilized in a parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

## Temperatures



$\dot{m}' = 0.0034 \text{ kg/s}$

$\dot{m}' = 0.0046 \text{ kg/s}$

**Figure 4.32.** Temperature contours in the u -corrugated plate utilized in a parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

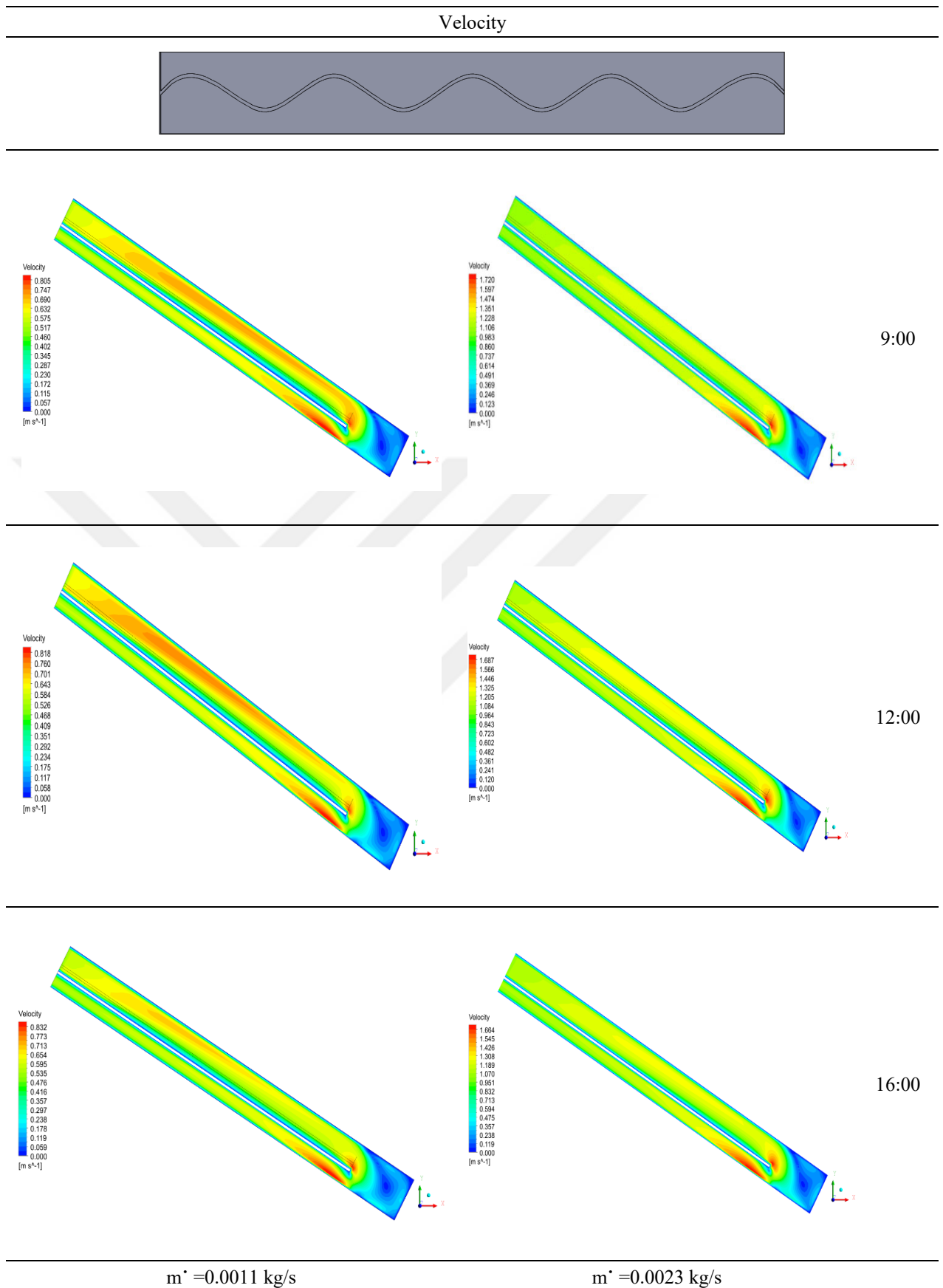


**Figure 4.33.** Velocity contours in the u -corrugated plate utilized in a parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

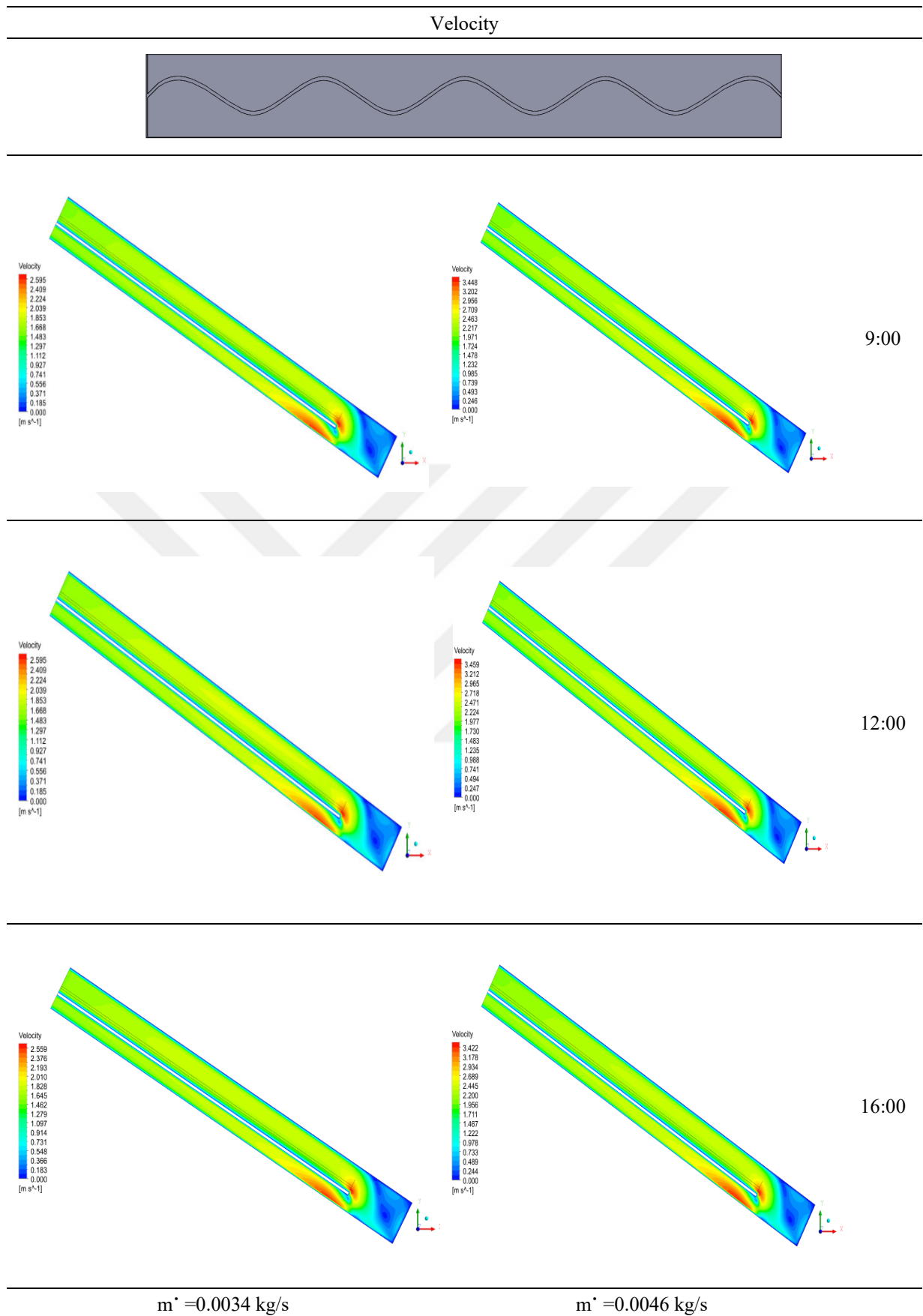


**Figure 4.34.** Velocity contours in the u -corrugated plate utilized in a parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

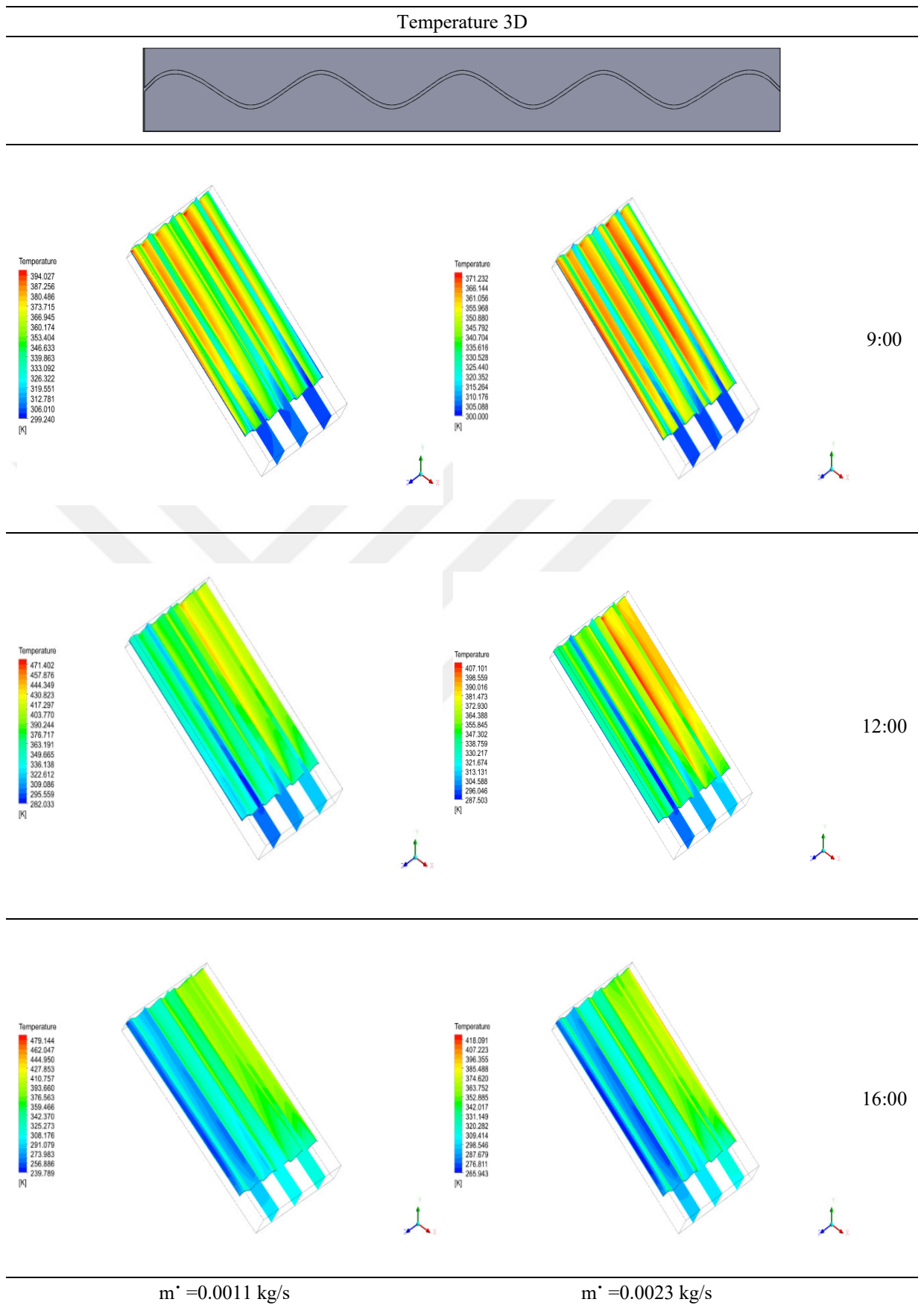
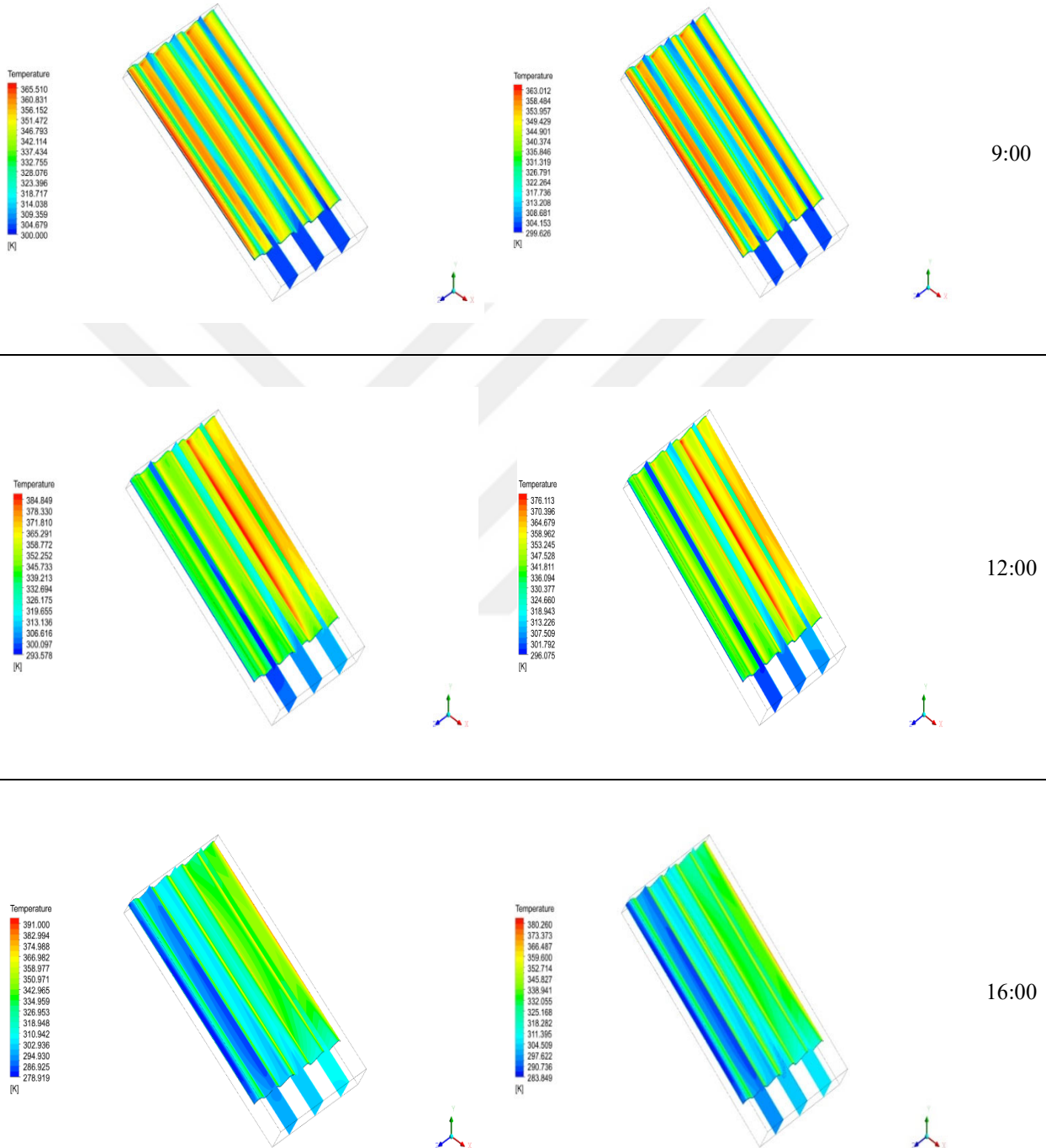
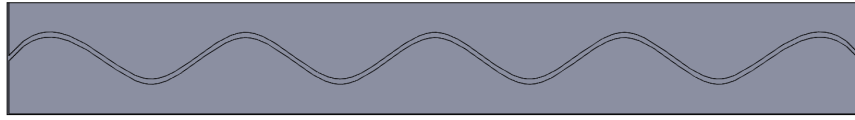


**Figure 4.35.** Absorber temperature 3D contours in the u-corrugated plate utilized in a parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

# Temperature 3D



$m^* = 0.0034 \text{ kg/s}$

$m^* = 0.0046 \text{ kg/s}$

**Figure 4.36.** Absorber temperature 3D contours in the u -corrugated plate utilized in a parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

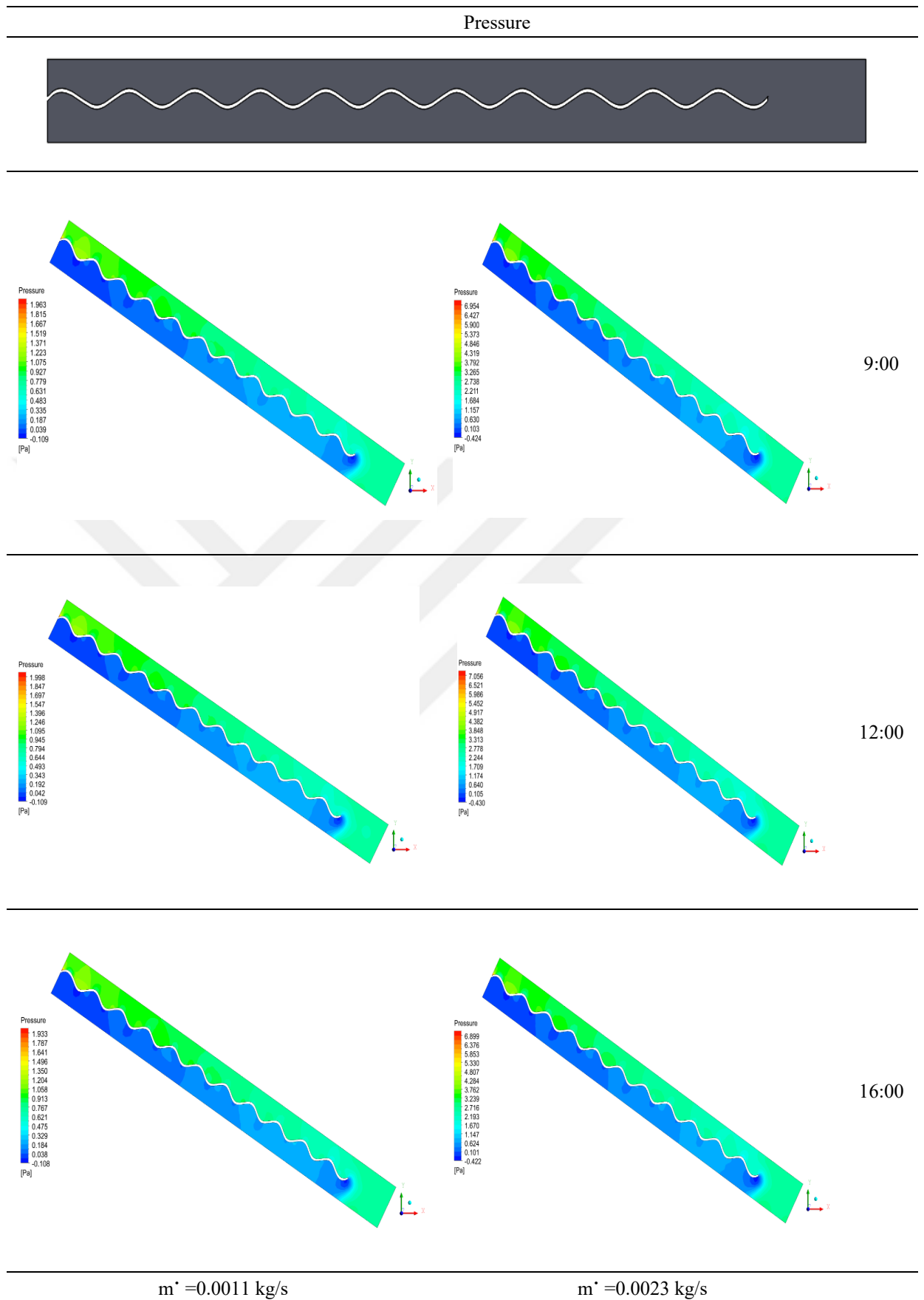


**Figure 4.37.** Pressure contours in the u -corrugated plate utilized in anti- parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

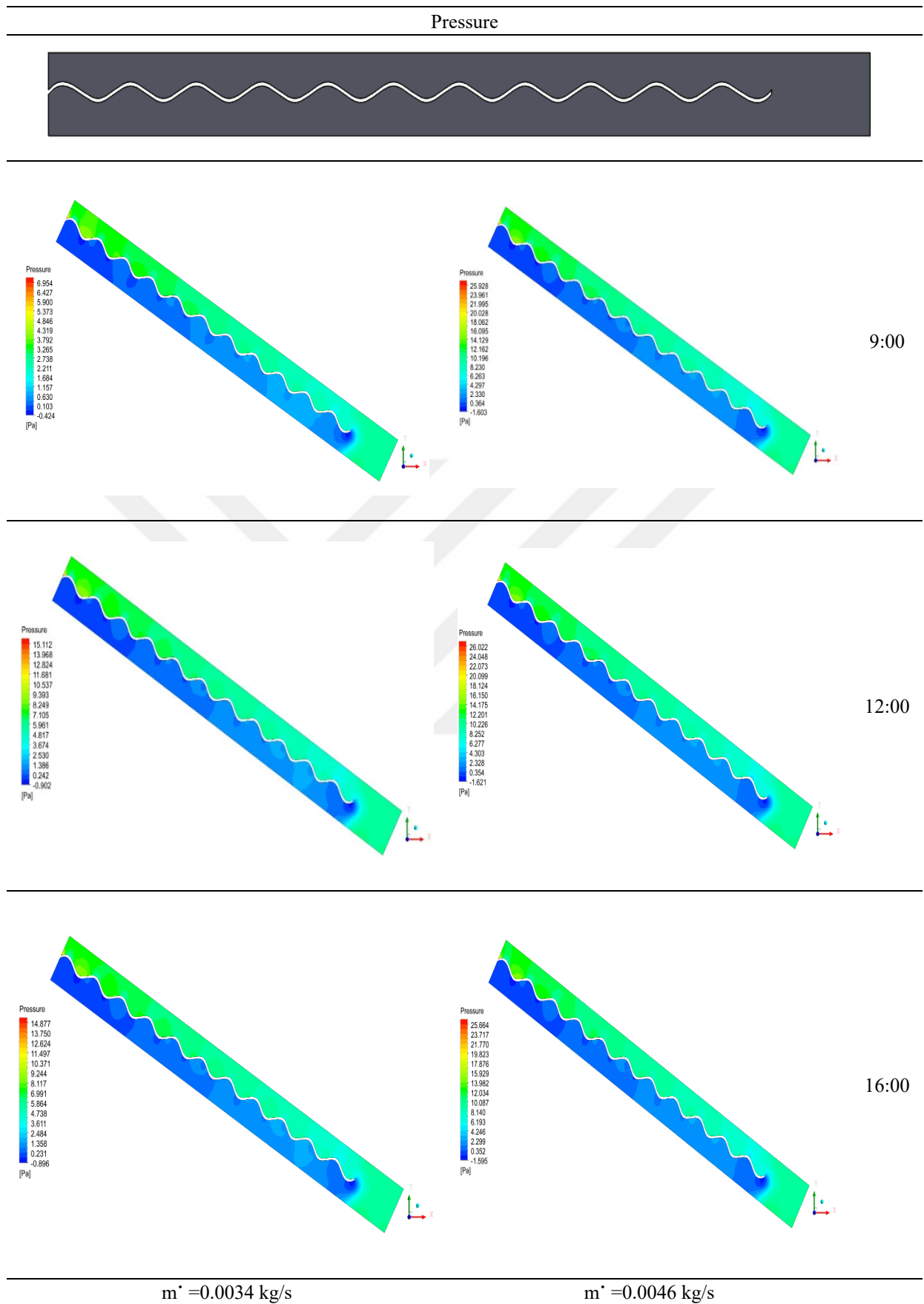


**Figure 4.38.** Pressure contours in the u -corrugated plate utilized in anti- parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

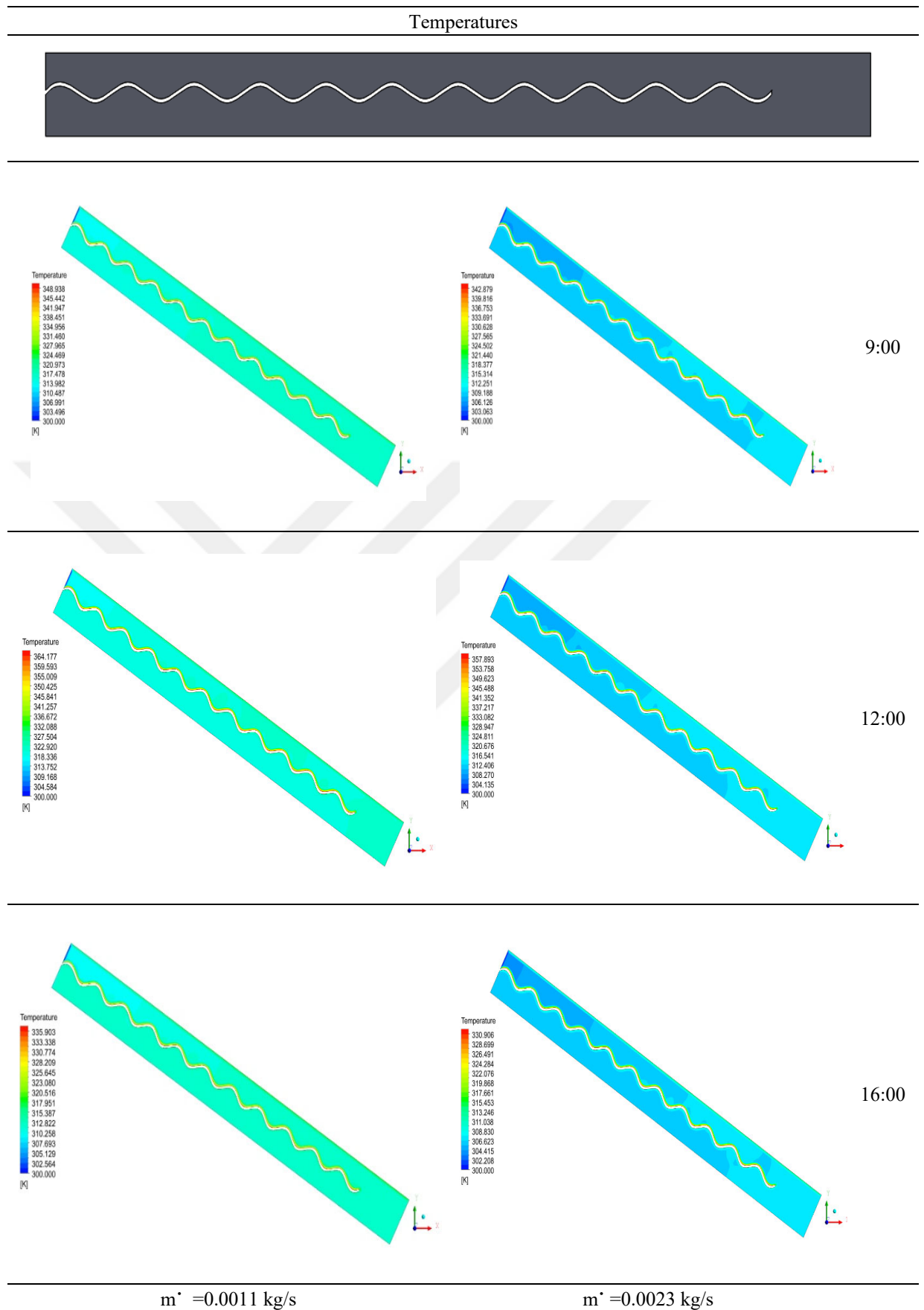


**Figure 4.39.** Temperatures contours in the u -corrugated plate utilized in anti- parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

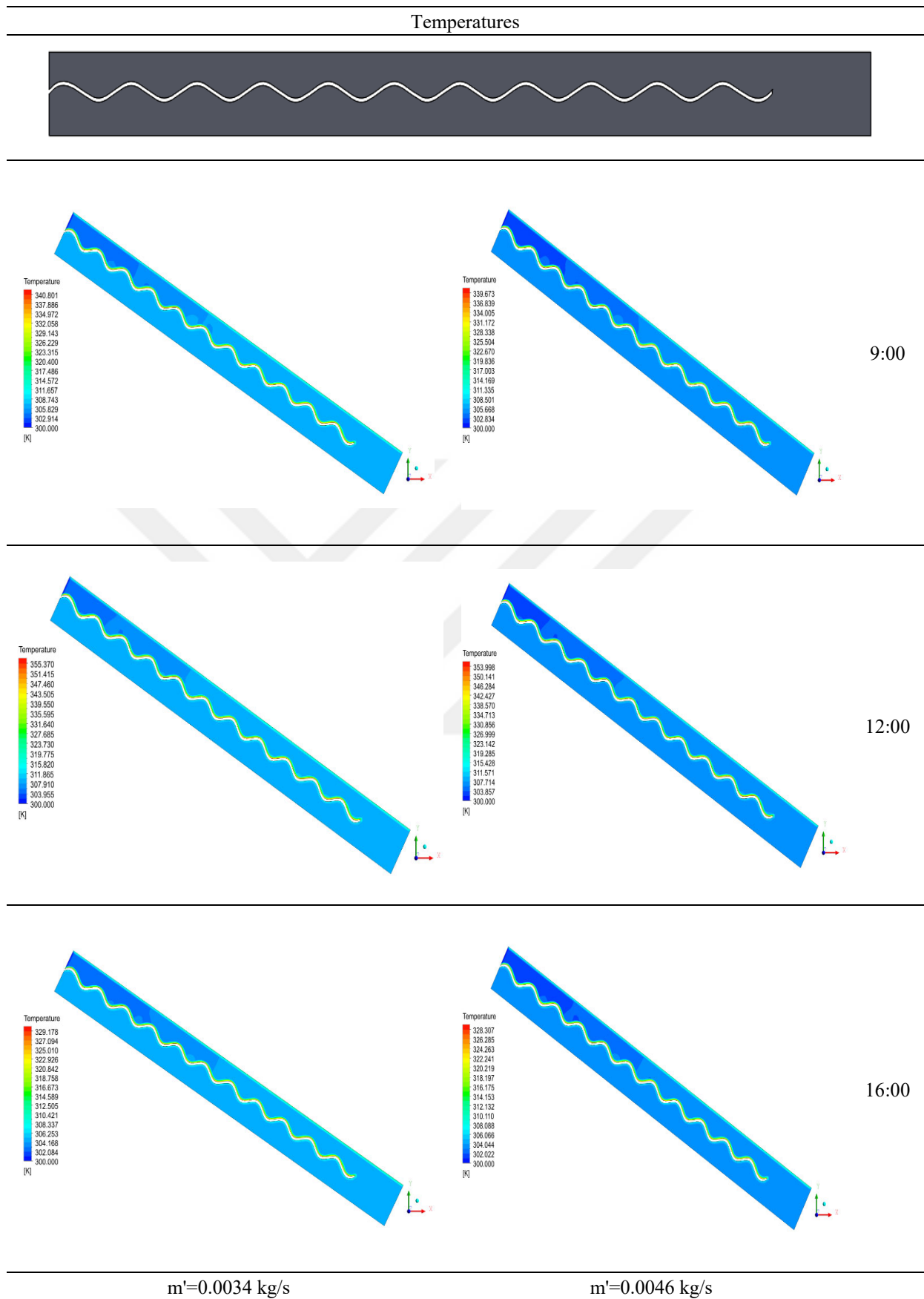


**Figure 4.40.** Temperatures contours in the u -corrugated plate utilized in anti- parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

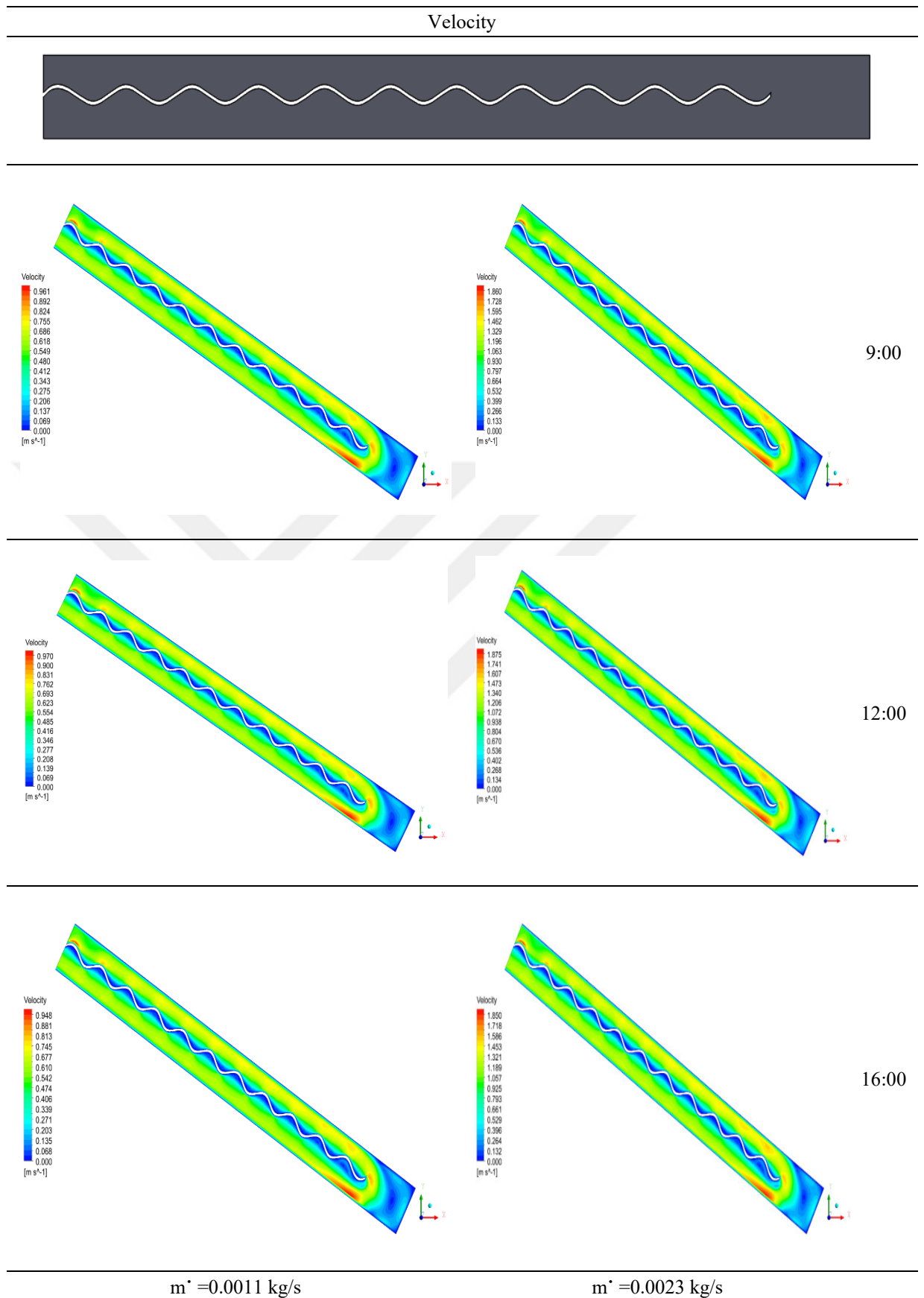


**Figure 4.41.** Velocity contours in the u -corrugated plate utilized in anti- parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

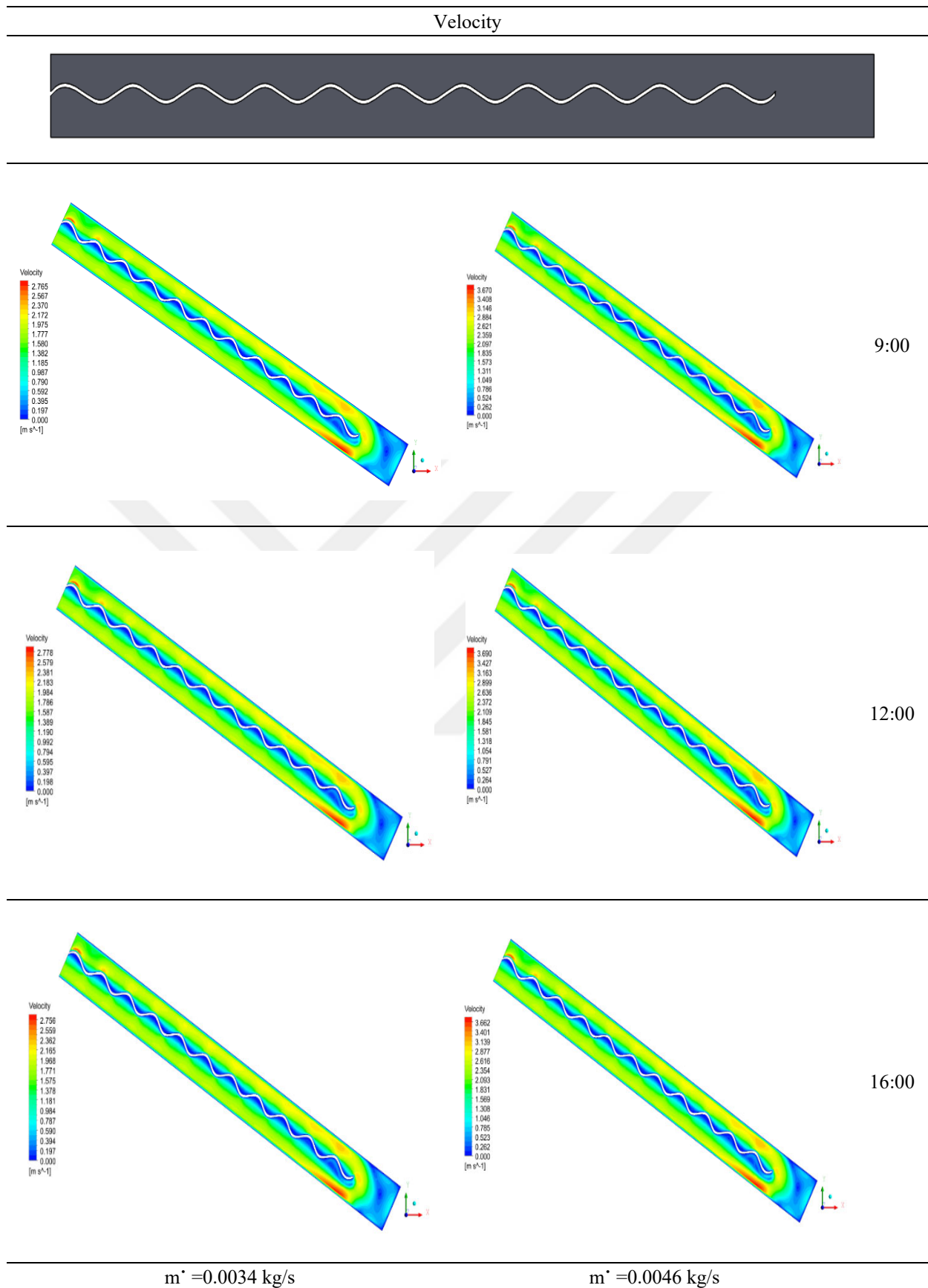
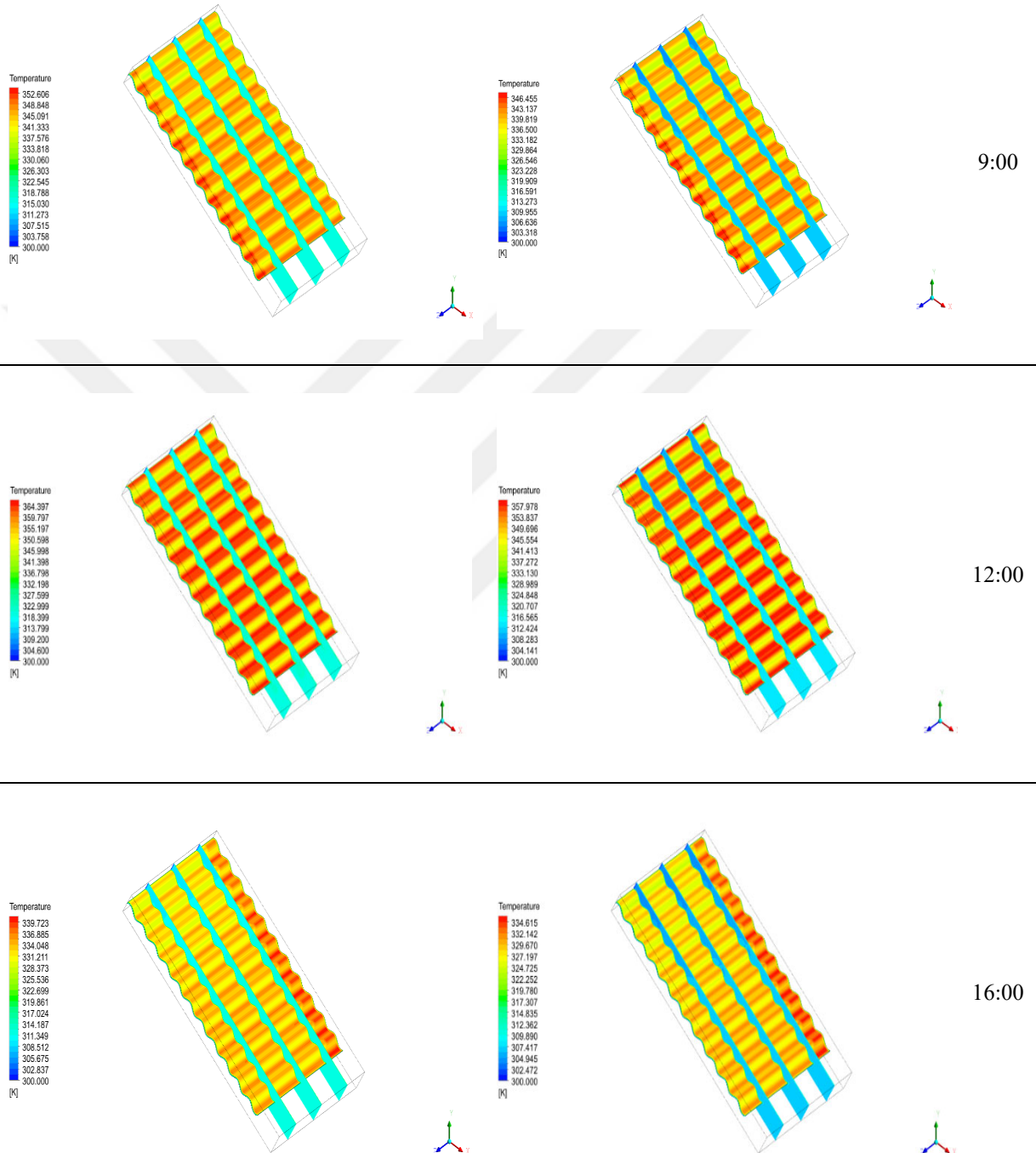


**Figure 4.42.** Velocity contours in the u -corrugated plate utilized in anti- parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

## Temperature 3D

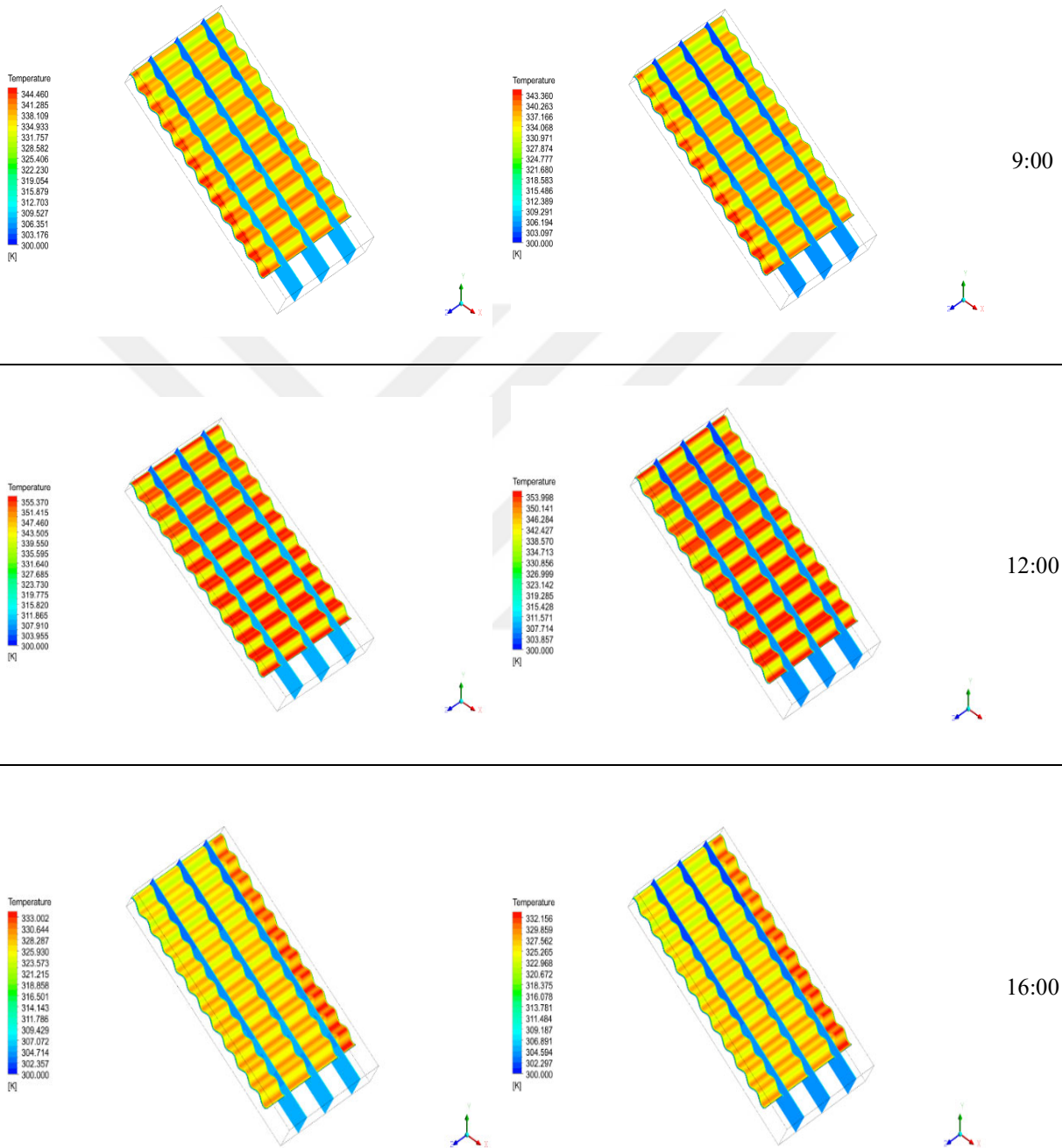


$\dot{m}^* = 0.0011 \text{ kg/s}$

$\dot{m}^* = 0.0023 \text{ kg/s}$

**Figure 4.43.** Absorber temperature 3D contours in the u -corrugated plate utilized in anti- parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

## Temperature 3D



$\dot{m}' = 0.0034 \text{ kg/s}$

$\dot{m}' = 0.0046 \text{ kg/s}$

**Figure 4.44.** Absorber temperature 3D contours in the u -corrugated plate utilized in anti- parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

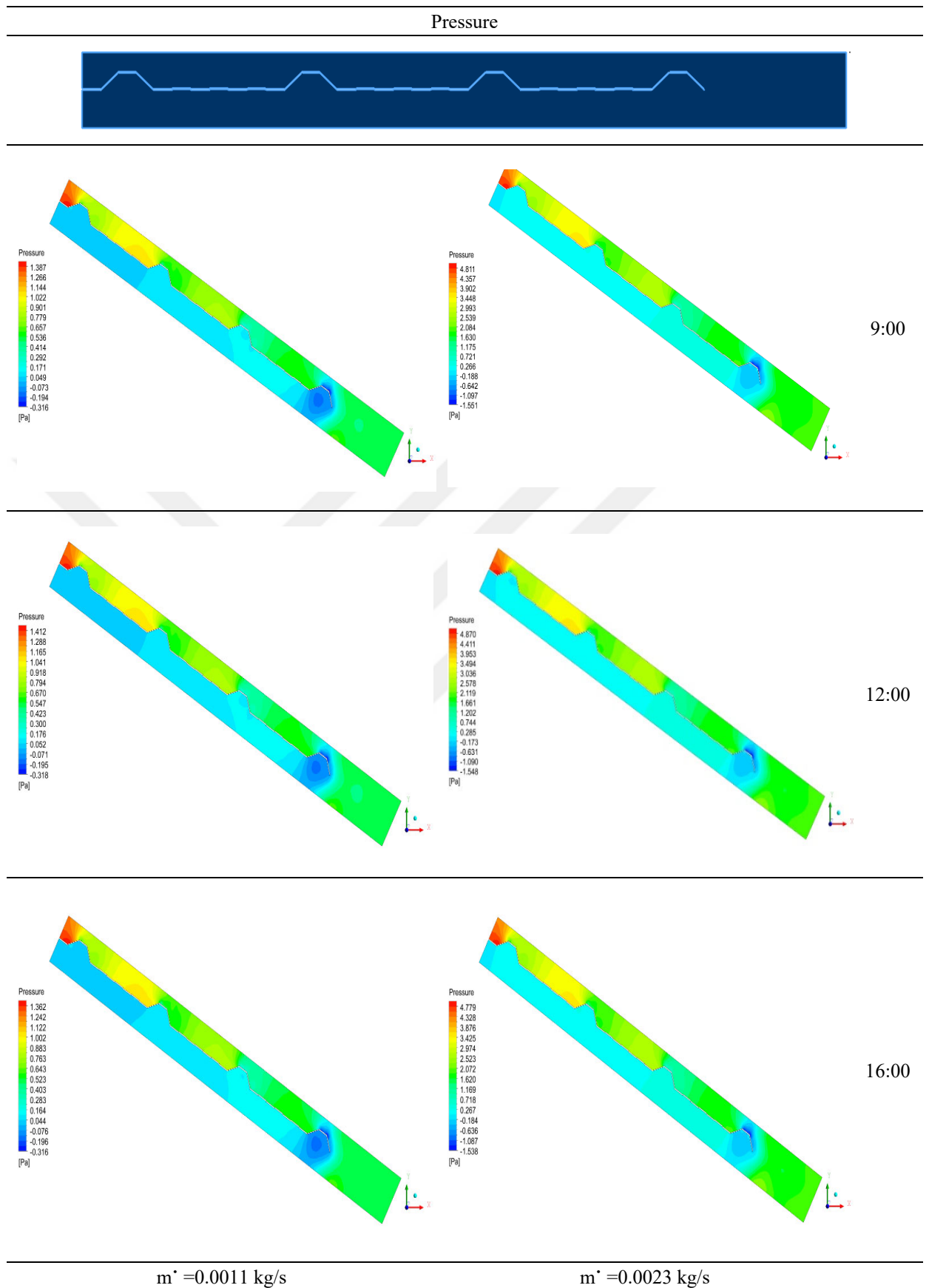


**Figure 4.45.** Pressure contours in the trapezoidal corrugated plate utilized in anti-parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

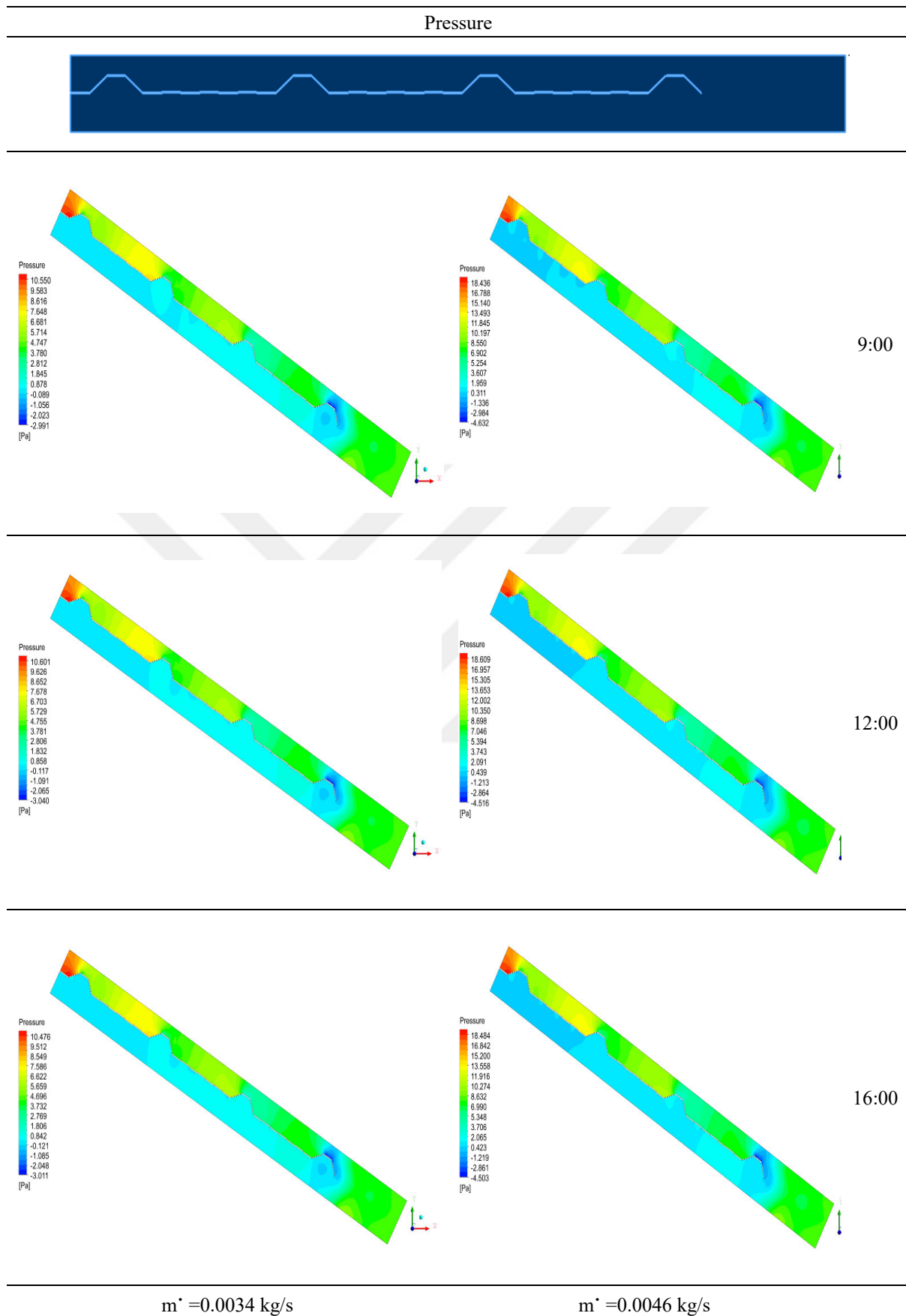
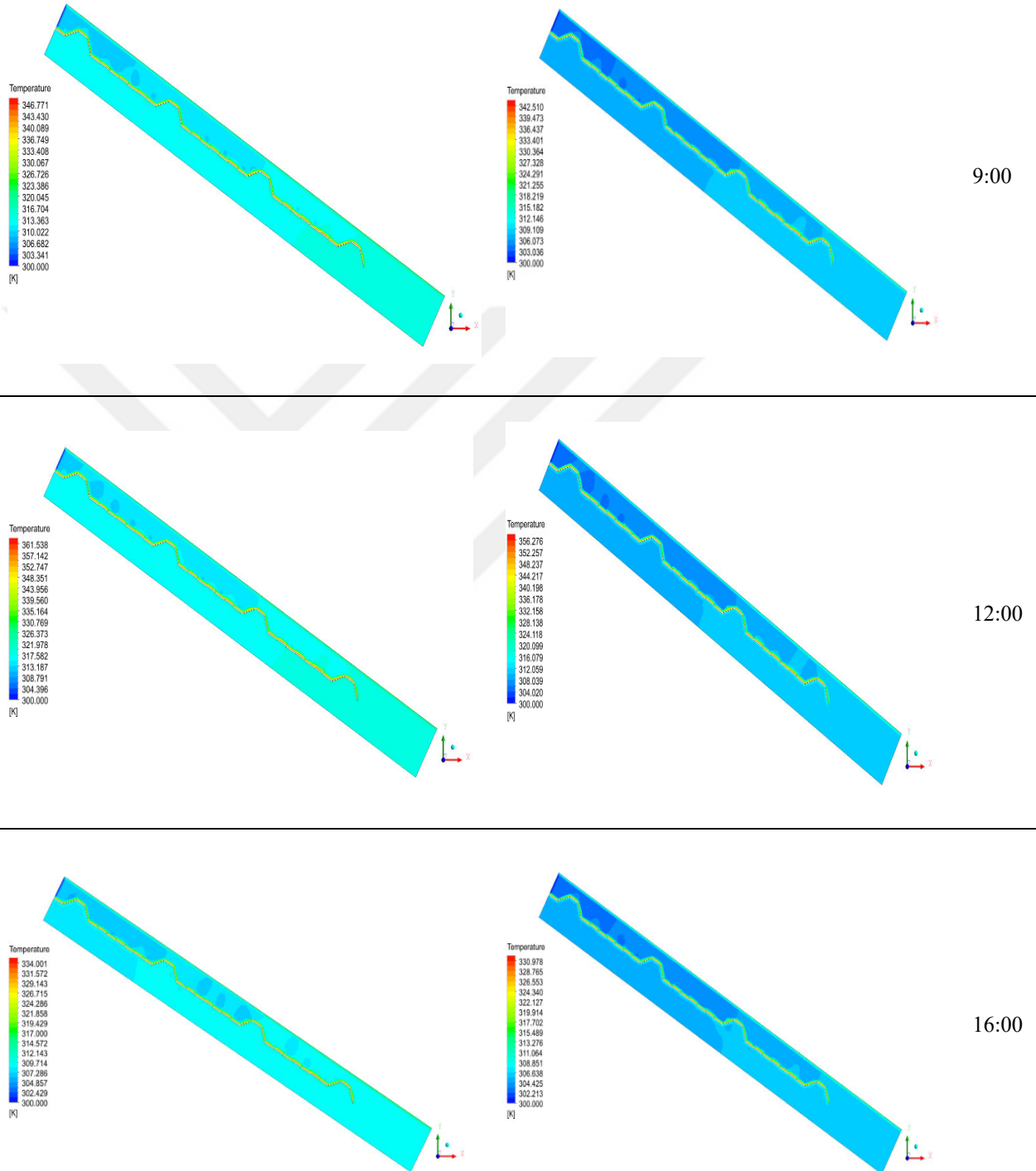


**Figure 4.46.** Pressure contours in the trapezoidal corrugated plate utilized in anti-parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

## Temperatures



$\dot{m} = 0.0011 \text{ kg/s}$

$\dot{m} = 0.0023 \text{ kg/s}$

**Figure 4.47.** Temperatures contours in the trapezoidal corrugated plate utilized in anti-parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

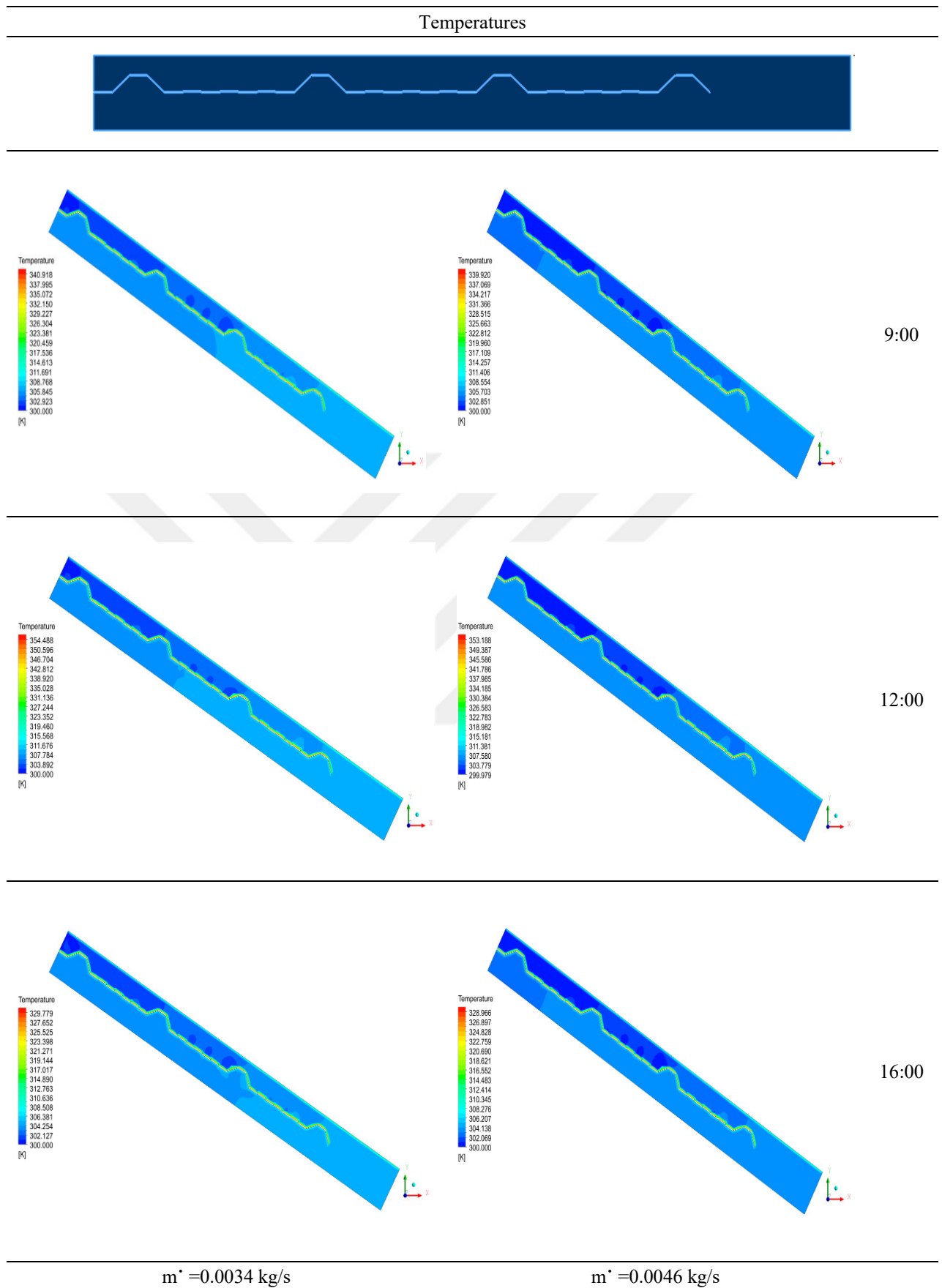


**Figure 4.48.** Temperatures contours in the trapezoidal corrugated plate utilized in anti-parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

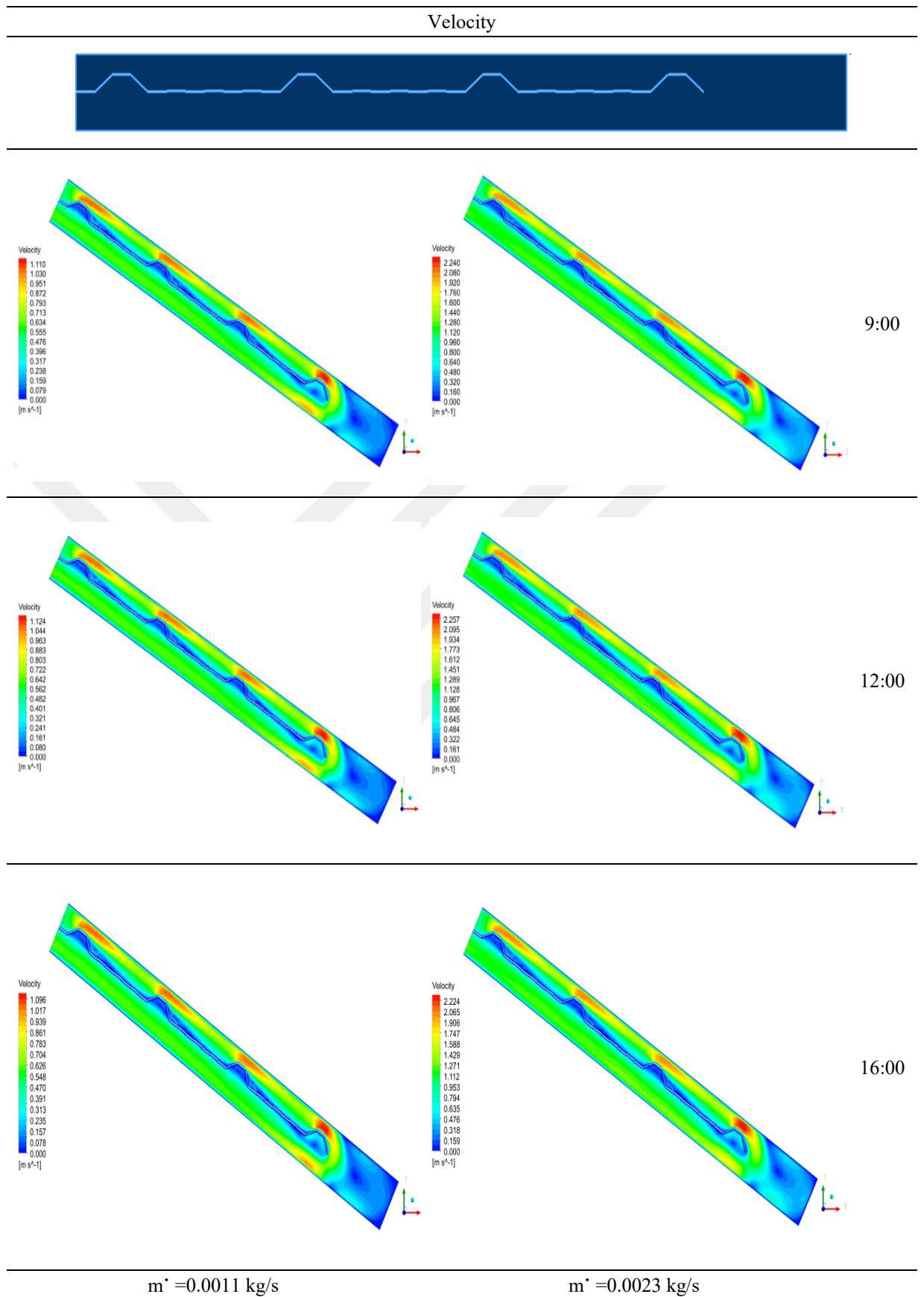


**Figure 4.49.** Velocity contours in the trapezoidal corrugated plate utilized in anti-parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

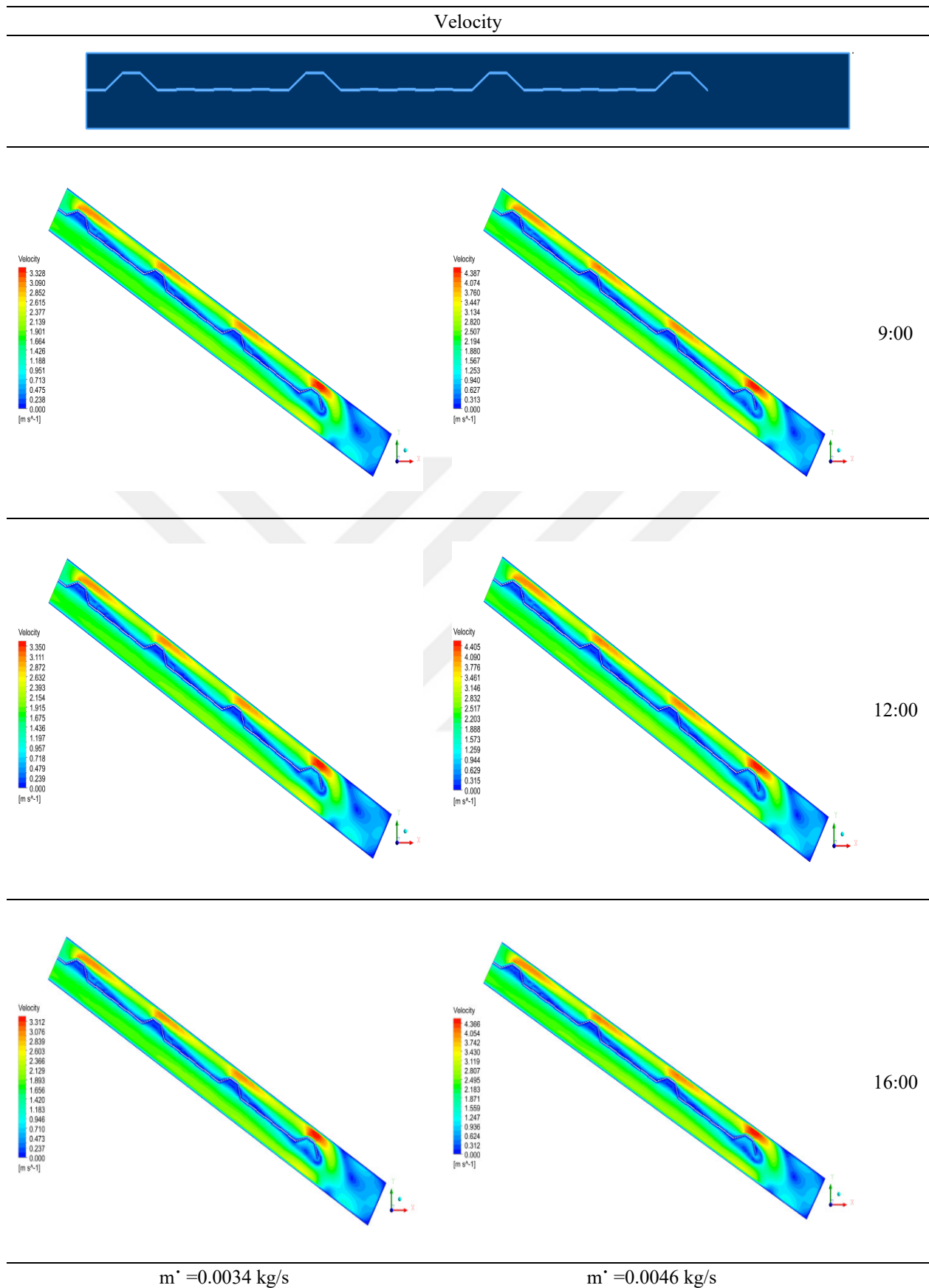


**Figure 4.50.** Velocity contours in the trapezoidal corrugated plate utilized in anti-parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

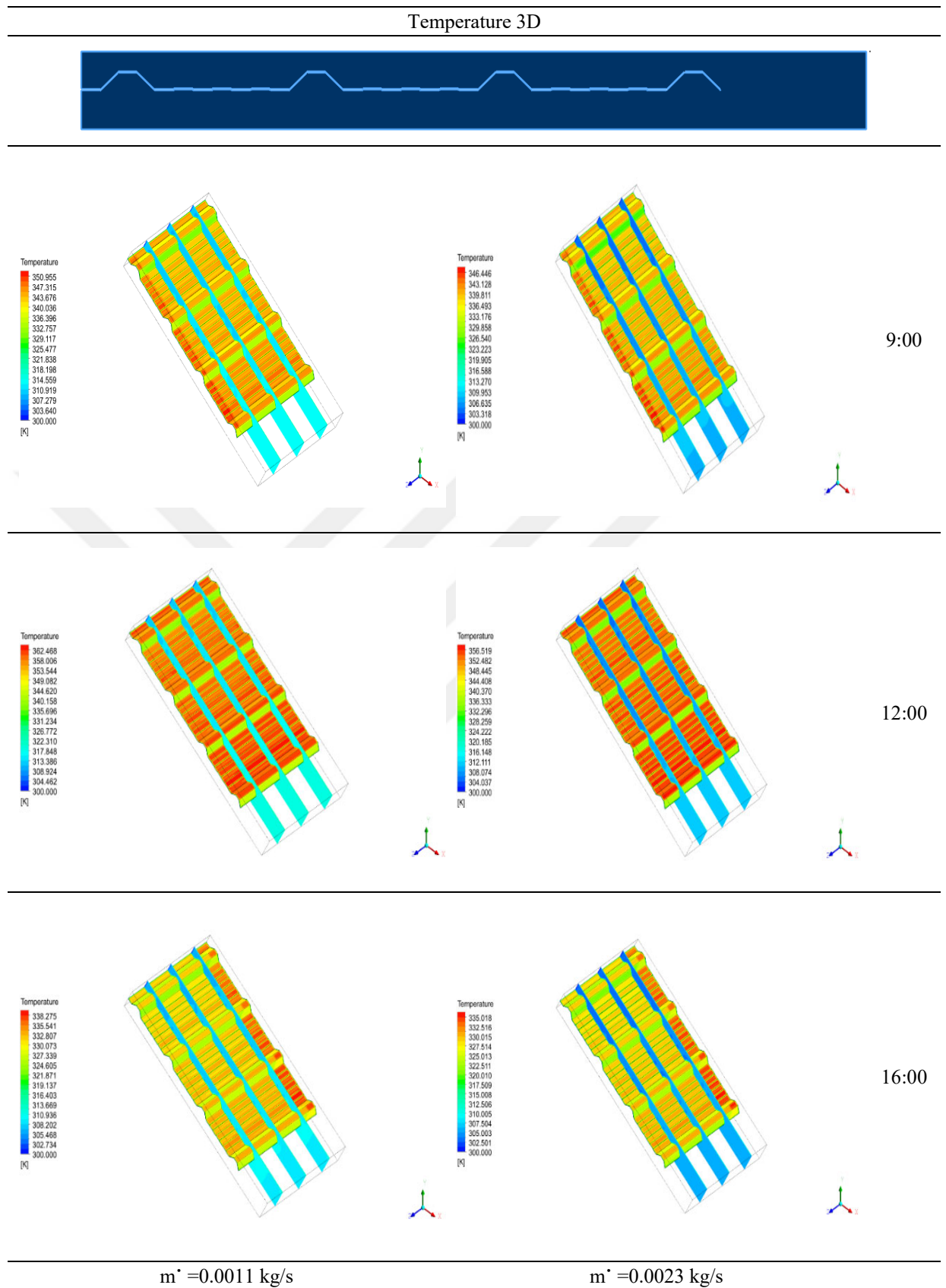


**Figure 4.51.** Absorber temperature 3D contours in the trapezoidal corrugated plate utilized in anti-parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

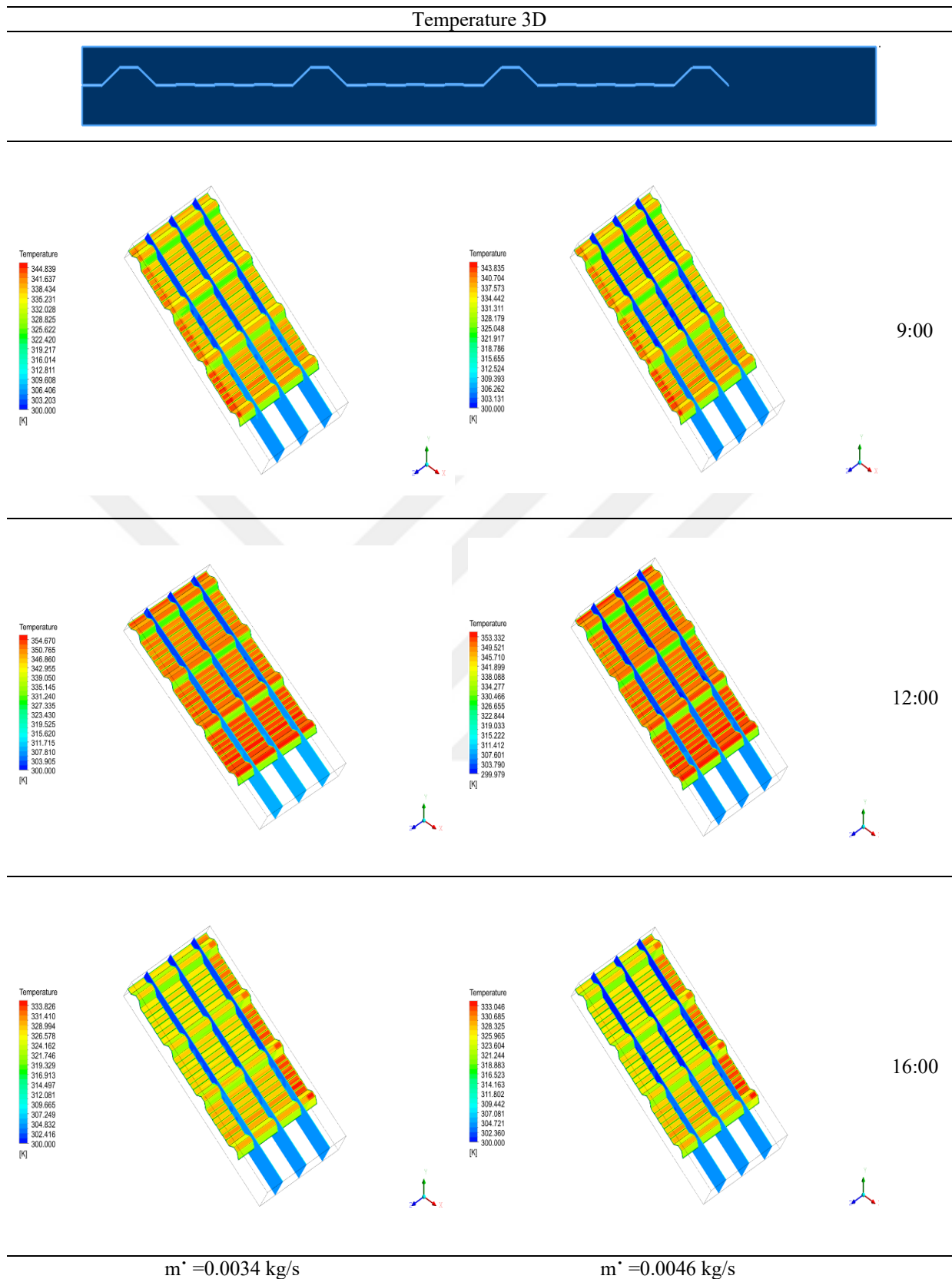
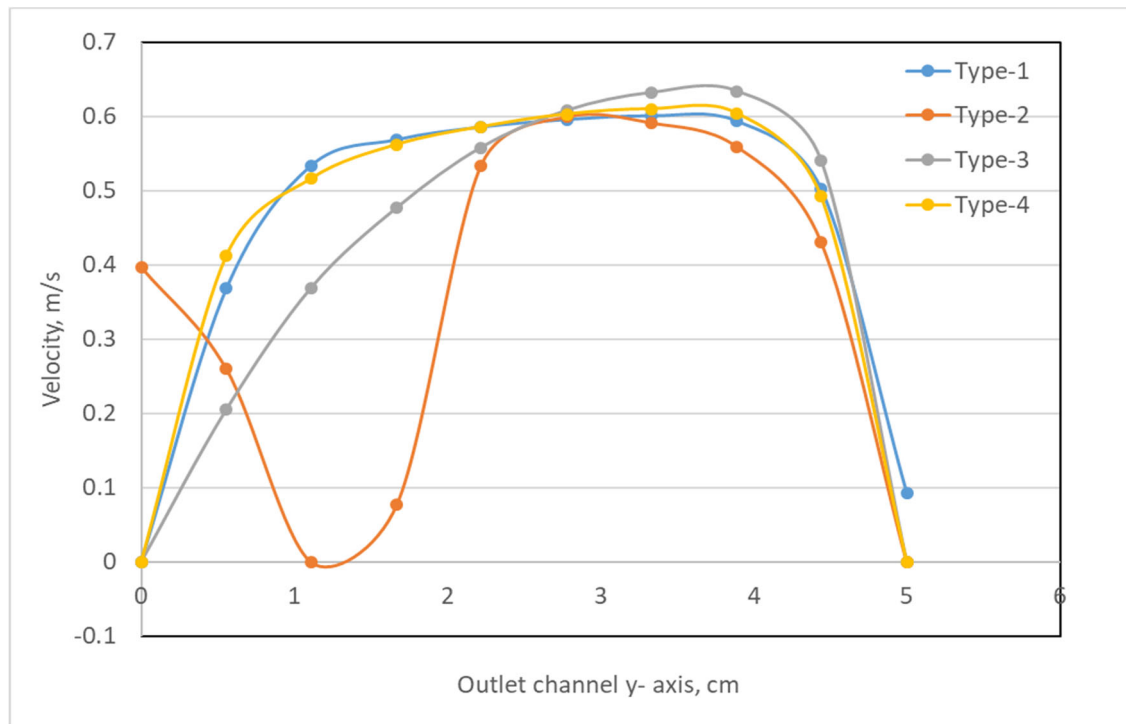


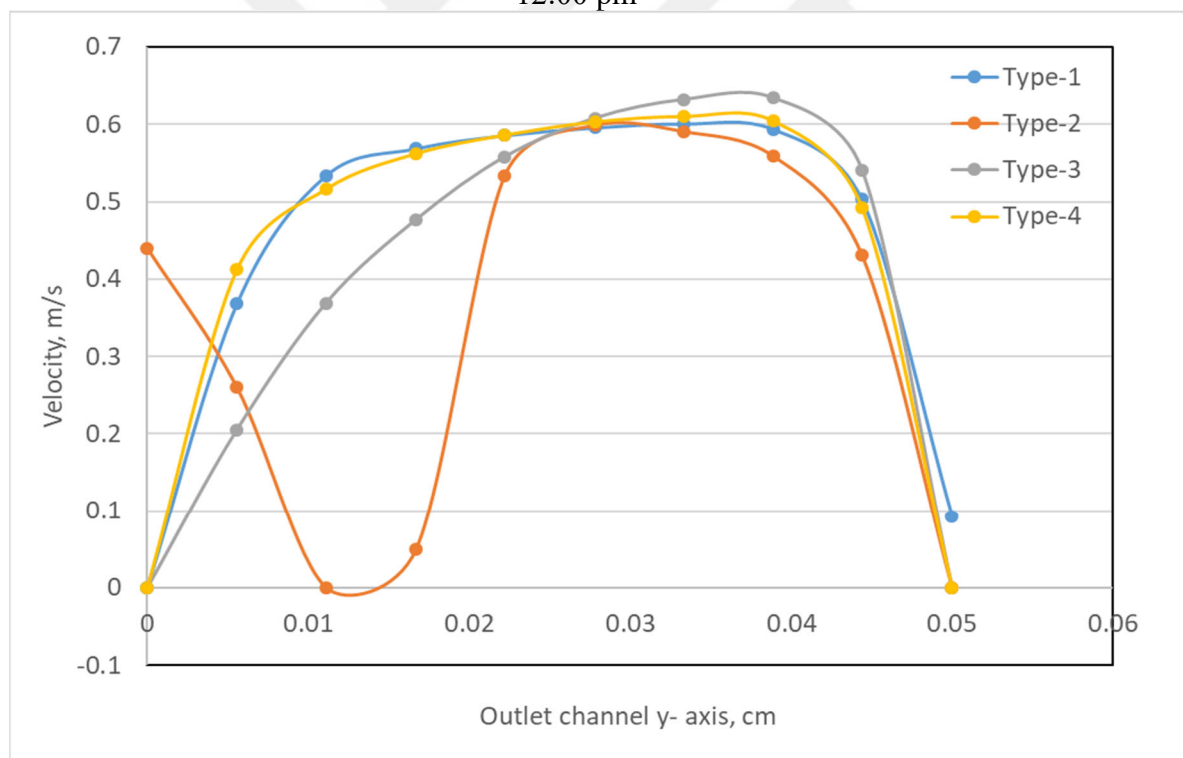
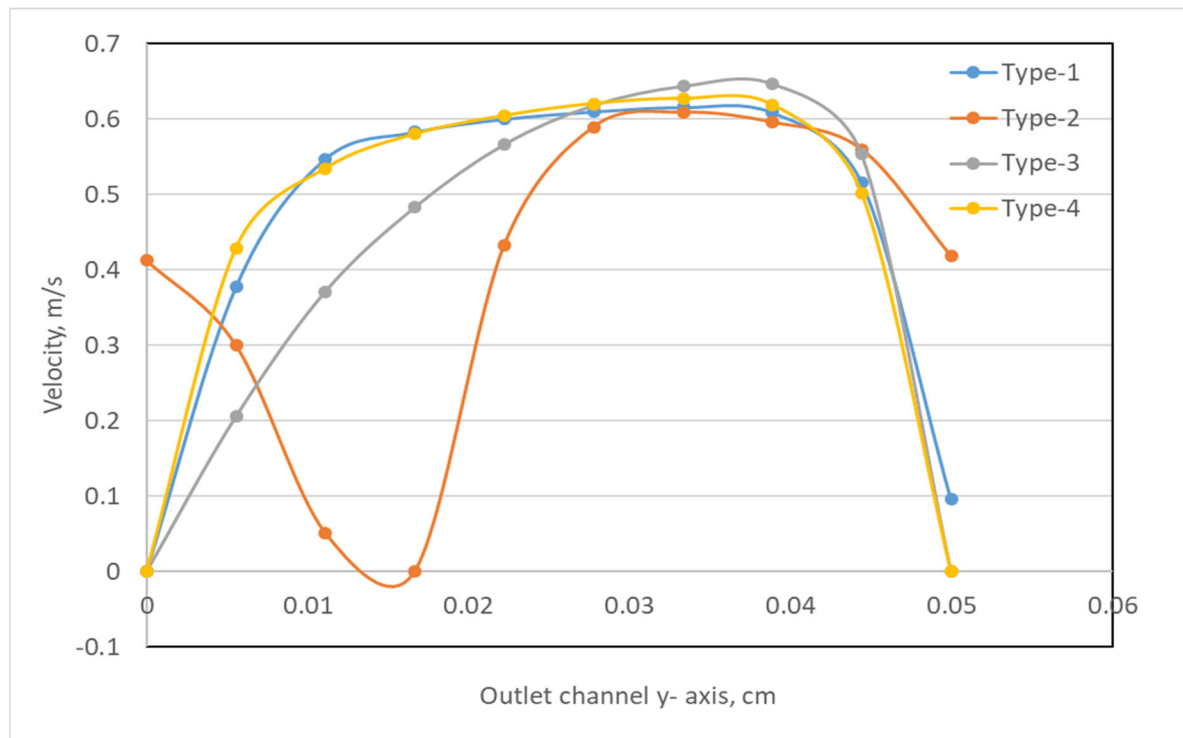
**Figure 4.52.** Absorber temperature 3D contours in the trapezoidal corrugated plate utilized in anti- parallel direction to airflow dual-flow SAH for three times and two flow rates of mass

#### 4.4. Comparison Between the Variety Types of Dual Flow Solar Air Heaters at Constant Flow Rates at Time

As presented in the Figs. 4.53 and Fig. 4.54, the impact of dual-flow SAH plate types at various daytime at  $x = 0.5$  cm in the outlet channel. The results demonstrated that the velocity reversed flow in the case of using u-corrugated plat utilized in a parallel direction to the airflow of dual-flow SAH. The maximum velocity is 0.7 m/sec at 9:00 am for all types simulating in this study. At this time, the maximum absorber temperature is located at the flat plate type. At daytime 12:00 pm, the velocity profile of the u-corrugated plate utilized in parallel direction to airflow type has two maximum velocity values of 0.4 kg/s and 0.6 m/sec and the maximum temperature of the u-corrugated plate utilized in parallel direction to airflow type at 310 K and the maximum velocity located at the u -corrugated plate utilized in anti-parallel direction to airflow absorber plate of 0.67 m/sec for all cases. The velocity profile at 4:00 pm seems a parabolic profile for all absorber plates except for the u-corrugated absorber plate type. It has reversed section near the absorber plate and has a maximum velocity of 0.4 m/sec. Fig.4.55 plotted the effect of the absorber plate types on the pressure profile at an inlet velocity of 0.5 m/sec. The outcomes showed that the (u-corrugated plate's parallel direction to airflow) presented a high-pressure drop in the outlet channel compared to the flat plate model.

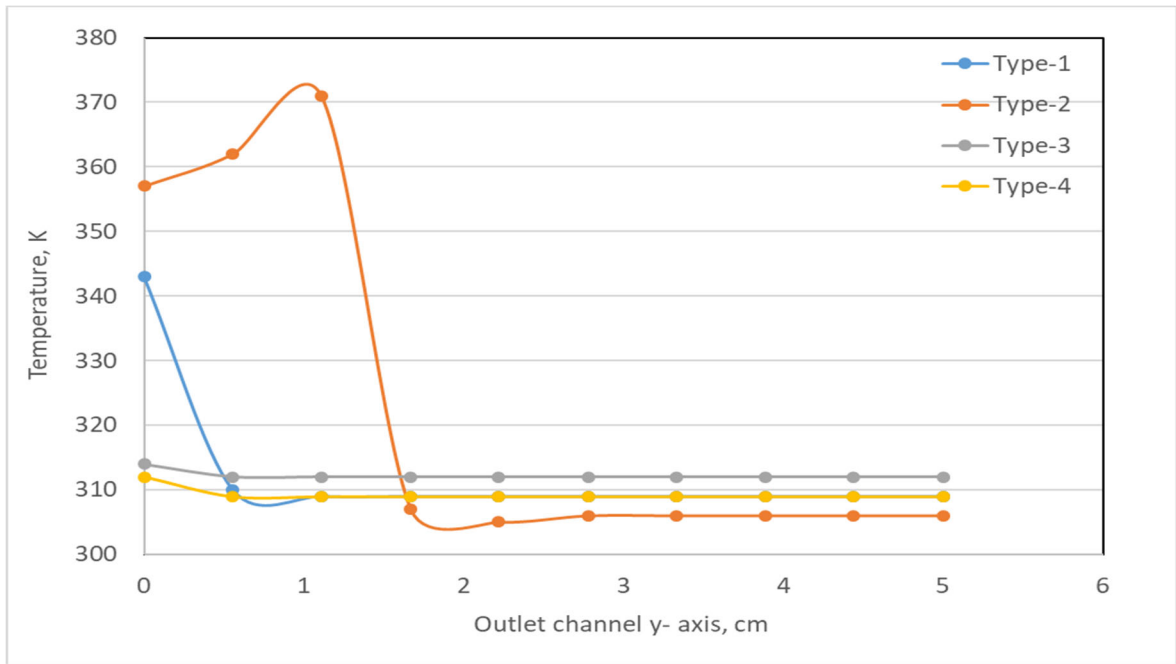


(a) 9:00 am

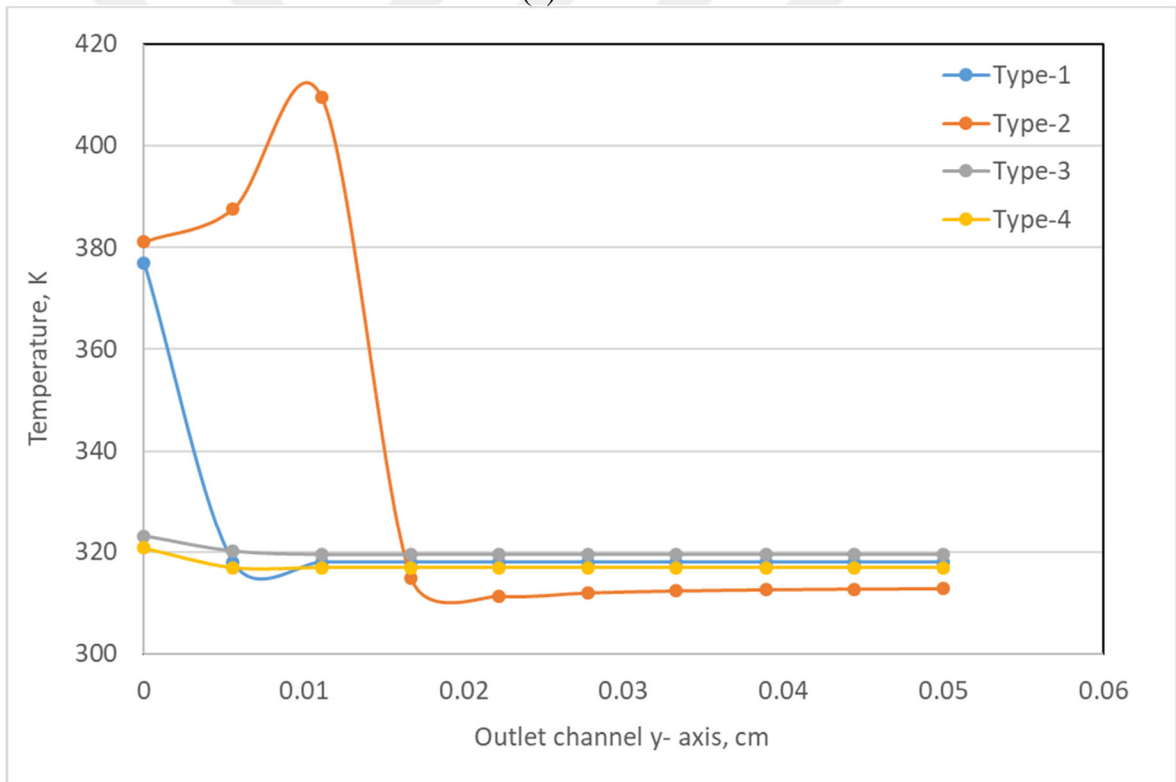


(b) 16:00 pm

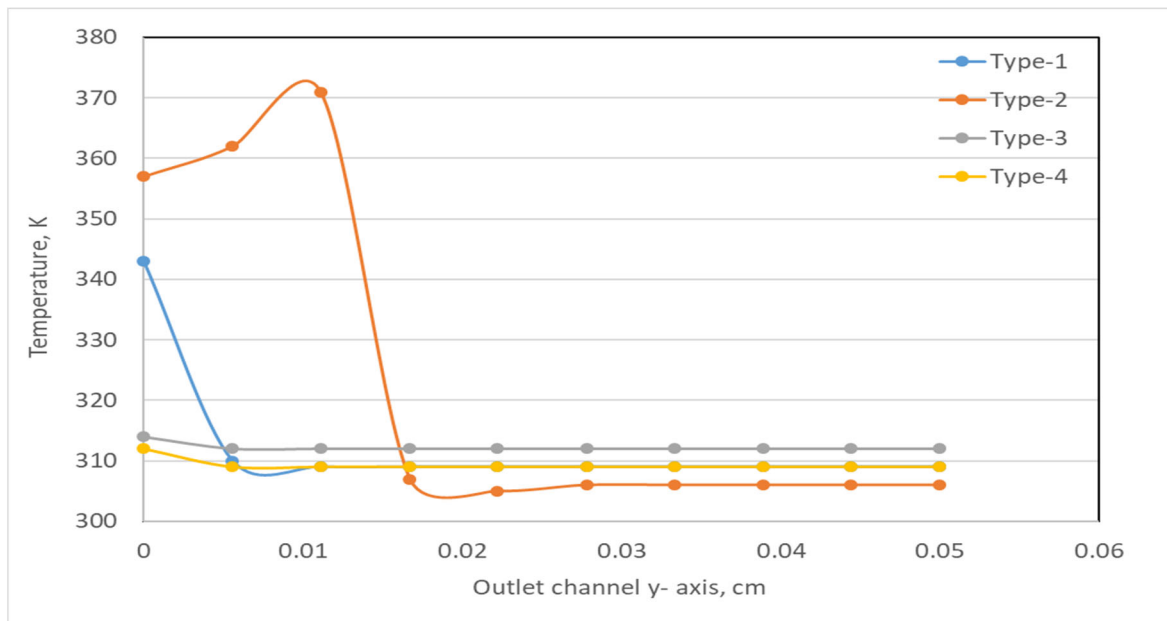
**Figure 4.53.** Effect of dual-flow SAH plate types on the velocity profile



(a) 9:00 am

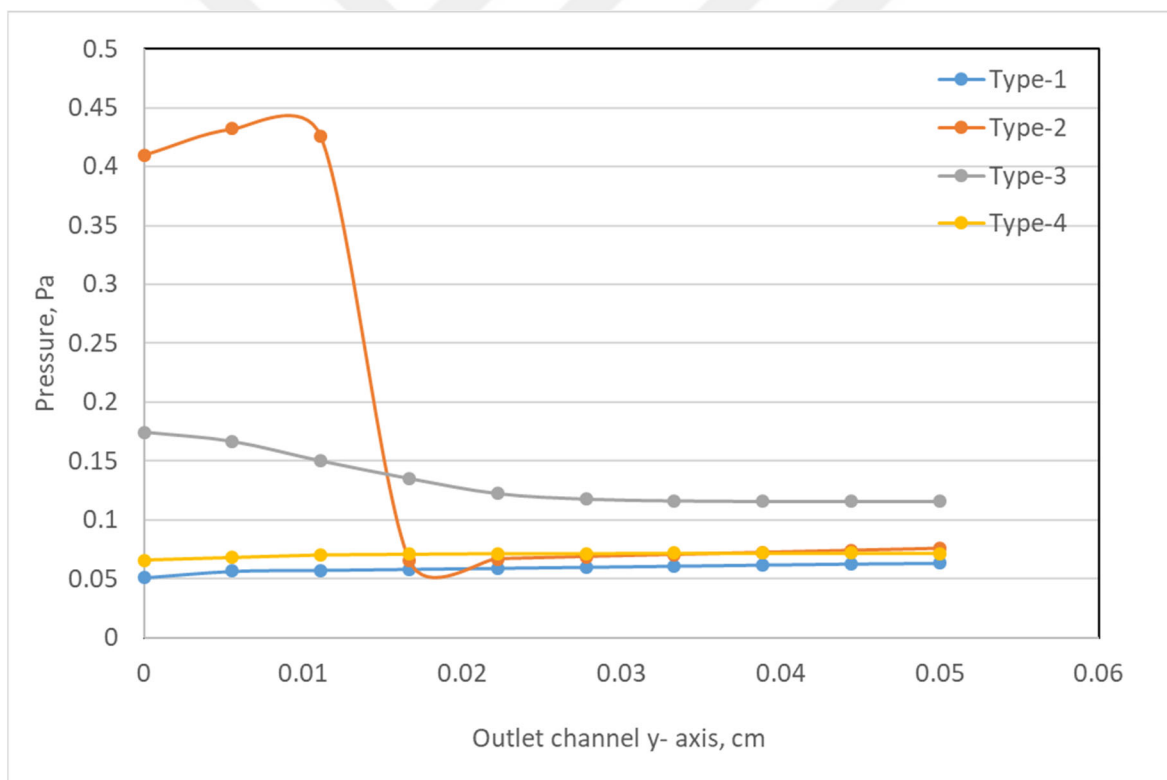


(b) 12:00 pm

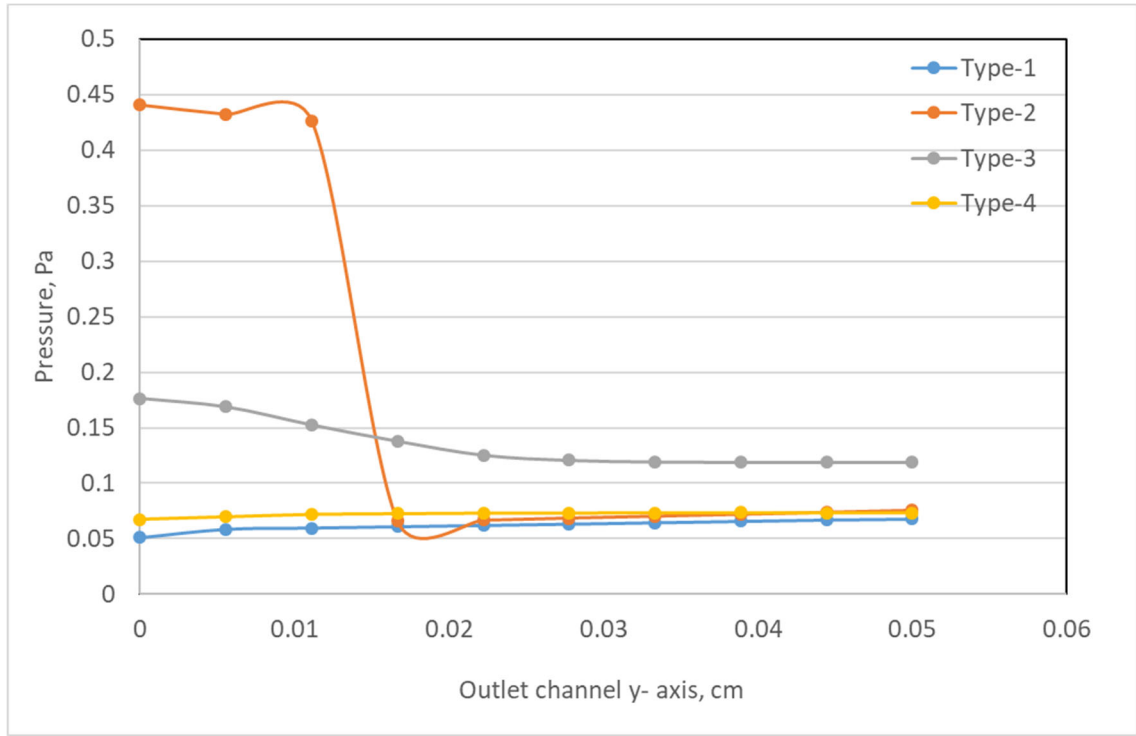


(c) 16:00 pm

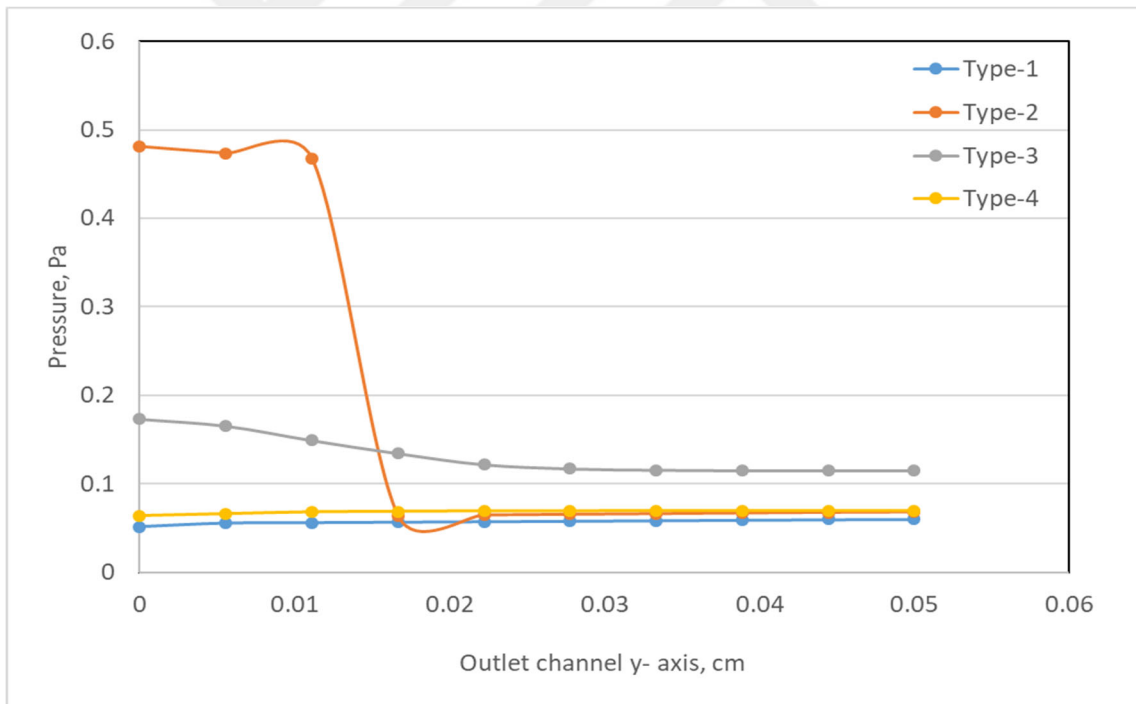
**Figure 4.54:** Effect of dual-flow SAH plate types on the temperatures profile



(a) 9:00 am



(b)12:00 pm



(c)16:00 pm

**Figure 4.55.** Effect of dual-flow SAH plate types on the pressure profile

#### 4.4.1. Comparison and Validation of the Experimental and Numerical

The input variables for the numerical model were air velocity, ambient temperature, inlet air temperature ( $T_i$ ), and sun irradiation ( $I$ ). The output air temperature ( $T_o$ ), pressure, air velocity, and absorber plate temperature ( $T_{ap}$ ) were all estimated using

the simulation. This model's steady-state simulation used the averaging of the observed data over a day of 9:00 am, 12:00 pm, and 4:00 pm. By contrasting the numerical findings with the outcomes of the experiments, the model was found to be valid. By comparing the results of thermal efficiency for experimental and numerical works for 0.0011 kg/s to 0.0046 kg/s as shown in Fig.4.56. The error ratio between theoretical results ( $X_{theo}$ ) and experimental results ( $X_{ex}$ ) is represented in the equation below used by (Gunjo et al., 2107):

$$Error \% = \frac{X_{theo} - X_{ex}}{X_{theo}} \times 100\% \quad (4.1)$$

With an average variance of 5.7% on average thermal efficiency for flat plate dual-flow SAH for four mass flow rates, the experimental and numerical findings were largely consistent. The numerical efficiency values within the same mass flow rates are greater than the experimental ones. As perfect circumstances were assumed for the numerical calculations, there is greater heat transfer between the absorbent plate and the flowing air than would otherwise be the case. The experimental outcomes are lower than the calculated efficiency values as a result. Furthermore, the present study's results were compared to those previously found in the research. The efficiency of the present dual-flow SAH at a flow rate of mass 0.0023 kg/s was compared to previous studies by (Hameed et al., 2021). Fig. 4.57 shows that the agreement with previous work is quite good.

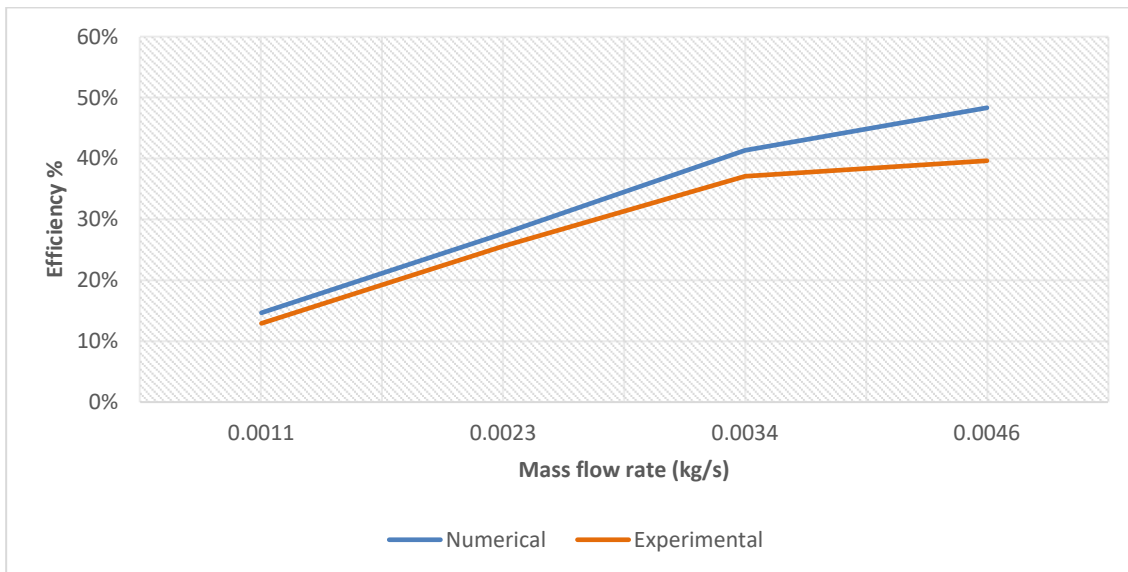


**Figure 4.56.** Experimental and numerical efficiency for flat plate SA at four mass flow rates

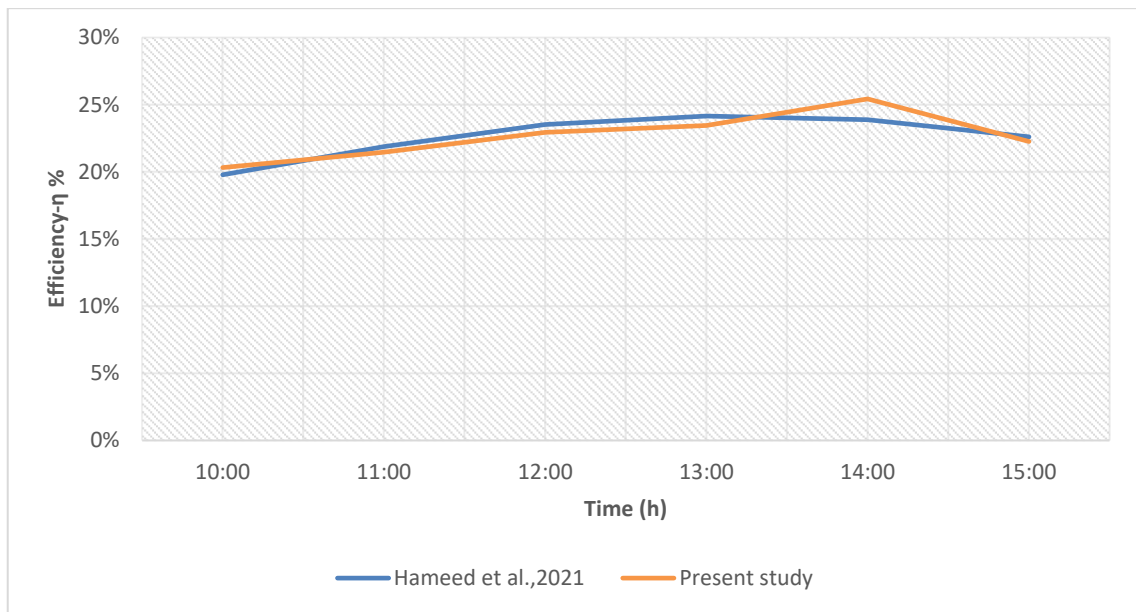


**Figure 4.57.** Validation of the thermal efficiency of dual-flow SAH



## 5. CONCLUSION AND RECOMMENDATIONS

Given the current meteorological conditions in Baghdad, Iraq, the performances of dual-flow SAHs with different channel flat and corrugated layers acting as absorber plates were investigated experimentally. The effects of the flow rate of air mass of 0.0011-0.0046 kg/s on thermal efficiency, absorbent plate temperature, and outlet air temperature were studied. The result showed that:

- The maximum average efficiency for four types studied dual-flow SAHs, flat plate, u-corrugate plate parallel to airflow, trapezoidal corrugated plate anti-parallel to airflow, and u-corrugated plate anti-parallel to airflow at mass flow rate 0.0046 kg/s were 42.80%, 51.33%, 54.38 %, and 55.53 %, respectively. The best absorbent plate, when compared to the traditional flat plate absorbent, was the anti-airflow u-corrugated plate, followed by the anti-parallel airflow trapezoidal plate, and lastly, the u-corrugated plate parallel to the airflow. In addition, the average efficiency of the four types of dual-flow SAH examined increases as the flow rate of mass increases from 0.0011 kg/s to 0.0046 kg/s. It could also be argued that increasing the turbulence intensity was what caused the efficiency to noticeably increase when the flow rate of air mass was increased from 0.0011 kg/s to 0.0046 kg/s.
- The temperature differences  $\Delta T$  at the same flow rate of mass were greater for the u-corrugated plate anti-parallel to airflow dual-flow SAH than for the other types of dual-flow SAH. The airflow creates more vortex flowing across the plate, which increases the area of heat transfer, hence causing  $\Delta T$  to enhance. The maximum  $\Delta T$  value was at noon 51 °C at a flow rate of mass of 0.0011 kg/s. Furthermore, the flow rate of mass affects the outlet air temperature. As a result, the flow rate of mass and the output air temperature are inversely related. The temperature differences decrease as the flow rate of mass increase.
- The maximum absorber plate temperature for four types studied dual-flow SAHs, flat plate, u-corrugated plate parallel to airflow, trapezoidal corrugated plate anti-parallel to airflow, and u-corrugated plate anti-parallel to airflow at a flow rate of mass 0.00411 kg/s were 98.76 °C, 94.72°C, 102.1°C, and 100.5 °C, respectively. During the day, the average absorber plate temperature is clearly greater than the outlet air temperature. This is caused by the heat transfer resistance between the absorbent plate surface and the flowing air.

- The maximum pressure drop within an hour of the day for four types of studied dual-flow SAHs: flat plate, u-corrugated plate parallel to airflow, trapezoidal corrugated plate anti-parallel to airflow, and u-corrugated plate anti-parallel to airflow at mass flow rate 0.0046 kg/s were increased from 0.041 Pa to 0.150 Pa, 0.150 Pa to 8.841 Pa, 0.150 Pa to 18.466 Pa, and 0.150 Pa to 25.664 Pa, respectively under the same condition of the day of 16:00 pm. Furthermore, the results showed that increasing the flow rate of air mass from 0.0011 to 0.0046 kg/s will lead to an increase in the pressure drop from 0.047 Pa to 0.157 Pa under the same condition of the day of 9:00 am for the flat plate dual-flow SAH.
- The maximum energy gained per hour of the day for four types studied dual-flow SAHs, flat plate, u-corrugated plate parallel to airflow, trapezoidal corrugated plate anti-parallel to airflow, and u-corrugated plate anti-parallel to airflow at a flow rate of mass 0.0046 kg/s were, 159.51 W, 173.88 W, 192.34 W, and 199.12 W at noon, respectively. It is obvious that the flow rate of mass directly relates to the amount of energy gained, i.e., as the flow rate of mass increases, the energy gained is increased too.

The investigation of the counter-flow dual-flow SAH with different absorber plates yields the following recommendations and other suggestions for further development.

- Investigate the impact of utilizing the different structures of the bottom plate instead of the flat plate on output air temperature, thermal efficiency, and pressure drop.
- Study the effect of utilizing a dual-glass cover on the air temperature increase over the SAH.
- Investigating the increase in the gap between the first absorbent plate of the SAH and the glass cover in order to avoid heat loss from the SAH's glass cover.
- More investigation is required to determine the impact of the new absorber plate structure on outlet air temperature, thermal efficiency, and pressure drop.

## 6. REFERENCES

- Abdullah, A. S., Abou Al-sood, M. M., Omara, Z. M., Bek, M. A., & Kabeel, A. E. (2018). Performance evaluation of a new counter flow double pass solar air heater with turbulators. *Solar Energy*, 173, 398–406. <https://doi.org/10.1016/j.solener.2018.07.073>
- Abdullah, Y. U., & Naiem, A. (2013). Existing Correlations Of Top Heat Loss Factor Of Flat Plate Solar Collectors And Impact On Useful Energy. *Department of Mechanical Engineering, Z. H. College of Engineering & Technology Aligarh Muslim University, Aligarh -202 002 (U.P.), India*.
- Akpınar, E. K., & Koçyiğit, F. (2010). Energy and exergy analysis of a new flat-plate solar air heater having different obstacles on absorber plates. *Applied Energy*, 87(11), 3438–3450. <https://doi.org/10.1016/j.apenergy.2010.05.017>
- Adem Acır, Mehmet Emin Canlı, Ata, İ., & Himmet Erdi Tanürün. (2018). Effects of a circular-shaped turbulator having varying hole numbers on energy and exergy efficiencies of a solar air heater. *International Journal of Ambient Energy*, 40(7), 739–748. <https://doi.org/10.1080/01430750.2017.1423385>
- Al Ghuol Fatah, O., Sopian, K., Abdullah, S., Al-Ghoul, M., & Whaad, A. (2015). Heat Transfer Enhancement Techniques for Solar Air Collector Hater. *Modern Applied Science*, 22;9(9).
- Alam, T., & Kim, M.-H. (2016). Numerical study on thermal hydraulic performance improvement in solar air heater duct with semi ellipse shaped obstacles. *Energy*, 112, 588–598. <https://doi.org/10.1016/j.energy.2016.06.105>.
- Aldabbagh, L. B. Y., Egelioglu, F., & Ilkan, M. (2010). Single and double pass solar air heaters with wire mesh as packing bed. *Energy*, 35(9), 3783–3787. <https://doi.org/10.1016/j.energy.2010.05.028>
- Alta, D., Bilgili, E., Ertekin, C., & Yaldiz, O. (2010). Experimental investigation of three different solar air heaters: Energy and exergy analyses. *Applied Energy*, 87(10), 2953–2973. <https://doi.org/10.1016/j.apenergy.2010.04.016>
- Alvarez, G., Arce, J., Lira, L., & Heras, M. R. (2004). Thermal performance of an air solar collector with an absorber plate made of recyclable aluminum cans. *Solar Energy*, 77(1), 107–113. <https://doi.org/10.1016/j.solener.2004.02.007>
- Ansys Fluent 2020 R1-Theory Guide; User Guide Full pdf. (2020). Ansys Learning Forum | Ansys Innovation Space. <https://forum.ansys.com/forums/topic/ansys-fluent-2020-r1-theory-guide-user-guide-full-pdf/>
- Bayrak, F., Oztop, H. F., & Hepbasli, A. (2013). Energy and exergy analyses of porous baffles inserted solar air heaters for building applications. *Energy and Buildings*, 57, 338–345. <https://doi.org/10.1016/j.enbuild.2012.10.055>
- Bhandari, D., & Singh, D. S. (2012). Performance Analysis of Flat Plate Solar Air Collectors With and Without Fins. *International Journal of Engineering Research & Technology*, 1(6). <https://doi.org/10.17577/IJERTV1IS6129>
- Chabane, F., Moummi, N., Benramache, S., Bensahal, D., & Belahssen, O. (2013). Effect Of Artificial Roughness On Heat Transfer In A Solar Air Heater. *Journal of Science and Engineering*, 2. 85-93.
- Choudhury, C., Chauhan, P. M., & Garg, H. P. (1995). Performance and cost analysis of two-pass solar air heaters. *Heat Recovery Systems and CHP*, 15(8), 755–773. [https://doi.org/10.1016/0890-4332\(95\)00003-h](https://doi.org/10.1016/0890-4332(95)00003-h)
- Churchill, S. W., & Chu, H. H. S. (1975). Correlating equations for laminar and turbulent free convection from a vertical plate. *International Journal of Heat and Mass Transfer*, 18(11), 1323–1329. [https://doi.org/10.1016/0017-9310\(75\)90243-4](https://doi.org/10.1016/0017-9310(75)90243-4)

- Dissa, A. O., Ouoba, S., Bathiebo, D., & Koulidiati, J. (2016). A study of a solar air collector with a mixed “porous” and “non-porous” composite absorber. *Solar Energy*, 129, 156–174. <https://doi.org/10.1016/j.solener.2016.01.048>
- Duffie, J. A., & Beckman, W. A. (2013). *Solar Engineering of Thermal Processes*. John Wiley & Sons, Inc. <https://doi.org/10.1002/9781118671603>
- El-Sebaili, A. A., Aboul-Enein, S., Ramadan, M. R. I., Shalaby, S. M., & Moharram, B. M. (2011). Investigation of thermal performance of double pass-flat and v-corrugated plate solar air heaters. *Energy*, 36(2), 1076–1086. <https://doi.org/10.1016/j.energy.2010.11.042>
- Esen, H. (2008). Experimental energy and exergy analysis of a double-flow solar air heater having different obstacles on absorber plates. *Building and Environment*, 43(6), 1046–1054. <https://doi.org/10.1016/j.buildenv.2007.02.016>
- Forson, F. K., Nazha, M. A. A., & Rajakaruna, H. (2003). Experimental and simulation studies on a single pass, double duct solar air heater. *Energy Conversion and Management*, 44(8), 1209–1227. [https://doi.org/10.1016/s0196-8904\(02\)00139-5](https://doi.org/10.1016/s0196-8904(02)00139-5)
- Fudholi, A., Sopian, K., Othman, M. Y., Ruslan, M. H., & Bakhtyar, B. (2013). Energy analysis and improvement potential of finned double-pass solar collector. *Energy Conversion and Management*, 75, 234–240. <https://doi.org/10.1016/j.enconman.2013.06.021>
- Fudholi, A., Sopian, K., Ruslan, M. H., Othman, M. Y., & Yahya, M. (2011). Thermal efficiency of double pass solar collector with longitudinal fins absorbers. *American Journal of Applied Sciences*, 8, 254.
- Gao, W., Lin, W., Liu, T., & Xia, C. (2007). Analytical and experimental studies on the thermal performance of cross-corrugated and flat-plate solar air heaters. *Applied Energy*, 84(4), 425–441. <https://doi.org/10.1016/j.apenergy.2006.02.005>
- Gaur, G. (2010). An Experimental investigation of a novel design of double pass solar air heater. *International Journal of Chem. Tech Research*, 5(1036-1040).
- Ghritlahre, H. K., & Prasad, R. K. (2018). Application of ANN technique to predict the performance of solar collector systems - A review. *Renewable and Sustainable Energy Reviews*, 84, 75–88. <https://doi.org/10.1016/j.rser.2018.01.001>
- Gilani, S. E., Al-Kayiem, H. H., Woldemichael, D. E., & Gilani, S. I. (2017). Performance enhancement of free convective solar air heater by pin protrusions on the absorber. *Solar Energy*, 151, 173–185. <https://doi.org/10.1016/j.solener.2017.05.038>
- Gunjo, D. G., Mahanta, P., & Robi, P. S. (2017). CFD and experimental investigation of flat plate solar water heating system under steady state condition. *Renewable Energy*, 106, 24–36. <https://doi.org/10.1016/j.renene.2016.12.041>
- Gupta, B., Waiker, J. K., Manikpuri, G. P., & Bhalavi, B. S. (2013). Experimental analysis of single and double pass smooth plate solar air collector with and without porous media. *American Journal of Engineering Research*, 2(12), 144–149.
- Hameed, H., Azeez, H., & Saeed, M. M. A. (2021). Performance of A New Model of Air Heating System Experimental Investigation. *Journal of Mechanical Engineering Research and Developments*, 44(5), 420–432.
- Hans, V. S., Saini, R. P., & Saini, J. S. (2010). Heat transfer and friction factor correlations for a solar air heater duct roughened artificially with multiple v-ribs. *Solar Energy*, 84(6), 898–911. <https://doi.org/10.1016/j.solener.2010.02.004>
- Hedayatizadeh, M., Sarhaddi, F., Safavinejad, A., Ranjbar, F., & Chaji, H. (2016). Exergy loss-based efficiency optimization of a double-pass/glazed v-corrugated plate solar air heater. *Energy*, 94, 799–810. <https://doi.org/10.1016/j.energy.2015.11.046>

- HERMANN, W. (2006). Quantifying global exergy resources. *Energy*, 31(12), 1685–1702. <https://doi.org/10.1016/j.energy.2005.09.006>
- Hernández, A. L., & Quiñonez, J. E. (2013). Analytical models of thermal performance of solar air heaters of double-parallel flow and double-pass counter flow. *Renewable Energy*, 55, 380–391. <https://doi.org/10.1016/j.renene.2012.12.050>
- Ho, C. D., Yeh, H. M., Cheng, T. W., Chen, T. C., & Wang, R. C. (2009). The influences of recycle on performance of baffled double-pass flat-plate solar air heaters with internal fins attached. *Applied Energy*, 86(9), 1470–1478. <https://doi.org/10.1016/j.apenergy.2008.12.013>
- Holman, J. P. (1990). *Heat Transfer, 6th Edition*. McGraw-Hill, New York, USA. 7th edition
- Jayatilleke, C. L. V. (1966). The influence of Prandtl number and surface roughness on the resistance of the laminar sub-layer to momentum and heat transfer. *Spiral.imperial.ac.uk*. <http://hdl.handle.net/10044/1/17357>
- John, L. L., Gatski, T. B., Hussaini, M. Y., & Lumley, J. L. (1996). *Simulation and Modeling of Turbulent Flows*. Oxford University Press. <https://doi.org/10.1093/oso/9780195106435.001.0001>
- Kafafi, Z. H., Martín-Palma, R. J., Nogueira, A. F., O’Carroll, D. M., Pietron, J. J., Samuel, I. D. W., So, F., Tansu, N., & Tsakalakos, L. (2015). The role of photonics in energy. *Journal of Photonics for Energy*, 5(1), 050997. <https://doi.org/10.1117/1.jpe.5.050997>
- KARIM, M., & HAWLADER, M. (2006). Performance investigation of flat plate, v-corrugated and finned air collectors. *Energy*, 31(4), 452–470. <https://doi.org/10.1016/j.energy.2005.03.007>
- Kumar, A., Gantasala Sreenivaslu, P. Srinivasa Rao, Arun Kumar D.T, Vinod, & Ashutosh Pattanaik. (2019). Experimental Investigation on Performance of Solar Air Heaters With Thermal Storage. *International Journal of Renewable Energy and Its Commercialization*, 5(1), 37–46. <https://doi.org/10.37628/jrec.v5i1.770>
- Kumar, A., Prasad, B., & Singh, K. (2017). Thermal and thermo hydraulic performance of three sides artificially roughened solar air heaters. *International Research Journal of Advanced Engineering and Science*, 2(2). 215-231.
- Kumar, N., Tyagi, A., Yadav, T., Prakash, O., Singh, V., & Tiwari, S. (2019). Heat Transfer Analysis of Flat Plate Air Collector. *IOP Conference Series: Materials Science and Engineering*, 691(1), 012075. <https://doi.org/10.1088/1757-899x/691/1/012075>
- Kurtbaş, İ., & Turgut, E. (2006). Experimental Investigation of Solar Air Heater with Free and Fixed Fins: Efficiency and Exergy Loss. *Turgut Firat University, Mechanical Education Department*, 23279, Elazig, Turkey.
- Launder, B. E., & Spalding, D. B. (1974). The numerical computation of turbulent flows. *Computer Methods in Applied Mechanics and Engineering*, 3(2), 269–289. [https://doi.org/10.1016/0045-7825\(74\)90029-2](https://doi.org/10.1016/0045-7825(74)90029-2)
- Liu, T., Lin, W., Gao, W., & Xia, C. (2007). A Comparative Study of the Thermal Performances of Cross-Corrugated and V-Groove Solar Air Collectors. *International Journal of Green Energy*, 4(4), 427–451. <https://doi.org/10.1080/15435070701465847>
- Maraba, G. (2012). *An experimental study on enhancement of heat transfer in a solar air heater collector by using porous medium*. Gcris.iyte.edu.tr. <https://hdl.handle.net/11147/3544>
- Menter, F. R. (1994a). Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal*, 32(8), 1598–1605. <https://doi.org/10.2514/3.12149>

- Menter, F. R. (1994b). Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal*, 32(8), 1598–1605. <https://doi.org/10.2514/3.12149>
- Metwally, M. N., Abou-Ziyan, H. Z., & El-Leathy, A. M. (1997). Performance of advanced corrugated-duct solar air collector compared with five conventional designs. *Renewable Energy*, 10(4), 519–537. [https://doi.org/10.1016/s0960-1481\(96\)00043-2](https://doi.org/10.1016/s0960-1481(96)00043-2)
- Moin, P., & Mahesh, K. (1998). DIRECT NUMERICAL SIMULATION: A Tool in Turbulence Research. *Annual Review of Fluid Mechanics*, 30(1), 539–578. <https://doi.org/10.1146/annurev.fluid.30.1.539>
- Omojaro, A. P., & Aldabbagh, L. B. Y. (2010). Experimental performance of single and double pass solar air heater with fins and steel wire mesh as absorber. *Applied Energy*, 87(12), 3759–3765. <https://doi.org/10.1016/j.apenergy.2010.06.020>
- Ovando Chacon, G. E., Ovando Chacon, S. L., & Prince Avelino, J. C. (2010). Numerical modeling of fluid dynamics and heat transfer of glass flow in a short channel. *Brazilian Journal of Chemical Engineering*, 27(4), 663–675. <https://doi.org/10.1590/s0104-66322010000400018>
- Ozgen, F., Esen, M., & Esen, H. (2009). Experimental investigation of thermal performance of a double-flow solar air heater having aluminium cans. *Renewable Energy*, 34(11), 2391–2398. <https://doi.org/10.1016/j.renene.2009.03.029>
- Peng, D., Zhang, X., Dong, H., & Kun Lv. (2010). Performance study of a novel solar air collector. *Applied Thermal Engineering*, 30(16), 2594–2601. <https://doi.org/10.1016/j.applthermaleng.2010.07.010>
- Planchard, D. (2020). *SOLIDWORKS 2020 Tutorial A Step-by-Step Project Based Approach Utilizing 3D Solid Modeling*. <https://static.sdcpublishations.com/pdfs/sample/978-1-63057-317-1-1-s8pm4q5glv.pdf>
- Prasad, S. B., Saini, J. S., & Singh, K. M. (2009). Investigation of heat transfer and friction characteristics of packed bed solar air heater using wire mesh as packing material. *Solar Energy*, 83(5), 773–783. <https://doi.org/10.1016/j.solener.2008.11.011>
- Ramani, B. M., Gupta, A., & Kumar, R. (2010). Performance of a double pass solar air collector. *Solar Energy*, 84(11), 1929–1937. <https://doi.org/10.1016/j.solener.2010.07.007>
- Rasham, A. M., & Alaskari, M. (2018). Thermal Analysis of Double-Pass Solar Air Collector with Different Materials of Absorber Plate and Different Dimensions of Air Channels. *International Journal of Science and Research*, 6(8), 901–908.
- Sataloff, R., Johns, M., & Kost, K. (2007). *Heat and Mass Transfer 7th*.
- Sawicka, P. M. M. (n.d.). Optimization Of Solar Air Collector. *Supervisors Prof. Per Heiselberg Associate, Prof. Rasmus-Lund Jensen, Aalborg*.
- Smil, V. (2006). *Energy at the crossroads : Organisation for Economic Co-operation and Development* (Vol. 12). The Mit Press.
- Sopian, K., Supranto, Daud, W. R. W., Othman, M. Y., & Yatim, B. (1999). Thermal performance of the double-pass solar collector with and without porous media. *Renewable Energy*, 18(4), 557–564. [https://doi.org/10.1016/s0960-1481\(99\)00007-5](https://doi.org/10.1016/s0960-1481(99)00007-5)
- Sukhatme, S. S. P. (1999). *Solar Energy 4th Edit*. Tata McGraw Hill Publishing Company Limited ; New Delhi.
- Ucar, A., & Inallı, M. (2006). Thermal and exergy analysis of solar air collectors with passive augmentation techniques. *International Communications in Heat and Mass Transfer*, 33(10), 1281–1290.

- <https://doi.org/10.1016/j.icheatmasstransfer.2006.08.006>
- Velmurugan, P., & Kalaivanan, R. (2016). Energy and exergy analysis in double-pass solar air heater. *Sadhana (Indian Academy of Sciences)* , 41(3)(369–376).
- Wijesundera, N. E., Ah, L. L., & Tjioe, L. E. (1982). Thermal performance study of two-pass solar air heaters. *Solar Energy*, 28(5), 363–370. [https://doi.org/10.1016/0038-092x\(82\)90253-5](https://doi.org/10.1016/0038-092x(82)90253-5)
- Yeh, H.-M. ., Ho, C.-D. ., & Hou, J.-Z. . (2002). Collector efficiency of double-flow solar air heaters with fins attached. *Energy*, 27(8), 715–727. [https://doi.org/10.1016/s0360-5442\(02\)00010-5](https://doi.org/10.1016/s0360-5442(02)00010-5)
- Yousef, B. A. A., & Adam, N. M. (2008). Performance analysis for flat plate collector with and without porous media. *Journal of Energy in Southern Africa*, 19(4), 32–42. <https://doi.org/10.17159/2413-3051/2008/v19i4a3336>
- Zhou, Y. (2006). *Implications of turbulence interactions: A path toward addressing very high Reynolds number flows*. 1-6.



# Appendixes

## Appendix A

### Calibration of Thermocouples and Thermometer

| Device No.                    | Freezing point | Boiling point |
|-------------------------------|----------------|---------------|
| Thermocouples and Thermometer | 0.0 °C         | 100.0 °C      |
| Sensor No.1                   | 0.1            | 99.5          |
| Sensor No.2                   | 0.3            | 99            |
| Sensor No.3                   | 0              | 99.3          |
| Sensor No.4                   | 0.5            | 99.4          |
| Sensor No.5                   | 0.7            | 99.9          |
| Sensor No.6                   | 0.3            | 99.6          |
| Sensor No.7                   | 0.4            | 98.9          |
| Sensor No.8                   | 0.3            | 99.8          |
| Sensor No.9                   | 0.8            | 99.6          |
| Sensor No.10                  | 0.7            | 100.2         |
| Sensor No.11                  | 0.3            | 99            |
| Sensor No.12                  | 0.1            | 99.6          |
| Sensor No.13                  | 0.7            | 100.2         |
| Sensor No.14                  | 0.4            | 99.8          |
| Sensor No.15                  | 0.5            | 100.5         |
| Sensor No.16                  | 0.9            | 98.7          |
| Sensor No.17                  | 0.4            | 99.2          |
| Sensor No.18                  | 1              | 99.9          |
| Sensor No.19                  | 1.5            | 100.1         |
| Sensor No.20                  | 0.4            | 99.6          |
| Sensor No.21                  | 0              | 99.2          |
| Sensor No.22                  | 0.5            | 99.1          |
| Sensor No.23                  | 0.3            | 100.1         |
| Sensor No.24                  | 0.6            | 99.6          |

# Appendix B

## Experimental results

### Test No.1 - Flat plate 30-04-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>P</sub> | m'     | Qu    | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|-------|-------|-----|-----|
| 7:30  | 39.6                     | 25.7                    | 13.9       | 1.129 | 0.002 | 0.5        | 1007           | 0.0011 | 15.49 | 325   | 0.5 | 10% |
| 8:00  | 49.1                     | 28.5                    | 20.6       | 1.096 | 0.002 | 0.5        | 1007           | 0.0011 | 22.95 | 386   | 0.5 | 12% |
| 8:30  | 55.7                     | 28.7                    | 27         | 1.074 | 0.002 | 0.5        | 1008           | 0.0011 | 30.11 | 533   | 0.5 | 11% |
| 9:00  | 61.6                     | 29.3                    | 32.3       | 1.055 | 0.002 | 0.5        | 1008           | 0.0011 | 36.02 | 638   | 0.5 | 11% |
| 9:30  | 67.3                     | 30.3                    | 37         | 1.038 | 0.002 | 0.5        | 1008           | 0.0011 | 41.26 | 695   | 0.5 | 12% |
| 10:00 | 73.5                     | 31.1                    | 42.4       | 1.019 | 0.002 | 0.5        | 1009           | 0.0011 | 47.33 | 785   | 0.5 | 12% |
| 10:30 | 77.8                     | 32.3                    | 45.5       | 1.007 | 0.002 | 0.5        | 1010           | 0.0011 | 50.84 | 835.5 | 0.5 | 12% |
| 11:00 | 77.5                     | 32.1                    | 45.4       | 1.008 | 0.002 | 0.5        | 1009           | 0.0011 | 50.68 | 845   | 0.5 | 12% |
| 11:30 | 79.7                     | 32.3                    | 47.4       | 1.001 | 0.002 | 0.5        | 1009           | 0.0011 | 52.92 | 880   | 0.5 | 12% |
| 12:00 | 78.9                     | 32.5                    | 46.4       | 1.004 | 0.002 | 0.5        | 1009           | 0.0011 | 51.80 | 862   | 0.5 | 12% |
| 12:30 | 77.6                     | 32.8                    | 44.8       | 1.007 | 0.002 | 0.5        | 1009           | 0.0011 | 50.01 | 820   | 0.5 | 12% |
| 13:00 | 75.4                     | 33                      | 42.4       | 1.014 | 0.002 | 0.5        | 1009           | 0.0011 | 47.33 | 743   | 0.5 | 13% |
| 13:30 | 72                       | 33                      | 39         | 1.024 | 0.002 | 0.5        | 1009           | 0.0011 | 43.54 | 725   | 0.5 | 12% |
| 14:00 | 67.9                     | 32                      | 35.9       | 1.039 | 0.002 | 0.5        | 1008           | 0.0011 | 40.04 | 715   | 0.5 | 11% |
| 14:30 | 64.3                     | 32                      | 32.3       | 1.053 | 0.002 | 0.5        | 1008           | 0.0011 | 36.02 | 550   | 0.5 | 13% |
| 15:00 | 58.5                     | 32                      | 26.5       | 1.075 | 0.002 | 0.5        | 1008           | 0.0011 | 29.55 | 525   | 0.5 | 11% |
| 15:30 | 53.5                     | 32                      | 21.5       | 1.099 | 0.002 | 0.5        | 1007           | 0.0011 | 23.95 | 328   | 0.5 | 15% |
| 16:00 | 49.8                     | 32                      | 17.8       | 1.111 | 0.002 | 0.5        | 1007           | 0.0011 | 19.83 | 255   | 0.5 | 16% |
| 16:30 | 44.7                     | 32                      | 12.7       | 1.121 | 0.002 | 0.5        | 1007           | 0.0011 | 14.15 | 154.5 | 0.5 | 18% |
| 17:00 | 41.4                     | 32                      | 9.4        | 1.123 | 0.002 | 0.5        | 1007           | 0.0011 | 10.47 | 97    | 0.5 | 22% |

**Test No.1 - U -corrugated plate parallel to airflow 30-04-22**

| Time  | T <sub>out</sub><br>(°Co) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>P</sub> | m'     | Qu    | I     | Ac  | η   |
|-------|---------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|-------|-------|-----|-----|
| 7:30  | 40                        | 25.7                    | 14.3       | 1.127 | 0.002 | 0.5        | 1007           | 0.0011 | 16.20 | 282   | 0.5 | 11% |
| 8:00  | 51.1                      | 28.5                    | 22.6       | 1.089 | 0.002 | 0.5        | 1007           | 0.0011 | 25.60 | 352   | 0.5 | 15% |
| 8:30  | 57.4                      | 28.7                    | 28.7       | 1.069 | 0.002 | 0.5        | 1008           | 0.0011 | 32.55 | 478   | 0.5 | 14% |
| 9:00  | 62.9                      | 29.3                    | 33.6       | 1.051 | 0.002 | 0.5        | 1008           | 0.0011 | 38.10 | 615   | 0.5 | 12% |
| 9:30  | 69.5                      | 30.3                    | 39.2       | 1.031 | 0.002 | 0.5        | 1008           | 0.0011 | 44.45 | 705   | 0.5 | 13% |
| 10:00 | 75.4                      | 31.1                    | 44.3       | 1.014 | 0.002 | 0.5        | 1008           | 0.0011 | 50.24 | 775   | 0.5 | 13% |
| 10:30 | 78.1                      | 32.3                    | 45.8       | 1.003 | 0.002 | 0.5        | 1009           | 0.0011 | 51.99 | 815.3 | 0.5 | 13% |
| 11:00 | 78.2                      | 32.1                    | 46.1       | 1.003 | 0.002 | 0.5        | 1009           | 0.0011 | 52.33 | 850   | 0.5 | 12% |
| 11:30 | 79.5                      | 32.3                    | 47.2       | 0.999 | 0.002 | 0.5        | 1009           | 0.0011 | 53.58 | 885   | 0.5 | 12% |
| 12:00 | 80.7                      | 32.5                    | 48.2       | 0.999 | 0.002 | 0.5        | 1009           | 0.0011 | 54.71 | 895   | 0.5 | 12% |
| 12:30 | 78.9                      | 32.8                    | 46.1       | 1.004 | 0.002 | 0.5        | 1009           | 0.0011 | 52.33 | 855   | 0.5 | 12% |
| 13:00 | 78.6                      | 33                      | 45.6       | 1.05  | 0.002 | 0.5        | 1009           | 0.0011 | 51.76 | 773   | 0.5 | 13% |
| 13:30 | 78                        | 33                      | 45         | 1.006 | 0.002 | 0.5        | 1009           | 0.0011 | 51.08 | 730   | 0.5 | 14% |
| 14:00 | 71.5                      | 32                      | 39.5       | 1.022 | 0.002 | 0.5        | 1009           | 0.0011 | 44.84 | 680   | 0.5 | 13% |
| 14:30 | 68.1                      | 32                      | 36.1       | 1.032 | 0.002 | 0.5        | 1008           | 0.0011 | 40.94 | 560   | 0.5 | 15% |
| 15:00 | 63.6                      | 32                      | 31.6       | 1.046 | 0.002 | 0.5        | 1008           | 0.0011 | 35.83 | 485   | 0.5 | 15% |
| 15:30 | 56.2                      | 32                      | 24.2       | 1.069 | 0.002 | 0.5        | 1008           | 0.0011 | 27.44 | 356   | 0.5 | 15% |
| 16:00 | 52.8                      | 32                      | 20.8       | 1.087 | 0.002 | 0.5        | 1007           | 0.0011 | 23.56 | 263   | 0.5 | 18% |
| 16:30 | 46.2                      | 32                      | 14.2       | 1.102 | 0.002 | 0.5        | 1007           | 0.0011 | 16.09 | 170   | 0.5 | 19% |
| 17:00 | 42.1                      | 32                      | 10.1       | 1.117 | 0.002 | 0.5        | 1007           | 0.0011 | 11.44 | 102   | 0.5 | 22% |

**Test No.1 - U -corrugated plate anti-parallel to airflow 18-05-22**

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>P</sub> | m'     | Qu    | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|-------|-------|-----|-----|
| 7:30  | 35.9                     | 26.2                    | 9.7        | 1.142 | 0.002 | 0.5        | 1006           | 0.0011 | 10.73 | 150.3 | 0.5 | 14% |
| 8:00  | 45.4                     | 27.1                    | 18.3       | 1.109 | 0.002 | 0.5        | 1007           | 0.0011 | 20.27 | 278.5 | 0.5 | 15% |
| 8:30  | 61.0                     | 28.1                    | 32.9       | 1.057 | 0.002 | 0.5        | 1008           | 0.0011 | 36.48 | 429.1 | 0.5 | 17% |
| 9:00  | 70.5                     | 29.1                    | 41.4       | 1.028 | 0.002 | 0.5        | 1009           | 0.0011 | 45.95 | 549.6 | 0.5 | 17% |
| 9:30  | 74.0                     | 30.3                    | 43.7       | 1.018 | 0.002 | 0.5        | 1009           | 0.0011 | 48.50 | 635.2 | 0.5 | 15% |
| 10:00 | 76.3                     | 30.4                    | 45.9       | 1.011 | 0.002 | 0.5        | 1009           | 0.0011 | 50.94 | 724.3 | 0.5 | 14% |
| 10:30 | 81.6                     | 31.1                    | 50.5       | 0.99  | 0.002 | 0.5        | 1010           | 0.0011 | 56.11 | 761.3 | 0.5 | 15% |
| 11:00 | 83.3                     | 32.3                    | 51         | 0.986 | 0.002 | 0.5        | 1010           | 0.0011 | 56.66 | 820.6 | 0.5 | 14% |
| 11:30 | 82.0                     | 33.0                    | 49         | 1     | 0.002 | 0.5        | 1009           | 0.0011 | 54.39 | 838.2 | 0.5 | 13% |
| 12:00 | 80.9                     | 33.2                    | 47.7       | 1.002 | 0.002 | 0.5        | 1009           | 0.0011 | 52.94 | 842.1 | 0.5 | 13% |
| 12:30 | 80.1                     | 33.4                    | 46.7       | 1.002 | 0.002 | 0.5        | 1009           | 0.0011 | 51.83 | 845.4 | 0.5 | 12% |
| 13:00 | 79.7                     | 33.4                    | 46.3       | 1.004 | 0.002 | 0.5        | 1009           | 0.0011 | 51.39 | 760.6 | 0.5 | 14% |
| 13:30 | 78.7                     | 35.0                    | 43.7       | 1.003 | 0.002 | 0.5        | 1009           | 0.0011 | 48.50 | 710.4 | 0.5 | 14% |
| 14:00 | 76.8                     | 35.1                    | 41.7       | 1.01  | 0.002 | 0.5        | 1009           | 0.0011 | 46.28 | 671.4 | 0.5 | 14% |
| 14:30 | 75.4                     | 35.2                    | 40.2       | 0.988 | 0.002 | 0.5        | 1010           | 0.0011 | 44.66 | 630.4 | 0.5 | 14% |
| 15:00 | 73.5                     | 35.4                    | 38.1       | 1.019 | 0.002 | 0.5        | 1009           | 0.0011 | 42.29 | 573.2 | 0.5 | 15% |
| 15:30 | 72.8                     | 35.4                    | 37.4       | 1.021 | 0.002 | 0.5        | 1009           | 0.0011 | 41.51 | 484.4 | 0.5 | 17% |
| 16:00 | 70.8                     | 35.6                    | 35.2       | 1.027 | 0.002 | 0.5        | 1009           | 0.0011 | 39.07 | 375.8 | 0.5 | 21% |
| 16:30 | 64.0                     | 35.6                    | 28.4       | 1.048 | 0.002 | 0.5        | 1008           | 0.0011 | 31.49 | 276.2 | 0.5 | 23% |
| 17:00 | 53.4                     | 35.4                    | 18         | 1.082 | 0.002 | 0.5        | 1007           | 0.0011 | 19.94 | 152.2 | 0.5 | 26% |
| 17:30 | 47.4                     | 35.2                    | 12.2       | 1.112 | 0.002 | 0.5        | 1007           | 0.0011 | 13.51 | 75.8  | 1.5 | 12% |

### Test No.1 - Trapezoidal corrugated plate 27-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ    | Ad    | U<br>(m/s) | C <sub>P</sub> | m'     | Qu    | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|------|-------|------------|----------------|--------|-------|-------|-----|-----|
| 7:30  | 38.7                     | 25.2                    | 13.5       | 1.32 | 0.002 | 0.5        | 1006           | 0.0011 | 14.94 | 211.8 | 0.5 | 14% |
| 8:00  | 47.4                     | 26.1                    | 21.3       | 1.1  | 0.002 | 0.5        | 1007           | 0.0011 | 23.59 | 325.5 | 0.5 | 14% |
| 8:30  | 55.0                     | 27.1                    | 27.9       | 1.08 | 0.002 | 0.5        | 1007           | 0.0011 | 30.90 | 433.0 | 0.5 | 14% |
| 9:00  | 59.8                     | 29.3                    | 30.5       | 1.06 | 0.002 | 0.5        | 1008           | 0.0011 | 33.82 | 532.8 | 0.5 | 13% |
| 9:30  | 66.4                     | 30.3                    | 36.1       | 1.04 | 0.002 | 0.5        | 1008           | 0.0011 | 40.03 | 630.4 | 0.5 | 13% |
| 10:00 | 68.4                     | 30.4                    | 38         | 1.03 | 0.002 | 0.5        | 1008           | 0.0011 | 42.13 | 660.2 | 0.5 | 13% |
| 10:30 | 70.0                     | 31.1                    | 38.9       | 1.03 | 0.002 | 0.5        | 1009           | 0.0011 | 43.18 | 690.1 | 0.5 | 13% |
| 11:00 | 75.0                     | 32.2                    | 42.8       | 1.02 | 0.002 | 0.5        | 1009           | 0.0011 | 47.50 | 765.3 | 0.5 | 12% |
| 11:30 | 77.0                     | 32.3                    | 44.7       | 1.01 | 0.002 | 0.5        | 1009           | 0.0011 | 49.61 | 810.5 | 0.5 | 12% |
| 12:00 | 80.6                     | 32.1                    | 48.5       | 1    | 0.002 | 0.5        | 1009           | 0.0011 | 53.83 | 860.6 | 0.5 | 13% |
| 12:30 | 79.0                     | 33.4                    | 45.6       | 1    | 0.002 | 0.5        | 1009           | 0.0011 | 50.61 | 824.4 | 0.5 | 12% |
| 13:00 | 79.1                     | 33.7                    | 45.4       | 1    | 0.002 | 0.5        | 1009           | 0.0011 | 50.39 | 770.7 | 0.5 | 13% |
| 13:30 | 80.1                     | 33.7                    | 46.4       | 1    | 0.002 | 0.5        | 1009           | 0.0011 | 51.50 | 756.3 | 0.5 | 14% |
| 14:00 | 79.6                     | 34.1                    | 45.5       | 1    | 0.002 | 0.5        | 1009           | 0.0011 | 50.50 | 735.2 | 0.5 | 14% |
| 14:30 | 75.2                     | 34.1                    | 41.1       | 1.01 | 0.002 | 0.5        | 1009           | 0.0011 | 45.62 | 645.5 | 0.5 | 14% |
| 15:00 | 73.1                     | 34.5                    | 38.6       | 1.02 | 0.002 | 0.5        | 1009           | 0.0011 | 42.84 | 578.3 | 0.5 | 15% |
| 15:30 | 71.3                     | 34.3                    | 37         | 1.03 | 0.002 | 0.5        | 1009           | 0.0011 | 41.07 | 500.2 | 0.5 | 16% |
| 16:00 | 64.4                     | 34.4                    | 30         | 1.05 | 0.002 | 0.5        | 1008           | 0.0011 | 33.26 | 370.4 | 0.5 | 18% |
| 16:30 | 64.1                     | 33.6                    | 30.5       | 1.05 | 0.002 | 0.5        | 1008           | 0.0011 | 33.82 | 300.2 | 0.5 | 23% |
| 17:00 | 57.0                     | 32.3                    | 24.7       | 1.07 | 0.002 | 0.5        | 1008           | 0.0011 | 27.39 | 213.2 | 0.5 | 26% |
| 17:30 | 45.7                     | 32.3                    | 13.4       | 1.11 | 0.002 | 0.5        | 1007           | 0.0011 | 14.84 | 75.4  | 1.5 | 13% |

### Test No.2 - Flat plate 02-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>P</sub> | m'     | Qu    | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|-------|-------|-----|-----|
| 7:30  | 27.6                     | 22.1                    | 5.5        | 1.174 | 0.002 | 1          | 1006           | 0.0023 | 12.73 | 355   | 0.5 | 7%  |
| 8:00  | 45.7                     | 22.4                    | 23.3       | 1.107 | 0.002 | 1          | 1007           | 0.0023 | 53.97 | 481   | 0.5 | 22% |
| 8:30  | 50.2                     | 23.3                    | 26.9       | 1.092 | 0.002 | 1          | 1007           | 0.0023 | 62.30 | 582   | 0.5 | 21% |
| 9:00  | 61.77                    | 25.1                    | 36.67      | 1.055 | 0.002 | 1          | 1008           | 0.0023 | 85.02 | 717   | 0.5 | 24% |
| 9:30  | 63.1                     | 27                      | 36.1       | 1.051 | 0.002 | 1          | 1008           | 0.0023 | 83.69 | 747   | 0.5 | 22% |
| 10:00 | 63.1                     | 27                      | 36.1       | 1.051 | 0.002 | 1          | 1008           | 0.0023 | 83.69 | 823.8 | 0.5 | 20% |
| 10:30 | 63.5                     | 28                      | 35.5       | 1.049 | 0.002 | 1          | 1008           | 0.0023 | 82.30 | 859.2 | 0.5 | 19% |
| 11:00 | 69.1                     | 29                      | 40.1       | 1.032 | 0.002 | 1          | 1008           | 0.0023 | 92.97 | 866.4 | 0.5 | 21% |
| 11:30 | 71                       | 28                      | 43         | 1.026 | 0.002 | 1          | 1009           | 0.0023 | 99.79 | 870.9 | 0.5 | 23% |
| 12:00 | 70.6                     | 29                      | 41.6       | 1.028 | 0.002 | 1          | 1009           | 0.0023 | 96.54 | 841.8 | 0.5 | 23% |
| 12:30 | 71.2                     | 30.2                    | 41         | 1.026 | 0.002 | 1          | 1009           | 0.0023 | 95.15 | 822.4 | 0.5 | 23% |
| 13:00 | 70.9                     | 30.7                    | 40.2       | 1.027 | 0.002 | 1          | 1009           | 0.0023 | 93.29 | 795.8 | 0.5 | 23% |
| 13:30 | 68.5                     | 30.7                    | 37.8       | 1.034 | 0.002 | 1          | 1008           | 0.0023 | 87.64 | 693.2 | 0.5 | 25% |
| 14:00 | 65.8                     | 30.6                    | 35.2       | 1.042 | 0.002 | 1          | 1008           | 0.0023 | 81.61 | 641.8 | 0.5 | 25% |
| 14:30 | 59.2                     | 30.1                    | 29.1       | 1.063 | 0.002 | 1          | 1008           | 0.0023 | 67.47 | 531.2 | 0.5 | 25% |
| 15:00 | 55.6                     | 32.1                    | 23.5       | 1.074 | 0.002 | 1          | 1007           | 0.0023 | 54.43 | 489.2 | 0.5 | 22% |
| 15:30 | 50.9                     | 31.1                    | 19.8       | 1.09  | 0.002 | 1          | 1007           | 0.0023 | 45.86 | 337.8 | 0.5 | 27% |
| 16:00 | 47.2                     | 30.9                    | 16.3       | 1.102 | 0.002 | 1          | 1007           | 0.0023 | 37.75 | 250.7 | 0.5 | 30% |
| 16:30 | 42.8                     | 30.7                    | 12.1       | 1.118 | 0.002 | 1          | 1007           | 0.0023 | 28.02 | 190.2 | 0.5 | 29% |
| 17:00 | 39.6                     | 29.1                    | 10.5       | 1.129 | 0.002 | 1          | 1007           | 0.0023 | 24.32 | 166.8 | 0.5 | 29% |
| 17:30 | 35.5                     | 29                      | 6.5        | 1.144 | 0.002 | 1          | 1006           | 0.0023 | 15.04 | 45.8  | 0.5 | 66% |

**Test No.2 - U -corrugated plate parallel to airflow 02-05-22**

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>p</sub> | m'     | Qu    | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|-------|-------|-----|-----|
| 7:30  | 29.9                     | 22.1                    | 7.8        | 1.165 | 0.002 | 1          | 1006           | 0.0023 | 18.05 | 206   | 0.5 | 18% |
| 8:00  | 42.7                     | 22.4                    | 20.3       | 1.118 | 0.002 | 1          | 1007           | 0.0023 | 47.02 | 462   | 0.5 | 20% |
| 8:30  | 55.4                     | 23.3                    | 32.1       | 1.075 | 0.002 | 1          | 1007           | 0.0023 | 74.35 | 533.1 | 0.5 | 28% |
| 9:00  | 60.3                     | 25.1                    | 35.2       | 1.065 | 0.002 | 1          | 1008           | 0.0023 | 81.61 | 680.8 | 0.5 | 24% |
| 9:30  | 62.1                     | 27                      | 35.1       | 1.044 | 0.002 | 1          | 1008           | 0.0023 | 81.38 | 695   | 0.5 | 23% |
| 10:00 | 63.8                     | 27                      | 36.8       | 1.039 | 0.002 | 1          | 1008           | 0.0023 | 85.32 | 763   | 0.5 | 22% |
| 10:30 | 69.3                     | 28                      | 41.3       | 1.035 | 0.002 | 1          | 1008           | 0.0023 | 95.75 | 868.3 | 0.5 | 22% |
| 11:00 | 71.1                     | 29                      | 42.1       | 1.03  | 0.002 | 1          | 1008           | 0.0023 | 97.60 | 883.2 | 0.5 | 22% |
| 11:30 | 71.8                     | 30                      | 41.8       | 1.019 | 0.002 | 1          | 1009           | 0.0023 | 97.01 | 821.4 | 0.5 | 24% |
| 12:00 | 72.9                     | 31.5                    | 41.4       | 1.014 | 0.002 | 1          | 1009           | 0.0023 | 96.08 | 797.2 | 0.5 | 24% |
| 12:30 | 74.1                     | 33.5                    | 40.6       | 1.012 | 0.002 | 1          | 1009           | 0.0023 | 94.22 | 780.4 | 0.5 | 24% |
| 13:00 | 71.2                     | 31.7                    | 39.5       | 1.02  | 0.002 | 1          | 1009           | 0.0023 | 91.67 | 742.1 | 0.5 | 25% |
| 13:30 | 71.3                     | 32.5                    | 38.8       | 1.02  | 0.002 | 1          | 1009           | 0.0023 | 90.04 | 676.4 | 0.5 | 27% |
| 14:00 | 67.9                     | 30.6                    | 37.3       | 1.036 | 0.002 | 1          | 1008           | 0.0023 | 86.48 | 642.6 | 0.5 | 27% |
| 14:30 | 64.2                     | 30.1                    | 34.1       | 1.047 | 0.002 | 1          | 1008           | 0.0023 | 79.06 | 535.6 | 0.5 | 30% |
| 15:00 | 60.2                     | 32.1                    | 28.1       | 1.06  | 0.002 | 1          | 1008           | 0.0023 | 65.15 | 491.3 | 0.5 | 27% |
| 15:30 | 53.2                     | 31.1                    | 22.1       | 1.082 | 0.002 | 1          | 1007           | 0.0023 | 51.19 | 340.3 | 0.5 | 30% |
| 16:00 | 50.9                     | 30.9                    | 20         | 1.09  | 0.002 | 1          | 1007           | 0.0023 | 46.32 | 245.8 | 0.5 | 38% |
| 16:30 | 46.6                     | 30.7                    | 15.9       | 1.104 | 0.002 | 1          | 1007           | 0.0023 | 36.83 | 192.4 | 0.5 | 38% |
| 17:00 | 40.1                     | 29.1                    | 11         | 1.127 | 0.002 | 1          | 1007           | 0.0023 | 25.48 | 168.6 | 0.5 | 30% |
| 17:30 | 37.1                     | 29                      | 8.1        | 1.138 | 0.002 | 1          | 1007           | 0.0023 | 18.76 | 66.5  | 0.5 | 56% |

**Test No.2 - U -corrugated plate anti-parallel to airflow 19-05-22**

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>p</sub> | m'     | Qu     | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|--------|-------|-----|-----|
| 7:30  | 42.2                     | 29.1                    | 13.1       | 1.12  | 0.002 | 1          | 1007           | 0.0023 | 30.34  | 266.7 | 0.5 | 23% |
| 8:00  | 51.7                     | 30.3                    | 21.4       | 1.087 | 0.002 | 1          | 1007           | 0.0023 | 49.56  | 345.8 | 0.5 | 29% |
| 8:30  | 67.2                     | 31.7                    | 35.5       | 1.038 | 0.002 | 1          | 1008           | 0.0023 | 82.30  | 463.4 | 0.5 | 36% |
| 9:00  | 71.1                     | 32.1                    | 39         | 1.02  | 0.002 | 1          | 1009           | 0.0023 | 90.51  | 534.9 | 0.5 | 34% |
| 9:30  | 74.2                     | 32.5                    | 41.7       | 1.017 | 0.002 | 1          | 1009           | 0.0023 | 96.77  | 641.3 | 0.5 | 30% |
| 10:00 | 75.1                     | 33.3                    | 41.8       | 1.014 | 0.002 | 1          | 1009           | 0.0023 | 97.01  | 760.8 | 0.5 | 26% |
| 10:30 | 77.3                     | 34.0                    | 43.3       | 1.008 | 0.002 | 1          | 1009           | 0.0023 | 100.49 | 832.3 | 0.5 | 24% |
| 11:00 | 80.1                     | 35.2                    | 44.9       | 1     | 0.002 | 1          | 1009           | 0.0023 | 104.20 | 823.5 | 0.5 | 25% |
| 11:30 | 81.3                     | 36.5                    | 44.8       | 0.997 | 0.002 | 1          | 1010           | 0.0023 | 104.07 | 844.3 | 0.5 | 25% |
| 12:00 | 83.0                     | 37.5                    | 45.5       | 0.992 | 0.002 | 1          | 1010           | 0.0023 | 105.70 | 806.5 | 0.5 | 26% |
| 12:30 | 82.3                     | 37.6                    | 44.7       | 0.99  | 0.002 | 1          | 1010           | 0.0023 | 103.84 | 780.1 | 0.5 | 27% |
| 13:00 | 83.7                     | 38.0                    | 45.7       | 0.985 | 0.002 | 1          | 1010           | 0.0023 | 106.16 | 745.8 | 0.5 | 28% |
| 13:30 | 81.2                     | 38.3                    | 42.9       | 0.997 | 0.002 | 1          | 1010           | 0.0023 | 99.66  | 738.9 | 0.5 | 27% |
| 14:00 | 78.1                     | 39.0                    | 39.1       | 1.006 | 0.002 | 1          | 1009           | 0.0023 | 90.74  | 692.8 | 0.5 | 26% |
| 14:30 | 75.4                     | 39.0                    | 36.4       | 1.014 | 0.002 | 1          | 1009           | 0.0023 | 84.47  | 598.5 | 0.5 | 28% |
| 15:00 | 74.9                     | 39.2                    | 35.7       | 1.015 | 0.002 | 1          | 1009           | 0.0023 | 82.85  | 519.2 | 0.5 | 32% |
| 15:30 | 69.1                     | 39.3                    | 29.8       | 1.032 | 0.002 | 1          | 1008           | 0.0023 | 69.09  | 453.4 | 0.5 | 30% |
| 16:00 | 66.9                     | 39.3                    | 27.6       | 1.039 | 0.002 | 1          | 1008           | 0.0023 | 63.99  | 325.8 | 0.5 | 39% |
| 16:30 | 59.2                     | 39.5                    | 19.7       | 1.063 | 0.002 | 1          | 1008           | 0.0023 | 45.67  | 246.8 | 0.5 | 37% |
| 17:00 | 54.1                     | 39.1                    | 15         | 1.079 | 0.002 | 1          | 1007           | 0.0023 | 34.74  | 132.7 | 0.5 | 52% |
| 17:30 | 47.3                     | 38.4                    | 8.9        | 1.102 | 0.002 | 1          | 1007           | 0.0023 | 20.61  | 80.3  | 0.5 | 51% |

### Test No.2 - Trapezoidal corrugated plate 28-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>p</sub> | m'     | Q <sub>u</sub> | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|----------------|-------|-----|-----|
| 7:30  | 42.5                     | 29.5                    | 13         | 1.119 | 0.002 | 1          | 1007           | 0.0023 | 30.11          | 235.3 | 0.5 | 26% |
| 8:00  | 50.1                     | 30.1                    | 20         | 1.093 | 0.002 | 1          | 1007           | 0.0023 | 46.32          | 329.7 | 0.5 | 28% |
| 8:30  | 58.2                     | 32.0                    | 26.2       | 1.063 | 0.002 | 1          | 1008           | 0.0023 | 60.74          | 416.8 | 0.5 | 29% |
| 9:00  | 61.7                     | 32.3                    | 29.4       | 1.055 | 0.002 | 1          | 1008           | 0.0023 | 68.16          | 518.3 | 0.5 | 26% |
| 9:30  | 70.3                     | 35.0                    | 35.3       | 1.029 | 0.002 | 1          | 1009           | 0.0023 | 81.92          | 626.5 | 0.5 | 26% |
| 10:00 | 73.0                     | 35.7                    | 37.3       | 1.021 | 0.002 | 1          | 1009           | 0.0023 | 86.56          | 703.1 | 0.5 | 25% |
| 10:30 | 75.7                     | 37.2                    | 38.5       | 1.1   | 0.002 | 1          | 1009           | 0.0023 | 89.35          | 782.3 | 0.5 | 23% |
| 11:00 | 79.0                     | 37.3                    | 41.7       | 0.999 | 0.002 | 1          | 1009           | 0.0023 | 96.77          | 818.2 | 0.5 | 24% |
| 11:30 | 82.2                     | 38.6                    | 43.6       | 0.994 | 0.002 | 1          | 1010           | 0.0023 | 101.28         | 838.4 | 0.5 | 24% |
| 12:00 | 82.5                     | 38.4                    | 44.1       | 0.993 | 0.002 | 1          | 1010           | 0.0023 | 102.44         | 851.7 | 0.5 | 24% |
| 12:30 | 81.5                     | 38.7                    | 42.8       | 0.996 | 0.002 | 1          | 1010           | 0.0023 | 99.42          | 826.6 | 0.5 | 24% |
| 13:00 | 80.6                     | 38.3                    | 42.3       | 0.999 | 0.002 | 1          | 1009           | 0.0023 | 98.17          | 785.3 | 0.5 | 25% |
| 13:30 | 80.6                     | 38.6                    | 42         | 0.999 | 0.002 | 1          | 1009           | 0.0023 | 97.47          | 735.4 | 0.5 | 27% |
| 14:00 | 80.0                     | 39.0                    | 41         | 0.999 | 0.002 | 1          | 1009           | 0.0023 | 95.15          | 700.3 | 0.5 | 27% |
| 14:30 | 78.3                     | 39.2                    | 39.1       | 1.005 | 0.002 | 1          | 1009           | 0.0023 | 90.74          | 644.8 | 0.5 | 28% |
| 15:00 | 74.9                     | 39.2                    | 35.7       | 1.015 | 0.002 | 1          | 1009           | 0.0023 | 82.85          | 545.8 | 0.5 | 30% |
| 15:30 | 73.7                     | 39.4                    | 34.3       | 1.019 | 0.002 | 1          | 1009           | 0.0023 | 79.60          | 505.9 | 0.5 | 31% |
| 16:00 | 69.0                     | 39.5                    | 29.5       | 1.032 | 0.002 | 1          | 1009           | 0.0023 | 68.46          | 400.2 | 0.5 | 34% |
| 16:30 | 63.7                     | 39.7                    | 24         | 1.049 | 0.002 | 1          | 1008           | 0.0023 | 55.64          | 303.4 | 0.5 | 37% |
| 17:00 | 54.5                     | 39.1                    | 15.4       | 1.078 | 0.002 | 1          | 1008           | 0.0023 | 35.70          | 188.5 | 0.5 | 38% |
| 17:30 | 45.0                     | 39.0                    | 6          | 1.11  | 0.002 | 1          | 1007           | 0.0023 | 13.90          | 76.5  | 0.5 | 36% |

### Test No.3 - Flat plate 03-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>p</sub> | m'     | Q <sub>u</sub> | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|----------------|-------|-----|-----|
| 7:30  | 29.4                     | 27.5                    | 1.9        | 1.167 | 0.002 | 1.5        | 1006           | 0.0034 | 6.57           | 130.8 | 0.5 | 10% |
| 8:00  | 35.2                     | 28.7                    | 6.5        | 1.145 | 0.002 | 1.5        | 1006           | 0.0034 | 22.47          | 267.1 | 0.5 | 17% |
| 8:30  | 49.4                     | 30.3                    | 19.1       | 1.095 | 0.002 | 1.5        | 1007           | 0.0034 | 66.11          | 414.2 | 0.5 | 32% |
| 9:00  | 57.1                     | 31.2                    | 25.9       | 1.069 | 0.002 | 1.5        | 1008           | 0.0034 | 89.73          | 488.8 | 0.5 | 37% |
| 9:30  | 61.1                     | 32.7                    | 28.4       | 1.057 | 0.002 | 1.5        | 1008           | 0.0034 | 98.39          | 561.5 | 0.5 | 35% |
| 10:00 | 67.2                     | 33.4                    | 33.8       | 1.038 | 0.002 | 1.5        | 1008           | 0.0034 | 117.10         | 658.9 | 0.5 | 36% |
| 10:30 | 69.2                     | 33.8                    | 35.4       | 1.032 | 0.002 | 1.5        | 1008           | 0.0034 | 122.64         | 749   | 0.5 | 33% |
| 11:00 | 70                       | 33.1                    | 36.9       | 1.029 | 0.002 | 1.5        | 1009           | 0.0034 | 127.97         | 819   | 0.5 | 31% |
| 11:30 | 76.8                     | 35.1                    | 41.7       | 1.01  | 0.002 | 1.5        | 1009           | 0.0034 | 144.61         | 883.7 | 0.5 | 33% |
| 12:00 | 76.3                     | 36.5                    | 39.8       | 1.011 | 0.002 | 1.5        | 1009           | 0.0034 | 138.02         | 846.6 | 0.5 | 33% |
| 12:30 | 74.6                     | 36.5                    | 38.1       | 1.016 | 0.002 | 1.5        | 1009           | 0.0034 | 132.13         | 818.3 | 0.5 | 32% |
| 13:00 | 71.7                     | 36.8                    | 34.9       | 1.024 | 0.002 | 1.5        | 1009           | 0.0034 | 121.03         | 752.4 | 0.5 | 32% |
| 13:30 | 69.6                     | 36.7                    | 32.9       | 1.031 | 0.002 | 1.5        | 1008           | 0.0034 | 113.98         | 696   | 0.5 | 33% |
| 14:00 | 69.7                     | 37.2                    | 32.5       | 1.03  | 0.002 | 1.5        | 1008           | 0.0034 | 112.60         | 631.4 | 0.5 | 36% |
| 14:30 | 66                       | 37.3                    | 28.7       | 1.032 | 0.002 | 1.5        | 1008           | 0.0034 | 99.43          | 551.4 | 0.5 | 36% |
| 15:00 | 62.2                     | 37.5                    | 24.7       | 1.04  | 0.002 | 1.5        | 1008           | 0.0034 | 85.57          | 455.9 | 0.5 | 38% |
| 15:30 | 57.7                     | 37.5                    | 20.2       | 1.068 | 0.002 | 1.5        | 1008           | 0.0034 | 69.98          | 365.9 | 0.5 | 38% |
| 16:00 | 54.6                     | 37.7                    | 16.9       | 1.078 | 0.002 | 1.5        | 1007           | 0.0034 | 58.49          | 279.2 | 0.5 | 42% |
| 16:30 | 50.7                     | 37.9                    | 12.8       | 1.082 | 0.002 | 1.5        | 1007           | 0.0034 | 44.30          | 167.1 | 0.5 | 53% |
| 17:00 | 47.1                     | 37.4                    | 9.7        | 1.103 | 0.002 | 1.5        | 1007           | 0.0034 | 33.57          | 92.4  | 0.5 | 73% |
| 17:30 | 41.8                     | 37.2                    | 4.6        | 1.121 | 0.002 | 1.5        | 1007           | 0.0034 | 15.92          | 45.3  | 0.5 | 70% |

### Test No.3 - U -corrugatedplate parallel to airflow 03-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|----------------|-------|-----|-----|
| 7:30  | 34.8                     | 27.5                    | 7.3        | 1.146 | 0.002 | 1.5        | 1006           | 0.0034 | 25.24          | 281.9 | 0.5 | 18% |
| 8:00  | 46.6                     | 28.7                    | 17.9       | 1.104 | 0.002 | 1.5        | 1007           | 0.0034 | 61.95          | 324.9 | 0.5 | 38% |
| 8:30  | 58.8                     | 30.3                    | 28.5       | 1.064 | 0.002 | 1.5        | 1008           | 0.0034 | 98.74          | 469.3 | 0.5 | 42% |
| 9:00  | 60.1                     | 31.2                    | 28.9       | 1.06  | 0.002 | 1.5        | 1008           | 0.0034 | 100.12         | 535   | 0.5 | 37% |
| 9:30  | 65.7                     | 32.7                    | 33         | 1.042 | 0.002 | 1.5        | 1008           | 0.0034 | 114.33         | 611.3 | 0.5 | 37% |
| 10:00 | 69.5                     | 33.4                    | 36.1       | 1.028 | 0.002 | 1.5        | 1009           | 0.0034 | 125.19         | 659   | 0.5 | 38% |
| 10:30 | 73.5                     | 33.8                    | 39.7       | 1.013 | 0.002 | 1.5        | 1009           | 0.0034 | 137.68         | 770   | 0.5 | 36% |
| 11:00 | 74.6                     | 33.1                    | 41.5       | 1.007 | 0.002 | 1.5        | 1009           | 0.0034 | 143.92         | 828.8 | 0.5 | 35% |
| 11:30 | 77.8                     | 35.1                    | 42.7       | 0.998 | 0.002 | 1.5        | 1009           | 0.0034 | 148.08         | 883.5 | 0.5 | 34% |
| 12:00 | 79.7                     | 36.5                    | 43.2       | 0.997 | 0.002 | 1.5        | 1009           | 0.0034 | 149.81         | 885.3 | 0.5 | 34% |
| 12:30 | 79.5                     | 36.5                    | 43         | 1.002 | 0.002 | 1.5        | 1009           | 0.0034 | 149.12         | 874.7 | 0.5 | 34% |
| 13:00 | 76                       | 36.8                    | 39.2       | 1.009 | 0.002 | 1.5        | 1009           | 0.0034 | 135.94         | 776.3 | 0.5 | 35% |
| 13:30 | 75.8                     | 36.7                    | 39.1       | 1.01  | 0.002 | 1.5        | 1009           | 0.0034 | 135.60         | 725.4 | 0.5 | 37% |
| 14:00 | 72.5                     | 37.2                    | 35.3       | 1.013 | 0.002 | 1.5        | 1009           | 0.0034 | 122.42         | 587.1 | 0.5 | 42% |
| 14:30 | 71.1                     | 37.3                    | 33.8       | 1.016 | 0.002 | 1.5        | 1009           | 0.0034 | 117.22         | 555.6 | 0.5 | 42% |
| 15:00 | 64.8                     | 37.5                    | 27.3       | 1.021 | 0.002 | 1.5        | 1009           | 0.0034 | 94.67          | 388.8 | 0.5 | 49% |
| 15:30 | 59.7                     | 37.5                    | 22.2       | 1.049 | 0.002 | 1.5        | 1008           | 0.0034 | 76.91          | 370.2 | 0.5 | 42% |
| 16:00 | 56.7                     | 37.7                    | 19         | 1.066 | 0.002 | 1.5        | 1008           | 0.0034 | 65.83          | 270.2 | 0.5 | 49% |
| 16:30 | 53.1                     | 37.9                    | 15.2       | 1.083 | 0.002 | 1.5        | 1007           | 0.0034 | 52.61          | 195.2 | 0.5 | 54% |
| 17:00 | 50.5                     | 37.4                    | 13.1       | 1.091 | 0.002 | 1.5        | 1007           | 0.0034 | 45.34          | 153.4 | 0.5 | 59% |
| 17:30 | 41.1                     | 37.2                    | 3.9        | 1.124 | 0.002 | 1.5        | 1007           | 0.0034 | 13.50          | 37.7  | 0.5 | 72% |

### Test No.3 - U -corrugatedplate anti-parallel to airflow 20-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad-   | U<br>(m/s) | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|----------------|-------|-----|-----|
| 7:30  | 44.9                     | 28.0                    | 16.9       | 1.11  | 0.002 | 1.5        | 1007           | 0.0034 | 58.49          | 260.8 | 0.5 | 45% |
| 8:00  | 51.2                     | 29.2                    | 22         | 1.089 | 0.002 | 1.5        | 1007           | 0.0034 | 76.14          | 309.1 | 0.5 | 49% |
| 8:30  | 59.2                     | 29.4                    | 29.8       | 1.063 | 0.002 | 1.5        | 1008           | 0.0034 | 103.24         | 403.8 | 0.5 | 51% |
| 9:00  | 61.8                     | 30.1                    | 31.7       | 1.055 | 0.002 | 1.5        | 1008           | 0.0034 | 109.82         | 480.7 | 0.5 | 46% |
| 9:30  | 68.7                     | 30.7                    | 38         | 1.033 | 0.002 | 1.5        | 1008           | 0.0034 | 131.65         | 594.4 | 0.5 | 44% |
| 10:00 | 73.2                     | 32.0                    | 41.2       | 1.02  | 0.002 | 1.5        | 1009           | 0.0034 | 142.88         | 648.1 | 0.5 | 44% |
| 10:30 | 75.6                     | 32.8                    | 42.8       | 1.013 | 0.002 | 1.5        | 1009           | 0.0034 | 148.43         | 728.4 | 0.5 | 41% |
| 11:00 | 76.8                     | 33.2                    | 43.6       | 1.018 | 0.002 | 1.5        | 1009           | 0.0034 | 151.20         | 778.4 | 0.5 | 39% |
| 11:30 | 77.9                     | 33.4                    | 44.5       | 1.006 | 0.002 | 1.5        | 1009           | 0.0034 | 154.32         | 616.4 | 0.5 | 50% |
| 12:00 | 77.8                     | 33.5                    | 44.3       | 1.006 | 0.002 | 1.5        | 1009           | 0.0034 | 153.63         | 720.1 | 0.5 | 43% |
| 12:30 | 77.3                     | 33.4                    | 43.9       | 1.008 | 0.002 | 1.5        | 1009           | 0.0034 | 152.24         | 800.3 | 0.5 | 38% |
| 13:00 | 77.0                     | 33.6                    | 43.4       | 1.01  | 0.002 | 1.5        | 1009           | 0.0034 | 150.51         | 820.7 | 0.5 | 37% |
| 13:30 | 74.5                     | 33.8                    | 40.7       | 1.032 | 0.002 | 1.5        | 1008           | 0.0034 | 141.00         | 638.7 | 0.5 | 44% |
| 14:00 | 72.0                     | 34.3                    | 37.7       | 1.026 | 0.002 | 1.5        | 1009           | 0.0034 | 130.74         | 795.4 | 0.5 | 33% |
| 14:30 | 68.6                     | 35.3                    | 33.3       | 1.037 | 0.002 | 1.5        | 1008           | 0.0034 | 115.37         | 438.5 | 0.5 | 53% |
| 15:00 | 66.4                     | 35.3                    | 31.1       | 1.046 | 0.002 | 1.5        | 1008           | 0.0034 | 107.75         | 567.1 | 0.5 | 38% |
| 15:30 | 64.3                     | 35.5                    | 28.8       | 1.05  | 0.002 | 1.5        | 1008           | 0.0034 | 99.78          | 430.3 | 0.5 | 46% |
| 16:00 | 58.8                     | 35.5                    | 23.3       | 1.064 | 0.002 | 1.5        | 1008           | 0.0034 | 80.72          | 287.6 | 0.5 | 56% |
| 16:30 | 50.9                     | 35.5                    | 15.4       | 1.09  | 0.002 | 1.5        | 1007           | 0.0034 | 53.30          | 150.1 | 0.5 | 71% |
| 17:00 | 47.3                     | 36.6                    | 10.7       | 1.102 | 0.002 | 1.5        | 1007           | 0.0034 | 37.03          | 101.1 | 0.5 | 73% |
| 17:30 | 42.3                     | 36.0                    | 6.3        | 1.102 | 0.002 | 1.5        | 1007           | 0.0034 | 21.80          | 50.1  | 0.5 | 87% |

### Test No.3 - Trapezoidal corrugated plate 30-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|----------------|-------|-----|-----|
| 7:30  | 42.3                     | 30.3                    | 12         | 1.119 | 0.002 | 1.5        | 1007           | 0.0034 | 41.53          | 225.8 | 0.5 | 37% |
| 8:00  | 49.6                     | 33.1                    | 16.5       | 1.094 | 0.002 | 1.5        | 1007           | 0.0034 | 57.11          | 322.8 | 0.5 | 35% |
| 8:30  | 56.5                     | 34.2                    | 22.3       | 1.071 | 0.002 | 1.5        | 1008           | 0.0034 | 77.26          | 424.1 | 0.5 | 36% |
| 9:00  | 63.3                     | 34.3                    | 29         | 1.05  | 0.002 | 1.5        | 1008           | 0.0034 | 100.47         | 490.2 | 0.5 | 41% |
| 9:30  | 69.4                     | 36.3                    | 33.1       | 1.031 | 0.002 | 1.5        | 1008           | 0.0034 | 114.67         | 585.3 | 0.5 | 39% |
| 10:00 | 74.0                     | 38.0                    | 36         | 1.015 | 0.002 | 1.5        | 1009           | 0.0034 | 124.85         | 657.4 | 0.5 | 38% |
| 10:30 | 76.0                     | 38.0                    | 38         | 1.012 | 0.002 | 1.5        | 1009           | 0.0034 | 131.78         | 744.2 | 0.5 | 35% |
| 11:00 | 77.6                     | 38.0                    | 39.6       | 1.007 | 0.002 | 1.5        | 1009           | 0.0034 | 137.33         | 789.4 | 0.5 | 35% |
| 11:30 | 79.1                     | 38.0                    | 41.1       | 1.003 | 0.002 | 1.5        | 1009           | 0.0034 | 142.53         | 829.6 | 0.5 | 34% |
| 12:00 | 81.5                     | 38.0                    | 43.5       | 0.992 | 0.002 | 1.5        | 1010           | 0.0034 | 151.00         | 773.2 | 0.5 | 39% |
| 12:30 | 80.0                     | 38.0                    | 42         | 0.996 | 0.002 | 1.5        | 1010           | 0.0034 | 145.80         | 805.4 | 0.5 | 36% |
| 13:00 | 78.0                     | 38.0                    | 40         | 1.006 | 0.002 | 1.5        | 1009           | 0.0034 | 138.72         | 787.2 | 0.5 | 35% |
| 13:30 | 77.8                     | 38.0                    | 39.8       | 1.007 | 0.002 | 1.5        | 1009           | 0.0034 | 138.02         | 747.6 | 0.5 | 37% |
| 14:00 | 76.1                     | 38.0                    | 38.1       | 1.012 | 0.002 | 1.5        | 1009           | 0.0034 | 132.13         | 684.1 | 0.5 | 39% |
| 14:30 | 73.9                     | 38.0                    | 35.9       | 1.018 | 0.002 | 1.5        | 1009           | 0.0034 | 124.50         | 625.9 | 0.5 | 40% |
| 15:00 | 71.9                     | 38.0                    | 33.9       | 1.024 | 0.002 | 1.5        | 1009           | 0.0034 | 117.56         | 526.4 | 0.5 | 45% |
| 15:30 | 68.5                     | 38.0                    | 30.5       | 1.034 | 0.002 | 1.5        | 1008           | 0.0034 | 105.67         | 400.8 | 0.5 | 53% |
| 16:00 | 64.5                     | 38.0                    | 26.5       | 1.046 | 0.002 | 1.5        | 1008           | 0.0034 | 91.81          | 328.8 | 0.5 | 56% |
| 16:30 | 57.7                     | 38.0                    | 19.7       | 1.068 | 0.002 | 1.5        | 1008           | 0.0034 | 68.25          | 200.4 | 0.5 | 68% |
| 17:00 | 54.1                     | 38.0                    | 16.1       | 1.079 | 0.002 | 1.5        | 1008           | 0.0034 | 55.78          | 125.5 | 0.5 | 89% |
| 17:30 | 49.3                     | 38.0                    | 11.3       | 1.095 | 0.002 | 1.5        | 1007           | 0.0034 | 39.11          | 80.3  | 0.5 | 97% |

### Test No.4 - Flat plate 06-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|----------------|-------|-----|-----|
| 7:30  | 30.1                     | 22.3                    | 7.8        | 1.164 | 0.002 | 2          | 1006           | 0.0046 | 36.10          | 229.8 | 0.5 | 31% |
| 8:00  | 34.6                     | 22.5                    | 12.1       | 1.147 | 0.002 | 2          | 1006           | 0.0046 | 55.99          | 308.9 | 0.5 | 36% |
| 8:30  | 38.9                     | 24.7                    | 14.2       | 1.131 | 0.002 | 2          | 1006           | 0.0046 | 65.71          | 342.3 | 0.5 | 38% |
| 9:00  | 39.1                     | 24.6                    | 14.5       | 1.131 | 0.002 | 2          | 1006           | 0.0046 | 67.10          | 346.2 | 0.5 | 39% |
| 9:30  | 40.9                     | 24.3                    | 16.6       | 1.124 | 0.002 | 2          | 1007           | 0.0046 | 76.89          | 384.5 | 0.5 | 40% |
| 10:00 | 48.4                     | 24.8                    | 23.6       | 1.098 | 0.002 | 2          | 1007           | 0.0046 | 109.32         | 636.7 | 0.5 | 34% |
| 10:30 | 55.2                     | 25.5                    | 29.7       | 1.076 | 0.002 | 2          | 1007           | 0.0046 | 137.58         | 788.2 | 0.5 | 35% |
| 11:00 | 59.9                     | 26.9                    | 33         | 1.061 | 0.002 | 2          | 1008           | 0.0046 | 153.01         | 761.4 | 0.5 | 40% |
| 11:30 | 61.2                     | 27.1                    | 34.1       | 1.044 | 0.002 | 2          | 1008           | 0.0046 | 158.11         | 790.3 | 0.5 | 40% |
| 12:00 | 62.9                     | 29.2                    | 33.7       | 1.061 | 0.002 | 2          | 1008           | 0.0046 | 156.26         | 875.7 | 0.5 | 36% |
| 12:30 | 63.8                     | 29.4                    | 34.4       | 1.048 | 0.002 | 2          | 1008           | 0.0046 | 159.51         | 884.3 | 0.5 | 36% |
| 13:00 | 62                       | 29.7                    | 32.3       | 1.057 | 0.002 | 2          | 1008           | 0.0046 | 149.77         | 860.6 | 0.5 | 35% |
| 13:30 | 60.5                     | 29.7                    | 30.8       | 1.049 | 0.002 | 2          | 1008           | 0.0046 | 142.81         | 700.3 | 0.5 | 41% |
| 14:00 | 60.3                     | 29.8                    | 30.5       | 1.053 | 0.002 | 2          | 1008           | 0.0046 | 141.42         | 625.5 | 0.5 | 45% |
| 14:30 | 55.5                     | 29.6                    | 25.9       | 1.068 | 0.002 | 2          | 1008           | 0.0046 | 120.09         | 502.3 | 0.5 | 48% |
| 15:00 | 52.5                     | 30.1                    | 22.4       | 1.085 | 0.002 | 2          | 1007           | 0.0046 | 103.76         | 432.4 | 0.5 | 48% |
| 15:30 | 50.6                     | 30.4                    | 20.2       | 1.084 | 0.002 | 2          | 1007           | 0.0046 | 93.57          | 332.5 | 0.5 | 56% |
| 16:00 | 46.4                     | 30.8                    | 15.6       | 1.105 | 0.002 | 2          | 1007           | 0.0046 | 72.26          | 325.3 | 0.5 | 44% |
| 16:30 | 41.7                     | 29.5                    | 12.2       | 1.121 | 0.002 | 2          | 1007           | 0.0046 | 56.51          | 226.8 | 0.5 | 50% |
| 17:00 | 38                       | 29.3                    | 8.7        | 1.135 | 0.002 | 2          | 1006           | 0.0046 | 40.26          | 132.1 | 0.5 | 61% |
| 17:30 | 35.2                     | 29.3                    | 5.9        | 1.145 | 0.002 | 2          | 1006           | 0.0046 | 27.30          | 84.5  | 0.5 | 65% |

#### Test No.4 - U -corrugatedplate parallel to airflow 06-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>p</sub> | m'     | Q <sub>u</sub> | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|----------------|-------|-----|-----|
| 7:30  | 34.6                     | 22.3                    | 12.3       | 1.147 | 0.002 | 2          | 1006           | 0.0046 | 56.92          | 268.2 | 0.5 | 42% |
| 8:00  | 40                       | 22.5                    | 17.5       | 1.127 | 0.002 | 2          | 1007           | 0.0046 | 81.06          | 324.1 | 0.5 | 50% |
| 8:30  | 42.1                     | 24.7                    | 17.4       | 1.12  | 0.002 | 2          | 1007           | 0.0046 | 80.60          | 354.8 | 0.5 | 45% |
| 9:00  | 42.5                     | 24.6                    | 17.9       | 1.119 | 0.002 | 2          | 1007           | 0.0046 | 82.92          | 354.6 | 0.5 | 47% |
| 9:30  | 44.8                     | 24.3                    | 20.5       | 1.111 | 0.002 | 2          | 1007           | 0.0046 | 94.96          | 384.4 | 0.5 | 49% |
| 10:00 | 53.2                     | 24.8                    | 28.4       | 1.082 | 0.002 | 2          | 1007           | 0.0046 | 131.55         | 645.7 | 0.5 | 41% |
| 10:30 | 60.2                     | 25.5                    | 34.7       | 1.06  | 0.002 | 2          | 1008           | 0.0046 | 160.90         | 788.7 | 0.5 | 41% |
| 11:00 | 64                       | 26.9                    | 37.1       | 1.048 | 0.002 | 2          | 1008           | 0.0046 | 172.03         | 758.9 | 0.5 | 45% |
| 11:30 | 63.7                     | 27.1                    | 36.6       | 1.049 | 0.002 | 2          | 1008           | 0.0046 | 169.71         | 858.9 | 0.5 | 40% |
| 12:00 | 64.5                     | 29.2                    | 35.3       | 1.046 | 0.002 | 2          | 1008           | 0.0046 | 163.68         | 866.2 | 0.5 | 38% |
| 12:30 | 66.2                     | 29.4                    | 36.8       | 1.041 | 0.002 | 2          | 1008           | 0.0046 | 170.63         | 877.8 | 0.5 | 39% |
| 13:00 | 65.7                     | 29.7                    | 36         | 1.042 | 0.002 | 2          | 1008           | 0.0046 | 166.92         | 823.5 | 0.5 | 41% |
| 13:30 | 67.2                     | 29.7                    | 37.5       | 1.038 | 0.002 | 2          | 1008           | 0.0046 | 173.88         | 736.7 | 0.5 | 47% |
| 14:00 | 62.9                     | 29.8                    | 33.1       | 1.051 | 0.002 | 2          | 1008           | 0.0046 | 153.48         | 640.3 | 0.5 | 48% |
| 14:30 | 63.2                     | 29.6                    | 33.6       | 1.05  | 0.002 | 2          | 1008           | 0.0046 | 155.80         | 524.6 | 0.5 | 59% |
| 15:00 | 56.3                     | 30.1                    | 26.2       | 1.072 | 0.002 | 2          | 1008           | 0.0046 | 121.48         | 423.6 | 0.5 | 57% |
| 15:30 | 51.1                     | 30.4                    | 20.7       | 1.073 | 0.002 | 2          | 1008           | 0.0046 | 95.98          | 317.1 | 0.5 | 61% |
| 16:00 | 49.5                     | 30.8                    | 18.7       | 1.088 | 0.002 | 2          | 1007           | 0.0046 | 86.62          | 280.4 | 0.5 | 62% |
| 16:30 | 45.4                     | 29.5                    | 15.9       | 1.109 | 0.002 | 2          | 1007           | 0.0046 | 73.65          | 205.3 | 0.5 | 72% |
| 17:00 | 38.8                     | 29.3                    | 9.5        | 1.132 | 0.002 | 2          | 1006           | 0.0046 | 43.96          | 118.7 | 0.5 | 74% |
| 17:30 | 35.8                     | 29.3                    | 6.5        | 1.143 | 0.002 | 2          | 1006           | 0.0046 | 30.08          | 75.1  | 0.5 | 80% |

#### Test No.4 - U -corrugatedplate anti-parallel to airflow 24-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>p</sub> | m'     | Q <sub>u</sub> | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|----------------|-------|-----|-----|
| 7:30  | 38.5                     | 23.5                    | 15         | 1.133 | 0.002 | 2          | 1006           | 0.0046 | 69.41          | 259.7 | 0.5 | 53% |
| 8:00  | 44.7                     | 24.2                    | 20.5       | 1.111 | 0.002 | 2          | 1007           | 0.0046 | 94.96          | 337.2 | 0.5 | 56% |
| 8:30  | 48.3                     | 25.1                    | 23.2       | 1.099 | 0.002 | 2          | 1007           | 0.0046 | 107.47         | 462.9 | 0.5 | 46% |
| 9:00  | 57.5                     | 26.7                    | 30.8       | 1.068 | 0.002 | 2          | 1007           | 0.0046 | 142.67         | 538.3 | 0.5 | 53% |
| 9:30  | 63.2                     | 26.9                    | 36.3       | 1.05  | 0.002 | 2          | 1008           | 0.0046 | 168.32         | 615.3 | 0.5 | 55% |
| 10:00 | 65.8                     | 27.1                    | 38.7       | 1.042 | 0.002 | 2          | 1008           | 0.0046 | 179.44         | 715.2 | 0.5 | 50% |
| 10:30 | 67.7                     | 28.6                    | 39.1       | 1.036 | 0.002 | 2          | 1008           | 0.0046 | 181.30         | 760.8 | 0.5 | 48% |
| 11:00 | 69.5                     | 29.8                    | 39.7       | 1.031 | 0.002 | 2          | 1008           | 0.0046 | 184.08         | 778   | 0.5 | 47% |
| 11:30 | 71.1                     | 31.4                    | 39.7       | 1.026 | 0.002 | 2          | 1009           | 0.0046 | 184.26         | 825.3 | 0.5 | 45% |
| 12:00 | 75.1                     | 32.9                    | 42.2       | 1.013 | 0.002 | 2          | 1009           | 0.0046 | 195.87         | 820.6 | 0.5 | 48% |
| 12:30 | 76.2                     | 34.1                    | 42.1       | 1.011 | 0.002 | 2          | 1009           | 0.0046 | 195.40         | 804.7 | 0.5 | 49% |
| 13:00 | 77.1                     | 34.2                    | 42.9       | 1.009 | 0.002 | 2          | 1009           | 0.0046 | 199.12         | 805.9 | 0.5 | 49% |
| 13:30 | 75.7                     | 35.2                    | 40.5       | 1.013 | 0.002 | 2          | 1009           | 0.0046 | 187.98         | 740   | 0.5 | 51% |
| 14:00 | 72.5                     | 35.4                    | 37.1       | 1.022 | 0.002 | 2          | 1008           | 0.0046 | 172.03         | 651.3 | 0.5 | 53% |
| 14:30 | 70.8                     | 35.4                    | 35.4       | 1.024 | 0.002 | 2          | 1008           | 0.0046 | 164.14         | 601.5 | 0.5 | 55% |
| 15:00 | 68.0                     | 35.6                    | 32.4       | 1.035 | 0.002 | 2          | 1008           | 0.0046 | 150.23         | 510.1 | 0.5 | 59% |
| 15:30 | 63.7                     | 35.7                    | 28         | 1.046 | 0.002 | 2          | 1008           | 0.0046 | 129.83         | 405.1 | 0.5 | 64% |
| 16:00 | 57.4                     | 36.2                    | 21.2       | 1.069 | 0.002 | 2          | 1007           | 0.0046 | 98.20          | 321.9 | 0.5 | 61% |
| 16:30 | 50.9                     | 36.5                    | 14.4       | 1.09  | 0.002 | 2          | 1007           | 0.0046 | 66.70          | 228.8 | 0.5 | 58% |
| 17:00 | 47.1                     | 36.3                    | 10.8       | 1.103 | 0.002 | 2          | 1007           | 0.0046 | 50.03          | 140   | 0.5 | 71% |
| 17:30 | 43.2                     | 35.6                    | 7.6        | 1.116 | 0.002 | 2          | 1007           | 0.0046 | 35.20          | 74.3  | 0.5 | 95% |

### Test No.4 - Trapezoidal corrugated plate 31-05-22

| Time  | T <sub>out</sub><br>(°C) | T <sub>in</sub><br>(°C) | ΔT<br>(°C) | ρ     | Ad    | U<br>(m/s) | C <sub>p</sub> | m'     | Q <sub>u</sub> | I     | Ac  | η   |
|-------|--------------------------|-------------------------|------------|-------|-------|------------|----------------|--------|----------------|-------|-----|-----|
| 7:30  | 45.4                     | 30.1                    | 15.3       | 1.109 | 0.002 | 2          | 1007           | 0.0046 | 70.87          | 291.6 | 0.5 | 49% |
| 8:00  | 50.6                     | 32.3                    | 18.3       | 1.091 | 0.002 | 2          | 1007           | 0.0046 | 84.77          | 392.3 | 0.5 | 43% |
| 8:30  | 57.9                     | 33.2                    | 24.7       | 1.067 | 0.002 | 2          | 1008           | 0.0046 | 114.53         | 487.2 | 0.5 | 47% |
| 9:00  | 63.0                     | 35.2                    | 27.8       | 1.042 | 0.002 | 2          | 1008           | 0.0046 | 128.90         | 538.7 | 0.5 | 48% |
| 9:30  | 68.4                     | 36.3                    | 32.1       | 1.039 | 0.002 | 2          | 1008           | 0.0046 | 148.84         | 718.4 | 0.5 | 41% |
| 10:00 | 69.3                     | 36.5                    | 32.8       | 1.032 | 0.002 | 2          | 1008           | 0.0046 | 152.09         | 740.5 | 0.5 | 41% |
| 10:30 | 72.8                     | 38.0                    | 34.8       | 1.021 | 0.002 | 2          | 1009           | 0.0046 | 161.52         | 822.3 | 0.5 | 39% |
| 11:00 | 77.0                     | 38.1                    | 38.9       | 1.009 | 0.002 | 2          | 1009           | 0.0046 | 180.55         | 842.8 | 0.5 | 43% |
| 11:30 | 78.1                     | 38.2                    | 39.9       | 1.006 | 0.002 | 2          | 1009           | 0.0046 | 185.19         | 858.9 | 0.5 | 43% |
| 12:00 | 79.2                     | 38.4                    | 40.8       | 1.003 | 0.002 | 2          | 1009           | 0.0046 | 189.37         | 856.7 | 0.5 | 44% |
| 12:30 | 80.2                     | 38.8                    | 41.4       | 1     | 0.002 | 2          | 1010           | 0.0046 | 192.34         | 820.4 | 0.5 | 47% |
| 13:00 | 80.0                     | 39.0                    | 41         | 0.995 | 0.002 | 2          | 1010           | 0.0046 | 190.49         | 761.9 | 0.5 | 50% |
| 13:30 | 76.5                     | 38.6                    | 37.9       | 1.01  | 0.002 | 2          | 1009           | 0.0046 | 175.91         | 695.4 | 0.5 | 51% |
| 14:00 | 74.6                     | 38.6                    | 36         | 1.016 | 0.002 | 2          | 1009           | 0.0046 | 167.09         | 676.9 | 0.5 | 49% |
| 14:30 | 72.4                     | 38.6                    | 33.8       | 1.022 | 0.002 | 2          | 1009           | 0.0046 | 156.88         | 571.1 | 0.5 | 55% |
| 15:00 | 70.3                     | 39.0                    | 31.3       | 1.029 | 0.002 | 2          | 1009           | 0.0046 | 145.28         | 516.3 | 0.5 | 56% |
| 15:30 | 66.2                     | 39.0                    | 27.2       | 1.041 | 0.002 | 2          | 1008           | 0.0046 | 126.12         | 374.4 | 0.5 | 67% |
| 16:00 | 62.1                     | 39.0                    | 23.1       | 1.054 | 0.002 | 2          | 1008           | 0.0046 | 107.11         | 274.8 | 0.5 | 78% |
| 16:30 | 56.8                     | 39.2                    | 17.6       | 1.07  | 0.002 | 2          | 1008           | 0.0046 | 81.61          | 192.3 | 0.5 | 85% |
| 17:00 | 52.7                     | 39.4                    | 13.3       | 1.084 | 0.002 | 2          | 1008           | 0.0046 | 61.67          | 140.3 | 0.5 | 88% |
| 17:30 | 45.7                     | 39.3                    | 6.4        | 1.107 | 0.002 | 2          | 1007           | 0.0046 | 29.65          | 76.9  | 0.5 | 77% |

# Experimental tests

## Test No.1 - Flat plate 30-04-22 ( $U = 0.5 \text{ m/s} \pm 0.1$ )

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 25.7                    | 35.7                   | 39.6                     | 49.2                   | 50.1                   | 48.3                   | 50.2                   | 47.9                   | 35.6                   | 41.6                   | 39.6                    | 45.9                    | 44.8                    | 325                      | 49.14                   |
| 8:00  | 28.5                    | 37.6                   | 49.1                     | 59.2                   | 57.7                   | 57.3                   | 60                     | 56.5                   | 41.2                   | 48.7                   | 46.2                    | 53.6                    | 51.5                    | 386                      | 58.14                   |
| 8:30  | 28.7                    | 43                     | 55.7                     | 71.7                   | 70.5                   | 69.6                   | 71.2                   | 69.2                   | 50.7                   | 60                     | 56.9                    | 65.2                    | 62.5                    | 505                      | 70.44                   |
| 9:00  | 29.3                    | 45.2                   | 61.6                     | 77.5                   | 76.1                   | 74.5                   | 78.4                   | 74.8                   | 54.8                   | 63.4                   | 61.2                    | 70                      | 68                      | 600                      | 76.26                   |
| 9:30  | 30.3                    | 50.9                   | 67.3                     | 85                     | 85.6                   | 84.3                   | 84.3                   | 84.4                   | 61.3                   | 70.5                   | 67.3                    | 76.3                    | 74.6                    | 675                      | 84.72                   |
| 10:00 | 31.1                    | 49.6                   | 73.5                     | 88                     | 92.6                   | 90.3                   | 89.2                   | 90.5                   | 66.5                   | 76.5                   | 71.8                    | 80.9                    | 79.3                    | 744                      | 90.12                   |
| 10:30 | 32.3                    | 62.1                   | 77.8                     | 95.6                   | 100                    | 99.3                   | 97.9                   | 98.3                   | 73.3                   | 82.5                   | 78.1                    | 89.4                    | 86.2                    | 778.5                    | 98.24                   |
| 11:00 | 32.1                    | 65.1                   | 77.5                     | 95.7                   | 101                    | 97.5                   | 103                    | 96.1                   | 74.2                   | 81.7                   | 70.7                    | 91                      | 86.5                    | 817                      | 98.76                   |
| 11:30 | 32.3                    | 68.4                   | 79.7                     | 97.2                   | 100                    | 98.9                   | 97                     | 98                     | 73.3                   | 80.8                   | 74.9                    | 92.3                    | 88.8                    | 809                      | 98.26                   |
| 12:00 | 32.5                    | 66.4                   | 78.9                     | 96                     | 98.4                   | 97.9                   | 94.7                   | 95.3                   | 72.6                   | 79.1                   | 73.7                    | 91.2                    | 89                      | 798                      | 96.46                   |
| 12:30 | 32.8                    | 63.3                   | 77.6                     | 89.1                   | 94.3                   | 94.8                   | 89.4                   | 91.8                   | 71.9                   | 76.3                   | 70.8                    | 87.1                    | 85.2                    | 725                      | 91.88                   |
| 13:00 | 33                      | 66.5                   | 75.4                     | 89.1                   | 92.3                   | 92.8                   | 89.4                   | 89.3                   | 69.1                   | 74.3                   | 70.6                    | 87                      | 82.2                    | 660                      | 90.58                   |
| 13:30 | 33                      | 67.6                   | 72                       | 86.7                   | 89.2                   | 90                     | 86.2                   | 85.9                   | 67.9                   | 73.8                   | 71.9                    | 85.3                    | 78.6                    | 619                      | 87.6                    |
| 14:00 | 32                      | 61.3                   | 67.9                     | 79.2                   | 81.5                   | 82.9                   | 77.8                   | 77.3                   | 62.4                   | 68.6                   | 69.3                    | 76                      | 69.3                    | 586                      | 79.74                   |
| 14:30 | 32                      | 55.7                   | 64.3                     | 73.1                   | 72.8                   | 75.7                   | 67.7                   | 67.2                   | 57.4                   | 63.5                   | 56                      | 66.6                    | 64.1                    | 434                      | 71.3                    |
| 15:00 | 32                      | 52.5                   | 58.5                     | 64.9                   | 62                     | 66.3                   | 59.8                   | 57.2                   | 48                     | 53.7                   | 49.9                    | 56.2                    | 55.2                    | 365                      | 62.04                   |
| 15:30 | 32                      | 47.2                   | 53.5                     | 56.8                   | 56.4                   | 58.7                   | 55.7                   | 53.2                   | 42.7                   | 48.1                   | 46                      | 50.3                    | 50.7                    | 169                      | 56.16                   |
| 16:00 | 32                      | 44.3                   | 49.8                     | 53.4                   | 53                     | 54.7                   | 53                     | 51.5                   | 40.3                   | 44.7                   | 43.7                    | 45.3                    | 45.2                    | 130                      | 53.12                   |
| 16:30 | 32                      | 41.3                   | 44.7                     | 44.7                   | 47.6                   | 47.4                   | 46.3                   | 44.7                   | 37.9                   | 41.7                   | 41                      | 42.4                    | 41.5                    | 89                       | 46.14                   |
| 17:00 | 32                      | 39.5                   | 41.4                     | 40.6                   | 41.2                   | 42.2                   | 40.9                   | 39.7                   | 36.1                   | 39.9                   | 38.7                    | 39.6                    | 39.7                    | 67                       | 40.92                   |

- 1- T<sub>in</sub>- Inlet Air Temperature
- 2- T<sub>out</sub>- Outlet Air Temperature
- 3- T<sub>1</sub>- Air temperature in the midpoint of the entrance section
- 4- T<sub>3</sub>- First point absorber plate temperature
- 5- T<sub>4</sub>- Absorber plate temperature in the midpoint
- 6- T<sub>5</sub>- Second point absorber plate temperature
- 7- T<sub>6</sub>- Third point absorber plate temperature
- 8- T<sub>7</sub>-Fourth point absorber plate temperature
- 9- T<sub>8</sub>- Glass temperature from inside
- 10- T<sub>9</sub>- Air temperature in the midpoint of solar collector between glass and absorber plate
- 11- T<sub>10</sub>- Air temperature at the endpoint of the solar collector
- 12- T<sub>11</sub> -Air temperature in the midpoint of solar collector between absorber plate and bottom plate.
- 13- T<sub>12</sub>-Temperature of the Bottom plate in the midpoint
- 14- T<sub>ap</sub>- Absorber plate temperature.

**Test No.1 - U -corrugatedplate parallel to airflow 30-04-22 (U = 0.5 m/s  $\pm$  0.1)**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 25.7                    | 34.2                   | 40                       | 42.5                   | 42.6                   | 40.3                   | 42.7                   | 41.9                   | 32                     | 36.1                   | 34.1                    | 37.4                    | 38.1                    | 282                      | 42                      |
| 8:00  | 28.5                    | 37.8                   | 51.1                     | 51.8                   | 54.2                   | 53.2                   | 54.7                   | 54.2                   | 39.6                   | 44.3                   | 41.1                    | 44.9                    | 46.2                    | 352                      | 53.62                   |
| 8:30  | 28.7                    | 44.4                   | 57.4                     | 67.6                   | 66.9                   | 65.9                   | 68.5                   | 67.3                   | 49.8                   | 53.8                   | 51.5                    | 58.8                    | 61.2                    | 478                      | 67.24                   |
| 9:00  | 29.3                    | 45.7                   | 62.9                     | 75.9                   | 74.6                   | 73.3                   | 76.5                   | 74.3                   | 54.8                   | 60.6                   | 53.8                    | 65.9                    | 67.5                    | 578                      | 74.92                   |
| 9:30  | 30.3                    | 49.8                   | 69.5                     | 78.7                   | 81.3                   | 79.9                   | 80.1                   | 64.9                   | 60.3                   | 61.7                   | 59                      | 67.6                    | 71.6                    | 653                      | 76.98                   |
| 10:00 | 31.1                    | 48.8                   | 75.4                     | 73.6                   | 82.1                   | 80                     | 80.1                   | 64.4                   | 58.4                   | 59.7                   | 57.6                    | 66.5                    | 70.7                    | 727                      | 76.04                   |
| 10:30 | 32.3                    | 61.3                   | 78.1                     | 93.8                   | 99.4                   | 99                     | 98.7                   | 82.7                   | 70.8                   | 77.4                   | 70.1                    | 80.8                    | 82.8                    | 774.5                    | 94.72                   |
| 11:00 | 32.1                    | 64.5                   | 78.2                     | 96.7                   | 99.1                   | 96.3                   | 95.8                   | 80.9                   | 68.7                   | 73.9                   | 68.1                    | 92.3                    | 88.8                    | 796                      | 93.76                   |
| 11:30 | 32.3                    | 65.6                   | 79.5                     | 96.2                   | 98.3                   | 94.2                   | 94.5                   | 83.1                   | 73.5                   | 77.2                   | 71.4                    | 83.6                    | 87.7                    | 820                      | 93.26                   |
| 12:00 | 32.5                    | 65.1                   | 80.7                     | 93.2                   | 95                     | 94                     | 93.5                   | 80                     | 74.1                   | 76.8                   | 70                      | 82.4                    | 87.9                    | 827                      | 91.14                   |
| 12:30 | 32.8                    | 66.7                   | 78.9                     | 92.5                   | 94.3                   | 93.1                   | 92.3                   | 78.2                   | 74.6                   | 75.9                   | 70.6                    | 84.3                    | 88.4                    | 753                      | 90.08                   |
| 13:00 | 33                      | 65.1                   | 78.6                     | 92.8                   | 93.2                   | 91.8                   | 90.2                   | 80.5                   | 70.8                   | 76.5                   | 71.2                    | 83.6                    | 86.1                    | 697                      | 89.7                    |
| 13:30 | 33                      | 67.5                   | 78                       | 91.7                   | 92.1                   | 90.4                   | 88                     | 80.3                   | 69.3                   | 78.5                   | 71.8                    | 83.5                    | 87.2                    | 682                      | 88.5                    |
| 14:00 | 32                      | 60.3                   | 71.5                     | 87.3                   | 89.3                   | 86.2                   | 82.6                   | 75.6                   | 68.2                   | 73.8                   | 68.2                    | 77.7                    | 84                      | 573                      | 84.2                    |
| 14:30 | 32                      | 57.5                   | 68.1                     | 81                     | 81.6                   | 78.8                   | 78.2                   | 73.2                   | 65.5                   | 71                     | 65.7                    | 74.7                    | 81.6                    | 472                      | 78.56                   |
| 15:00 | 32                      | 58                     | 63.6                     | 75.4                   | 74.3                   | 73.2                   | 72.6                   | 68                     | 60.9                   | 67.1                   | 62.3                    | 69.3                    | 75.8                    | 394                      | 72.7                    |
| 15:30 | 32                      | 48.6                   | 56.2                     | 65.5                   | 65.8                   | 64.1                   | 62.8                   | 60                     | 54.5                   | 58.2                   | 56.4                    | 61.6                    | 68.3                    | 289                      | 63.64                   |
| 16:00 | 32                      | 45.9                   | 52.8                     | 59.4                   | 60.4                   | 58.7                   | 55.6                   | 55.8                   | 49.8                   | 53.9                   | 52.1                    | 61.9                    | 56.8                    | 225                      | 57.97                   |
| 16:30 | 32                      | 43.5                   | 46.2                     | 51.3                   | 52.7                   | 51.2                   | 50.3                   | 49.9                   | 44.3                   | 47.6                   | 45.3                    | 52.2                    | 48.4                    | 134                      | 51.08                   |
| 17:00 | 32                      | 41.8                   | 42.1                     | 45.9                   | 47.1                   | 48.1                   | 45.1                   | 44                     | 39.5                   | 41.8                   | 41.2                    | 42.8                    | 44.7                    | 92                       | 46.04                   |

**Test No.1 - U -corrugatedplate anti-parallel to airflow 18-05-22 (U = 0.5 m/s  $\pm$  0.1)**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 26.2                    | 35.6                   | 35.9                     | 39.6                   | 39.0                   | 36.7                   | 39.0                   | 38.1                   | 31.2                   | 35.5                   | 35.8                    | 34.0                    | 33.9                    | 202.3                    | 38.48                   |
| 8:00  | 27.1                    | 39.5                   | 45.4                     | 51.9                   | 53.2                   | 49.9                   | 52.1                   | 50.5                   | 39.1                   | 44.9                   | 44.9                    | 44.3                    | 46.0                    | 298.5                    | 51.52                   |
| 8:30  | 28.1                    | 45.9                   | 61.0                     | 70.7                   | 69.9                   | 68.5                   | 64.6                   | 69.2                   | 54.5                   | 59.1                   | 59.6                    | 61.7                    | 57.8                    | 429.1                    | 68.58                   |
| 9:00  | 29.1                    | 49.6                   | 70.5                     | 80.5                   | 80.0                   | 76.5                   | 74.3                   | 82.1                   | 62.0                   | 64.9                   | 70.9                    | 71.9                    | 66.0                    | 549.6                    | 78.68                   |
| 9:30  | 30.3                    | 57.3                   | 74.0                     | 90.4                   | 90.9                   | 88.1                   | 82.9                   | 92.5                   | 70.4                   | 73.9                   | 84.7                    | 80.7                    | 78.1                    | 635.2                    | 88.96                   |
| 10:00 | 30.4                    | 57.1                   | 76.3                     | 88.9                   | 100.1                  | 96.4                   | 86.9                   | 98.8                   | 76.5                   | 80.8                   | 83.0                    | 85.0                    | 85.7                    | 724.3                    | 94.22                   |
| 10:30 | 31.1                    | 63.9                   | 81.6                     | 100.9                  | 103.5                  | 102.8                  | 91.0                   | 104.1                  | 80.0                   | 85.3                   | 87.1                    | 88.8                    | 85.0                    | 791.3                    | 100.5                   |
| 11:00 | 32.3                    | 70.7                   | 83.3                     | 95.2                   | 96.6                   | 97.9                   | 94.5                   | 97.2                   | 72.0                   | 76.5                   | 75.9                    | 80.7                    | 88.1                    | 837.6                    | 96.28                   |
| 11:30 | 33.0                    | 67.2                   | 82.0                     | 97.2                   | 99.3                   | 100.0                  | 94.0                   | 98.0                   | 72.7                   | 76.5                   | 69.2                    | 75.2                    | 89.9                    | 863.2                    | 97.7                    |
| 12:00 | 33.2                    | 65.7                   | 80.9                     | 98.5                   | 100.2                  | 100.8                  | 91.5                   | 100.0                  | 73.3                   | 77.7                   | 77.1                    | 80.3                    | 90.0                    | 884.1                    | 98.2                    |
| 12:30 | 33.4                    | 67.6                   | 80.1                     | 98.8                   | 100.8                  | 100.9                  | 92.1                   | 100.4                  | 74.4                   | 78.5                   | 76.5                    | 82.6                    | 88.8                    | 899.4                    | 98.6                    |
| 13:00 | 33.4                    | 63.4                   | 79.7                     | 98.1                   | 99.8                   | 100.1                  | 88.2                   | 99.5                   | 73.7                   | 80.3                   | 75.9                    | 81.7                    | 89.0                    | 859.6                    | 97.14                   |
| 13:30 | 35.0                    | 66.5                   | 78.7                     | 96.1                   | 98.4                   | 99.1                   | 90.1                   | 97.4                   | 73.1                   | 77.9                   | 75.4                    | 79.7                    | 88.2                    | 836.4                    | 96.22                   |
| 14:00 | 35.1                    | 66.0                   | 76.8                     | 94.4                   | 96.9                   | 96.5                   | 84.6                   | 96.1                   | 73.1                   | 79.7                   | 72.7                    | 78.8                    | 85.8                    | 780.4                    | 93.7                    |
| 14:30 | 35.2                    | 57.8                   | 75.4                     | 89.7                   | 91.6                   | 92.5                   | 84.4                   | 90.7                   | 70.1                   | 74.6                   | 72.9                    | 75.0                    | 84.7                    | 706.4                    | 89.78                   |
| 15:00 | 35.4                    | 63.5                   | 73.5                     | 85.9                   | 87.8                   | 88.9                   | 78.4                   | 87.9                   | 69.8                   | 77.5                   | 71.9                    | 75.9                    | 82.3                    | 633.2                    | 85.78                   |
| 15:30 | 35.4                    | 60.9                   | 72.8                     | 82.8                   | 84.0                   | 84.0                   | 79.2                   | 83.7                   | 65.8                   | 70.1                   | 66.6                    | 73.0                    | 79.7                    | 532.4                    | 82.74                   |
| 16:00 | 35.6                    | 56.7                   | 70.8                     | 78.8                   | 79.7                   | 79.4                   | 74.9                   | 79.6                   | 64.4                   | 69.3                   | 64.7                    | 70.2                    | 77.2                    | 434.8                    | 78.48                   |
| 16:30 | 35.6                    | 52.1                   | 64.0                     | 71.0                   | 72.2                   | 73.3                   | 65.6                   | 70.5                   | 57.8                   | 62.1                   | 59.8                    | 63.2                    | 69.5                    | 305.2                    | 70.52                   |
| 17:00 | 35.4                    | 45.7                   | 53.4                     | 60.4                   | 60.8                   | 60.5                   | 58.6                   | 60.3                   | 50.9                   | 54.9                   | 55.3                    | 54.8                    | 59.5                    | 218.2                    | 60.12                   |
| 17:30 | 35.2                    | 42.9                   | 47.4                     | 46.1                   | 46.3                   | 45.9                   | 46.8                   | 46.9                   | 40.7                   | 42.9                   | 42.0                    | 43.3                    | 44.9                    | 75.8                     | 46.4                    |

### Test No.1 - Trapezoidal corrugated plate 27-05-22 ( $U = 0.5 \text{ m/s} \pm 0.1$ )

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 25.2                    | 39.8                   | 38.7                     | 43.4                   | 42.3                   | 40.6                   | 41.4                   | 45.0                   | 34.1                   | 38.7                   | 39.3                    | 38.5                    | 38.4                    | 253.8                    | 42.54                   |
| 8:00  | 26.1                    | 39.3                   | 47.4                     | 51.9                   | 53.7                   | 52.8                   | 55.8                   | 56.4                   | 42.8                   | 50.7                   | 51.5                    | 47.8                    | 51.8                    | 372.5                    | 54.12                   |
| 8:30  | 27.1                    | 41.9                   | 55.0                     | 60.6                   | 64.7                   | 63.5                   | 66.1                   | 67.4                   | 46.1                   | 57.2                   | 55.0                    | 53.1                    | 58.7                    | 464.0                    | 64.46                   |
| 9:00  | 29.3                    | 48.2                   | 59.8                     | 72.0                   | 76.0                   | 71.9                   | 75.7                   | 77.7                   | 55.9                   | 67.0                   | 63.4                    | 62.4                    | 65.6                    | 559.8                    | 74.66                   |
| 9:30  | 30.3                    | 49.7                   | 66.4                     | 73.8                   | 78.8                   | 79.8                   | 79.9                   | 83.8                   | 56.4                   | 68.0                   | 64.1                    | 64.0                    | 68.7                    | 675.4                    | 79.22                   |
| 10:00 | 30.4                    | 44.5                   | 68.4                     | 75.5                   | 81.8                   | 80.4                   | 81.8                   | 84.8                   | 56.5                   | 69.0                   | 65.8                    | 66.8                    | 70.8                    | 737.2                    | 80.86                   |
| 10:30 | 31.1                    | 47.2                   | 70.0                     | 76.5                   | 83.3                   | 85.0                   | 85.9                   | 88.8                   | 58.4                   | 70.0                   | 68.8                    | 69.9                    | 74.3                    | 809.1                    | 83.9                    |
| 11:00 | 32.2                    | 50.7                   | 75.0                     | 83.8                   | 91.4                   | 89.4                   | 90.4                   | 95.7                   | 63.2                   | 77.6                   | 75.1                    | 75.0                    | 79.5                    | 860.3                    | 90.14                   |
| 11:30 | 32.3                    | 53.6                   | 77.0                     | 87.9                   | 95.4                   | 94.8                   | 94.1                   | 99.2                   | 64.7                   | 79.0                   | 76.8                    | 77.8                    | 81.8                    | 915.5                    | 94.28                   |
| 12:00 | 32.1                    | 53.8                   | 80.6                     | 89.5                   | 98.2                   | 96.1                   | 108.4                  | 99.9                   | 68.0                   | 82.6                   | 77.4                    | 88.0                    | 87.2                    | 928.6                    | 98.42                   |
| 12:30 | 33.4                    | 66.4                   | 79.0                     | 98.6                   | 103.6                  | 102.8                  | 99.5                   | 106.0                  | 73.4                   | 88.8                   | 80.0                    | 80.1                    | 84.5                    | 862.4                    | 102.1                   |
| 13:00 | 33.7                    | 61.2                   | 79.1                     | 93.1                   | 100.0                  | 98.5                   | 97.0                   | 102.8                  | 68.6                   | 89.8                   | 80.2                    | 77.9                    | 89.6                    | 857.7                    | 98.28                   |
| 13:30 | 33.7                    | 66.9                   | 80.1                     | 97.8                   | 102.2                  | 101.8                  | 98.6                   | 104.4                  | 72.6                   | 88.4                   | 80.3                    | 85.0                    | 94.5                    | 796.3                    | 101                     |
| 14:00 | 34.1                    | 60.0                   | 79.6                     | 92.8                   | 98.7                   | 97.7                   | 94.7                   | 101.6                  | 69.0                   | 85.3                   | 80.1                    | 84.8                    | 92.3                    | 806.2                    | 97.1                    |
| 14:30 | 34.1                    | 59.4                   | 75.2                     | 85.9                   | 91.2                   | 90.8                   | 82.9                   | 94.6                   | 64.5                   | 79.2                   | 76.6                    | 69.2                    | 76.4                    | 738.5                    | 89.08                   |
| 15:00 | 34.5                    | 55.3                   | 73.1                     | 79.5                   | 85.3                   | 85.2                   | 76.1                   | 88.1                   | 60.8                   | 74.1                   | 70.3                    | 66.9                    | 74.1                    | 662.3                    | 82.84                   |
| 15:30 | 34.3                    | 60.1                   | 71.3                     | 80.5                   | 83.9                   | 83.9                   | 80.6                   | 86.4                   | 61.3                   | 73.2                   | 69.7                    | 74.0                    | 70.5                    | 539.2                    | 83.06                   |
| 16:00 | 34.4                    | 55.5                   | 64.4                     | 72.3                   | 75.7                   | 75.2                   | 75.9                   | 77.6                   | 55.9                   | 68.2                   | 66.1                    | 68.6                    | 73.5                    | 452.4                    | 75.34                   |
| 16:30 | 33.6                    | 52.7                   | 64.1                     | 67.6                   | 72.5                   | 69.9                   | 61.8                   | 69.2                   | 51.2                   | 61.6                   | 60.0                    | 56.6                    | 65.6                    | 356.2                    | 68.2                    |
| 17:00 | 32.3                    | 50.1                   | 57.0                     | 59.2                   | 64.8                   | 64.2                   | 58.2                   | 65.6                   | 51.2                   | 56.7                   | 54.0                    | 53.7                    | 57.4                    | 267.2                    | 62.4                    |
| 17:30 | 32.3                    | 45.3                   | 45.7                     | 46.2                   | 48.5                   | 48.6                   | 46.6                   | 46.1                   | 41.4                   | 45.4                   | 41.3                    | 44.5                    | 47.4                    | 136.4                    | 47.2                    |

### Test No.2 - Flat plate 02-05-22 ( $U = 1 \text{ m/s} \pm 0.1$ )

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 22.1                    | 26.8                   | 27.6                     | 30.7                   | 30.5                   | 30.5                   | 30.7                   | 29.6                   | 24.5                   | 28.2                   | 26.4                    | 28.2                    | 28.3                    | 355                      | 30.4                    |
| 8:00  | 22.4                    | 38.9                   | 45.7                     | 50.9                   | 52.7                   | 51.7                   | 55.5                   | 54.5                   | 37.6                   | 42.5                   | 41                      | 46.3                    | 48.3                    | 481                      | 53.06                   |
| 8:30  | 23.3                    | 43                     | 50.2                     | 56.4                   | 64.6                   | 62.4                   | 61.6                   | 63.7                   | 45.7                   | 48.6                   | 46.6                    | 52.2                    | 53.6                    | 582                      | 61.74                   |
| 9:00  | 25.1                    | 42.5                   | 61.77                    | 64.4                   | 70.5                   | 69                     | 67.2                   | 70.2                   | 48.7                   | 52.8                   | 49                      | 56.5                    | 62.9                    | 717                      | 68.26                   |
| 9:30  | 27                      | 38.2                   | 63.1                     | 68                     | 75.3                   | 69.2                   | 76.6                   | 75                     | 51.8                   | 58.1                   | 50.9                    | 60.2                    | 61.3                    | 747                      | 72.82                   |
| 10:00 | 27                      | 37.2                   | 63.1                     | 69.4                   | 77.9                   | 71.1                   | 78.7                   | 76.8                   | 53.8                   | 59.8                   | 51.9                    | 63.3                    | 67.4                    | 823.8                    | 74.78                   |
| 10:30 | 28                      | 39.9                   | 63.5                     | 71.3                   | 79.6                   | 72.6                   | 79.9                   | 77.9                   | 54.8                   | 58.4                   | 52.9                    | 63.8                    | 68.3                    | 859.2                    | 76.26                   |
| 11:00 | 29                      | 45.1                   | 69.1                     | 83.4                   | 88                     | 83.7                   | 84.8                   | 85.3                   | 59.7                   | 66.7                   | 59.9                    | 71.3                    | 75.1                    | 866.4                    | 85.04                   |
| 11:30 | 28                      | 42.3                   | 71                       | 78                     | 87.2                   | 78.9                   | 82.2                   | 84.9                   | 59.1                   | 63.8                   | 56.4                    | 67.4                    | 77.6                    | 856.9                    | 82.24                   |
| 12:00 | 29                      | 47.9                   | 70.6                     | 85.4                   | 88.7                   | 86.2                   | 88.1                   | 85.2                   | 59.5                   | 68                     | 60.8                    | 72.3                    | 78.4                    | 841.8                    | 86.72                   |
| 12:30 | 30.2                    | 49.9                   | 71.2                     | 86.7                   | 90.6                   | 87.3                   | 89.7                   | 88                     | 63                     | 71.2                   | 64.2                    | 73.7                    | 78.7                    | 822.4                    | 88.46                   |
| 13:00 | 30.7                    | 53.1                   | 70.9                     | 87.1                   | 90.4                   | 88.2                   | 89.4                   | 87.9                   | 63.5                   | 71.3                   | 67.2                    | 76.6                    | 80.6                    | 795.8                    | 88.6                    |
| 13:30 | 30.7                    | 55                     | 68.5                     | 85.8                   | 89.2                   | 87.6                   | 86.8                   | 86.8                   | 61.8                   | 71.8                   | 67.3                    | 74.8                    | 79.7                    | 693.2                    | 87.24                   |
| 14:00 | 30.6                    | 55.7                   | 65.8                     | 81.3                   | 84.9                   | 84.4                   | 82.6                   | 83.3                   | 60.7                   | 68.9                   | 65.5                    | 73.5                    | 77.4                    | 641.8                    | 83.3                    |
| 14:30 | 30.1                    | 45.5                   | 59.2                     | 64.2                   | 71.1                   | 67.9                   | 69.7                   | 70                     | 52.7                   | 56.4                   | 52.7                    | 59.5                    | 65.7                    | 531.2                    | 68.58                   |
| 15:00 | 32.1                    | 44.7                   | 55.6                     | 60.7                   | 66.6                   | 68.8                   | 60.9                   | 65.1                   | 50.5                   | 54.8                   | 51.2                    | 56.5                    | 61.3                    | 489.2                    | 64.42                   |
| 15:30 | 31.1                    | 43.3                   | 50.9                     | 56.7                   | 62.3                   | 64.3                   | 56.7                   | 58.6                   | 45.5                   | 49.7                   | 47.5                    | 51.5                    | 53.7                    | 337.8                    | 59.72                   |
| 16:00 | 30.9                    | 41.3                   | 47.2                     | 49.9                   | 54.8                   | 56.5                   | 49.6                   | 51.1                   | 42.3                   | 46.4                   | 44.6                    | 47.2                    | 50.7                    | 238.7                    | 52.38                   |
| 16:30 | 30.7                    | 39.3                   | 42.8                     | 43.8                   | 47.2                   | 50.1                   | 43                     | 46.2                   | 38.8                   | 44                     | 41                      | 42.9                    | 45.2                    | 190.2                    | 46.06                   |
| 17:00 | 29.1                    | 37.4                   | 39.6                     | 40                     | 41.2                   | 42.6                   | 41.5                   | 41.2                   | 34.5                   | 38.3                   | 37.3                    | 38.9                    | 40.7                    | 166.8                    | 41.3                    |
| 17:30 | 29                      | 35.3                   | 35.5                     | 35.8                   | 36.4                   | 37.2                   | 37.1                   | 35.2                   | 31.7                   | 35                     | 34.7                    | 34.9                    | 35.4                    | 45.8                     | 36.34                   |

**Test No.2 - U -corrugatedplate parallel to airflow 02-05-22 (U = 1 m/s ± 0.1)**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 22.1                    | 25                     | 29.9                     | 30                     | 29.9                   | 28.6                   | 29.6                   | 29.2                   | 23.8                   | 25.9                   | 25.6                    | 28.4                    | 26                      | 206                      | 29.46                   |
| 8:00  | 22.4                    | 33.4                   | 42.7                     | 48.8                   | 47.7                   | 40.5                   | 47.5                   | 43.7                   | 34.8                   | 39.2                   | 33.8                    | 47.9                    | 35.1                    | 462                      | 45.64                   |
| 8:30  | 23.3                    | 38.3                   | 55.4                     | 62.5                   | 63.7                   | 55.7                   | 63.6                   | 64                     | 48.7                   | 52                     | 45.9                    | 52.8                    | 53                      | 533.1                    | 61.9                    |
| 9:00  | 25.1                    | 40.2                   | 60.3                     | 69.7                   | 72.1                   | 65.5                   | 72.3                   | 75.6                   | 56.2                   | 58.7                   | 54.1                    | 60.6                    | 61.1                    | 700.8                    | 71.04                   |
| 9:30  | 27                      | 39.5                   | 62.1                     | 81.7                   | 83.5                   | 73.3                   | 77.7                   | 82.2                   | 62                     | 65.4                   | 59.2                    | 65.5                    | 65.3                    | 750                      | 79.68                   |
| 10:00 | 27                      | 39.9                   | 63.8                     | 83.1                   | 85.2                   | 74.2                   | 80.4                   | 83.9                   | 63.2                   | 65.9                   | 61.4                    | 67.5                    | 66.5                    | 824                      | 81.36                   |
| 10:30 | 28                      | 40                     | 69.3                     | 84.4                   | 86.5                   | 74.7                   | 82.3                   | 88                     | 67                     | 69.1                   | 64.6                    | 68.6                    | 67.7                    | 845.3                    | 83.18                   |
| 11:00 | 29                      | 44                     | 71.1                     | 83.1                   | 86.5                   | 75.3                   | 84.9                   | 84.8                   | 63                     | 63.9                   | 58.5                    | 71.7                    | 71.6                    | 868.2                    | 82.92                   |
| 11:30 | 30                      | 43.2                   | 71.8                     | 85.3                   | 88.4                   | 77.6                   | 88.1                   | 86.2                   | 64.1                   | 66.7                   | 59.9                    | 75.6                    | 77.3                    | 857.4                    | 85.12                   |
| 12:00 | 31.5                    | 48.3                   | 72.9                     | 88.3                   | 90.1                   | 84.5                   | 83.9                   | 86                     | 65                     | 69.6                   | 61.8                    | 77.8                    | 77.2                    | 843.2                    | 86.56                   |
| 12:30 | 33.5                    | 50.1                   | 74.1                     | 87.5                   | 90                     | 83.1                   | 83.1                   | 88.5                   | 66.2                   | 68.7                   | 64.6                    | 75.9                    | 76.9                    | 837.4                    | 86.44                   |
| 13:00 | 31.7                    | 50.9                   | 71.2                     | 86                     | 88                     | 82.7                   | 85.4                   | 85.3                   | 65.8                   | 70.2                   | 64.4                    | 76.1                    | 76.6                    | 779.1                    | 85.48                   |
| 13:30 | 32.5                    | 50.6                   | 71.3                     | 85.3                   | 86.8                   | 83.5                   | 86.6                   | 84.6                   | 63.1                   | 68.5                   | 63.6                    | 76.3                    | 76                      | 710.4                    | 85.36                   |
| 14:00 | 30.6                    | 51.7                   | 67.9                     | 82.2                   | 83.7                   | 82.1                   | 83.1                   | 81.1                   | 63.3                   | 66.4                   | 64.4                    | 67.8                    | 75.6                    | 643.6                    | 82.44                   |
| 14:30 | 30.1                    | 41.8                   | 64.2                     | 68.9                   | 72.1                   | 65.4                   | 71.9                   | 71                     | 56.5                   | 58.6                   | 54.6                    | 65.3                    | 65                      | 535.6                    | 69.86                   |
| 15:00 | 32.1                    | 40.5                   | 60.2                     | 63.1                   | 66.4                   | 60.9                   | 65.9                   | 66.4                   | 53.2                   | 55.6                   | 51.9                    | 61.6                    | 60.6                    | 491.3                    | 64.54                   |
| 15:30 | 31.1                    | 41.1                   | 53.2                     | 57.9                   | 59.1                   | 60.3                   | 55.6                   | 61.6                   | 50.5                   | 50.7                   | 47.2                    | 54.7                    | 52.5                    | 340.3                    | 58.9                    |
| 16:00 | 30.9                    | 40.1                   | 50.9                     | 52.8                   | 54.2                   | 57.2                   | 49.4                   | 53.9                   | 44.2                   | 47                     | 43.7                    | 51.4                    | 50                      | 245.8                    | 53.5                    |
| 16:30 | 30.7                    | 39                     | 46.6                     | 46.8                   | 47.4                   | 49.7                   | 44.4                   | 50                     | 40.4                   | 42.9                   | 41.2                    | 47.5                    | 45.4                    | 192.4                    | 47.66                   |
| 17:00 | 29.1                    | 38                     | 40.1                     | 42.9                   | 42.3                   | 43.5                   | 41.3                   | 42.7                   | 37.1                   | 38.9                   | 37.5                    | 39.6                    | 40.6                    | 168.6                    | 42.54                   |
| 17:30 | 29                      | 35.3                   | 37.1                     | 37.7                   | 37.3                   | 36.9                   | 37.6                   | 37.7                   | 32.6                   | 34.4                   | 34.6                    | 37.3                    | 37.6                    | 66.5                     | 37.44                   |

**Test No.2 - U -corrugatedplate anti-parallel to airflow 19-05-22 (U = 1 m/s ± 0.1)**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 29.1                    | 39.1                   | 42.2                     | 46.4                   | 45.6                   | 43.8                   | 45.8                   | 45.2                   | 36.8                   | 41.6                   | 41.2                    | 39.8                    | 39.7                    | 266.7                    | 45.36                   |
| 8:00  | 30.3                    | 42.2                   | 51.7                     | 55.6                   | 55.3                   | 55.6                   | 54.1                   | 55.6                   | 40.8                   | 46.4                   | 47.8                    | 47.4                    | 50.5                    | 345.8                    | 55.24                   |
| 8:30  | 31.7                    | 48.4                   | 67.2                     | 73.7                   | 71.9                   | 71.4                   | 66.8                   | 68.9                   | 52.4                   | 60.0                   | 63.6                    | 62.8                    | 61.7                    | 463.4                    | 70.54                   |
| 9:00  | 32.1                    | 50.3                   | 71.1                     | 76.3                   | 77.9                   | 77.5                   | 77.5                   | 77.9                   | 60.5                   | 67.0                   | 64.3                    | 68.8                    | 71.4                    | 562.9                    | 77.42                   |
| 9:30  | 32.5                    | 54.9                   | 74.2                     | 78.7                   | 84.2                   | 81.6                   | 76.7                   | 77.8                   | 59.7                   | 62.1                   | 62.6                    | 67.2                    | 73.5                    | 641.3                    | 79.8                    |
| 10:00 | 33.3                    | 60.3                   | 75.1                     | 91.3                   | 92.5                   | 85.5                   | 83.0                   | 84.1                   | 63.7                   | 67.8                   | 66.8                    | 71.2                    | 77.9                    | 725.8                    | 87.28                   |
| 10:30 | 34.0                    | 61.9                   | 77.3                     | 97.6                   | 100.2                  | 95.3                   | 82.0                   | 90.3                   | 63.7                   | 66.8                   | 69.1                    | 79.6                    | 84.3                    | 775.3                    | 93.08                   |
| 11:00 | 35.2                    | 59.3                   | 80.1                     | 101.9                  | 103.9                  | 103.3                  | 85.4                   | 102.3                  | 77.7                   | 80.9                   | 78.8                    | 86.6                    | 86.6                    | 786.5                    | 99.36                   |
| 11:30 | 36.5                    | 56.1                   | 81.3                     | 103.2                  | 105.6                  | 106.2                  | 85.1                   | 104.6                  | 82.0                   | 84.0                   | 82.2                    | 89.6                    | 89.1                    | 824.3                    | 100.9                   |
| 12:00 | 37.5                    | 62.2                   | 83.0                     | 99.2                   | 101.1                  | 101.2                  | 96.2                   | 100.7                  | 78.2                   | 83.2                   | 78.5                    | 84.2                    | 92.1                    | 806.5                    | 99.68                   |
| 12:30 | 37.6                    | 66.1                   | 82.3                     | 99.8                   | 101.4                  | 102.2                  | 95.1                   | 100.5                  | 76.7                   | 81.3                   | 80.7                    | 85.2                    | 95.6                    | 808.1                    | 99.8                    |
| 13:00 | 38.0                    | 65.8                   | 83.7                     | 96.9                   | 101.3                  | 102.3                  | 90.6                   | 100.4                  | 78.4                   | 84.6                   | 85.0                    | 88.9                    | 89.8                    | 777.8                    | 98.3                    |
| 13:30 | 38.3                    | 64.9                   | 81.2                     | 92.0                   | 94.4                   | 97.8                   | 85.2                   | 93.5                   | 72.4                   | 74.9                   | 73.1                    | 80.1                    | 90.8                    | 738.9                    | 92.58                   |
| 14:00 | 39.0                    | 56.7                   | 78.1                     | 88.1                   | 90.4                   | 93.6                   | 79.9                   | 89.1                   | 69.5                   | 72.7                   | 70.6                    | 76.9                    | 83.2                    | 692.8                    | 88.22                   |
| 14:30 | 39.0                    | 56.0                   | 75.4                     | 83.4                   | 85.5                   | 88.6                   | 80.0                   | 84.5                   | 66.2                   | 69.1                   | 67.9                    | 73.2                    | 77.9                    | 598.5                    | 84.4                    |
| 15:00 | 39.2                    | 55.0                   | 74.9                     | 80.9                   | 82.4                   | 85.7                   | 78.7                   | 81.7                   | 64.8                   | 67.8                   | 66.9                    | 71.7                    | 76.4                    | 519.2                    | 81.88                   |
| 15:30 | 39.3                    | 53.6                   | 69.1                     | 76.2                   | 76.2                   | 79.0                   | 71.2                   | 75.8                   | 60.7                   | 63.7                   | 65.1                    | 66.7                    | 69.7                    | 453.4                    | 75.68                   |
| 16:00 | 39.3                    | 51.5                   | 66.9                     | 70.3                   | 68.6                   | 72.7                   | 61.6                   | 68.3                   | 56.0                   | 58.5                   | 57.4                    | 61.5                    | 56.1                    | 325.8                    | 68.3                    |
| 16:30 | 39.5                    | 49.9                   | 59.2                     | 62.2                   | 63.8                   | 65.1                   | 57.0                   | 62.0                   | 52.1                   | 55.0                   | 54.2                    | 57.4                    | 60.0                    | 246.8                    | 62.02                   |
| 17:00 | 39.1                    | 48.2                   | 54.1                     | 55.7                   | 55.9                   | 56.8                   | 55.8                   | 55.8                   | 48.2                   | 50.7                   | 49.6                    | 52.7                    | 54.3                    | 132.7                    | 56                      |
| 17:30 | 38.4                    | 45.1                   | 47.3                     | 48.5                   | 48.3                   | 48.4                   | 49.2                   | 48.9                   | 43.0                   | 45.4                   | 45.6                    | 46.6                    | 46.8                    | 80.3                     | 48.66                   |

**Test No.2 - Trapezoidal corrugated plate 28-05-22 ( $U = 1 \text{ m/s} \pm 0.1$ )**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 29.5                    | 37.0                   | 42.5                     | 44.4                   | 43.4                   | 42.1                   | 44.6                   | 42.9                   | 35.8                   | 39.9                   | 39.2                    | 39.1                    | 37.6                    | 242.3                    | 43.5                    |
| 8:00  | 30.1                    | 39.1                   | 50.1                     | 60.5                   | 55.3                   | 56.3                   | 54.5                   | 60.1                   | 46.8                   | 53.8                   | 55.4                    | 47.5                    | 48.6                    | 339.7                    | 57.3                    |
| 8:30  | 32.0                    | 43.3                   | 58.2                     | 66.1                   | 66.0                   | 65.2                   | 62.9                   | 72.3                   | 52.8                   | 60.4                   | 61.5                    | 53.6                    | 57.6                    | 457.8                    | 66.5                    |
| 9:00  | 32.3                    | 42.2                   | 61.7                     | 62.6                   | 65.0                   | 64.8                   | 67.5                   | 70.3                   | 48.8                   | 58.0                   | 59.2                    | 57.4                    | 61.3                    | 568.3                    | 66                      |
| 9:30  | 35.0                    | 47.4                   | 70.3                     | 74.5                   | 77.6                   | 72.2                   | 78.5                   | 82.3                   | 56.6                   | 67.2                   | 66.5                    | 66.5                    | 71.1                    | 666.5                    | 77                      |
| 10:00 | 35.7                    | 47.0                   | 73.0                     | 76.9                   | 82.9                   | 76.7                   | 81.8                   | 85.3                   | 55.8                   | 69.7                   | 70.9                    | 70.0                    | 82.0                    | 743.1                    | 80.7                    |
| 10:30 | 37.2                    | 49.2                   | 75.7                     | 79.3                   | 85.3                   | 86.1                   | 85.8                   | 78.6                   | 53.5                   | 67.2                   | 70.9                    | 72.8                    | 80.0                    | 822.3                    | 83                      |
| 11:00 | 37.3                    | 50.6                   | 79.0                     | 82.8                   | 89.3                   | 90.0                   | 89.1                   | 92.4                   | 56.0                   | 71.0                   | 73.7                    | 75.4                    | 81.5                    | 867.2                    | 88.7                    |
| 11:30 | 38.6                    | 51.6                   | 82.2                     | 87.0                   | 93.0                   | 96.4                   | 92.8                   | 98.4                   | 77.5                   | 82.6                   | 77.1                    | 80.7                    | 84.0                    | 938.4                    | 93.5                    |
| 12:00 | 38.4                    | 50.6                   | 82.5                     | 86.5                   | 94.4                   | 97.0                   | 93.1                   | 97.6                   | 67.3                   | 79.1                   | 76.9                    | 70.7                    | 82.9                    | 931.7                    | 93.7                    |
| 12:30 | 38.7                    | 51.3                   | 81.5                     | 87.8                   | 94.7                   | 97.1                   | 91.5                   | 97.2                   | 66.2                   | 78.3                   | 78.7                    | 79.3                    | 84.5                    | 926.6                    | 93.7                    |
| 13:00 | 38.3                    | 51.0                   | 80.6                     | 8.8                    | 93.4                   | 96.3                   | 82.8                   | 96.4                   | 65.6                   | 78.2                   | 77.5                    | 77.7                    | 81.3                    | 916.3                    | 75.5                    |
| 13:30 | 38.6                    | 49.9                   | 80.6                     | 83.6                   | 91.3                   | 93.8                   | 87.7                   | 94.5                   | 65.3                   | 77.6                   | 76.2                    | 75.5                    | 87.0                    | 853.4                    | 90.2                    |
| 14:00 | 39.0                    | 54.4                   | 80.0                     | 87.3                   | 93.5                   | 95.5                   | 82.2                   | 96.4                   | 68.1                   | 80.8                   | 80.1                    | 75.0                    | 81.5                    | 800.3                    | 91                      |
| 14:30 | 39.2                    | 51.7                   | 78.3                     | 79.1                   | 85.4                   | 87.7                   | 83.3                   | 89.1                   | 63.1                   | 73.9                   | 72.7                    | 72.3                    | 80.7                    | 724.8                    | 84.9                    |
| 15:00 | 39.2                    | 52.2                   | 74.9                     | 76.2                   | 82.0                   | 84.0                   | 77.9                   | 85.4                   | 61.3                   | 72.4                   | 70.2                    | 69.3                    | 73.5                    | 625.8                    | 81.1                    |
| 15:30 | 39.4                    | 50.9                   | 73.7                     | 75.8                   | 81.3                   | 82.7                   | 75.2                   | 84.1                   | 60.5                   | 71.5                   | 71.1                    | 67.9                    | 70.9                    | 550.9                    | 79.8                    |
| 16:00 | 39.5                    | 51.3                   | 69.0                     | 73.3                   | 75.4                   | 76.0                   | 67.9                   | 77.6                   | 56.9                   | 68.7                   | 67.6                    | 62.0                    | 67.5                    | 430.2                    | 74                      |
| 16:30 | 39.7                    | 48.2                   | 63.7                     | 69.1                   | 71.4                   | 68.9                   | 58.8                   | 69.1                   | 52.4                   | 62.0                   | 64.1                    | 58.8                    | 60.9                    | 333.4                    | 67.5                    |
| 17:00 | 39.1                    | 46.7                   | 54.5                     | 58.5                   | 59.6                   | 59.4                   | 57.5                   | 60.3                   | 48.4                   | 55.4                   | 54.8                    | 54.6                    | 54.3                    | 221.5                    | 59.1                    |
| 17:30 | 39.0                    | 43.8                   | 45.0                     | 45.5                   | 45.5                   | 44.9                   | 47.2                   | 46.2                   | 40.8                   | 43.9                   | 42.3                    | 45.2                    | 44.8                    | 66.5                     | 45.9                    |

**Test No.3 - Flat plate 03-05-22 ( $U = 1.5 \text{ m/s} \pm 0.1$ )**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 27.5                    | 27.8                   | 29.4                     | 30.2                   | 28.1                   | 31.3                   | 29.9                   | 30.4                   | 26.5                   | 31.1                   | 28.6                    | 30                      | 30.4                    | 130.8                    | 29.98                   |
| 8:00  | 28.7                    | 33.1                   | 35.2                     | 35.5                   | 33.4                   | 36.2                   | 37.7                   | 36.5                   | 29.6                   | 37.5                   | 36.2                    | 36.3                    | 36                      | 308.7                    | 35.86                   |
| 8:30  | 30.3                    | 32                     | 49.4                     | 51.3                   | 47.8                   | 54.1                   | 60.7                   | 59.6                   | 45.8                   | 61.4                   | 46.9                    | 51.2                    | 55.7                    | 457.5                    | 54.7                    |
| 9:00  | 31.2                    | 32.3                   | 57.1                     | 58.4                   | 52                     | 61.5                   | 65                     | 66.6                   | 50.9                   | 67.5                   | 51.8                    | 54.9                    | 59.9                    | 526.8                    | 60.7                    |
| 9:30  | 32.7                    | 36.1                   | 61.1                     | 66                     | 58.2                   | 69.6                   | 72.7                   | 73.9                   | 56.6                   | 76.2                   | 56.9                    | 60.3                    | 65.9                    | 620.5                    | 68.08                   |
| 10:00 | 33.4                    | 43.3                   | 67.2                     | 72                     | 62.3                   | 76.7                   | 80.1                   | 81.3                   | 62.4                   | 85.5                   | 63.7                    | 67.1                    | 72.6                    | 717.7                    | 74.48                   |
| 10:30 | 33.8                    | 44.8                   | 69.2                     | 77.8                   | 66.7                   | 80.1                   | 85.3                   | 84.6                   | 64.3                   | 88.2                   | 64.3                    | 70.2                    | 76.5                    | 812.5                    | 78.9                    |
| 11:00 | 33.1                    | 48.1                   | 70                       | 84.4                   | 73.6                   | 87.4                   | 88.6                   | 90.5                   | 69.1                   | 92.6                   | 68.4                    | 73.8                    | 78.2                    | 863.3                    | 84.9                    |
| 11:30 | 35.1                    | 57.1                   | 76.8                     | 96.3                   | 79.1                   | 96.7                   | 90.4                   | 98.4                   | 70                     | 104                    | 75.2                    | 80.7                    | 86.4                    | 906.4                    | 92.18                   |
| 12:00 | 36.5                    | 47.9                   | 76.3                     | 90                     | 74.3                   | 90.6                   | 93.8                   | 94                     | 70.1                   | 96.8                   | 67.8                    | 81.4                    | 86.6                    | 888.6                    | 88.54                   |
| 12:30 | 36.5                    | 47.3                   | 74.6                     | 81.2                   | 72.2                   | 83.9                   | 84.7                   | 90.8                   | 68.3                   | 92.8                   | 65                      | 76.8                    | 84.1                    | 882.3                    | 82.56                   |
| 13:00 | 36.8                    | 48.2                   | 71.7                     | 79.5                   | 68.2                   | 81.9                   | 88.7                   | 87.8                   | 66.4                   | 89.2                   | 63.6                    | 74                      | 80.8                    | 838.4                    | 81.22                   |
| 13:30 | 36.7                    | 46.7                   | 69.6                     | 76.3                   | 67.3                   | 79.7                   | 82.3                   | 84.7                   | 65                     | 86.9                   | 62.8                    | 72.9                    | 81.5                    | 795.6                    | 78.06                   |
| 14:00 | 37.2                    | 55.3                   | 69.7                     | 77.9                   | 70.6                   | 90.1                   | 81.1                   | 66.6                   | 67.9                   | 88.4                   | 65                      | 75.1                    | 82.4                    | 681.4                    | 77.26                   |
| 14:30 | 37.3                    | 54.8                   | 66                       | 75.6                   | 67.1                   | 85.2                   | 78                     | 81.1                   | 63.1                   | 83.2                   | 62.8                    | 71.6                    | 76.8                    | 646.8                    | 77.4                    |
| 15:00 | 37.5                    | 52.7                   | 62.2                     | 70.4                   | 63.8                   | 79.3                   | 73.1                   | 75.6                   | 61                     | 77.3                   | 60.6                    | 67.7                    | 72.5                    | 548.8                    | 72.44                   |
| 15:30 | 37.5                    | 47.8                   | 57.7                     | 59.5                   | 54.4                   | 66.6                   | 61.2                   | 62.7                   | 52.1                   | 64.3                   | 52.7                    | 69.5                    | 58.6                    | 485.3                    | 60.88                   |
| 16:00 | 37.7                    | 47                     | 54.6                     | 56.6                   | 52.7                   | 63.1                   | 57.2                   | 59.3                   | 50.3                   | 61.1                   | 51                      | 55.6                    | 58.9                    | 328.7                    | 57.78                   |
| 16:30 | 37.9                    | 46.1                   | 50.7                     | 55                     | 51.1                   | 59.9                   | 55.1                   | 56.6                   | 46.9                   | 57.3                   | 48.9                    | 53.6                    | 56                      | 240.3                    | 55.54                   |
| 17:00 | 37.4                    | 41.9                   | 47.1                     | 46.5                   | 44.5                   | 50.8                   | 48.5                   | 47.6                   | 42.1                   | 49                     | 43.8                    | 46.5                    | 48.4                    | 159.4                    | 47.58                   |
| 17:30 | 37.2                    | 39.8                   | 41.8                     | 41.9                   | 40.2                   | 44.1                   | 43.9                   | 41.6                   | 37.6                   | 42.9                   | 39.9                    | 41.4                    | 42.3                    | 74.5                     | 42.34                   |

**Test No.3 - U -corrugatedplate parallel to airflow 03-05-22 (U = 1.5 m/s ± 0.1)**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 27.5                    | 28.7                   | 34.8                     | 35.1                   | 34                     | 32.9                   | 34.5                   | 35.3                   | 28.8                   | 31.2                   | 33.9                    | 33.8                    | 34.4                    | 205.3                    | 34.4                    |
| 8:00  | 28.7                    | 32.6                   | 46.6                     | 47.7                   | 50.7                   | 46.9                   | 48.5                   | 52.7                   | 40                     | 44.1                   | 43.3                    | 46.1                    | 48.3                    | 306.9                    | 49.3                    |
| 8:30  | 30.3                    | 36.3                   | 58.8                     | 64.4                   | 65.7                   | 61.2                   | 60.5                   | 68                     | 51.5                   | 54.8                   | 53                      | 56.2                    | 60                      | 469.3                    | 64                      |
| 9:00  | 31.2                    | 36.6                   | 60.1                     | 69.2                   | 70.6                   | 66.4                   | 64.4                   | 73.1                   | 54.9                   | 57.8                   | 55.6                    | 60.4                    | 63.5                    | 525                      | 68.7                    |
| 9:30  | 32.7                    | 39.5                   | 65.7                     | 80.6                   | 80.8                   | 76.1                   | 72.4                   | 81.5                   | 62.6                   | 64.9                   | 61.8                    | 66.1                    | 70.1                    | 620.3                    | 78.3                    |
| 10:00 | 33.4                    | 45.7                   | 69.5                     | 88.8                   | 89.2                   | 84.3                   | 79.5                   | 89.8                   | 69.7                   | 72                     | 65.9                    | 73.7                    | 77.6                    | 713.9                    | 86.3                    |
| 10:30 | 33.8                    | 48.3                   | 73.5                     | 93.7                   | 94.3                   | 89.4                   | 84.2                   | 94.4                   | 71.3                   | 74.3                   | 68.1                    | 76.4                    | 78.3                    | 809.5                    | 91.2                    |
| 11:00 | 33.1                    | 53.7                   | 74.6                     | 103                    | 104                    | 99.5                   | 91.1                   | 104                    | 79.2                   | 84                     | 76.6                    | 81.8                    | 83.6                    | 849.8                    | 100                     |
| 11:30 | 35.1                    | 58.5                   | 77.8                     | 103                    | 106                    | 99.4                   | 93.4                   | 103                    | 79.5                   | 86.9                   | 76.9                    | 86.3                    | 89.4                    | 890.5                    | 101                     |
| 12:00 | 36.5                    | 52.1                   | 79.7                     | 98.2                   | 101                    | 97                     | 88.3                   | 80.9                   | 76.4                   | 80.9                   | 72.1                    | 87.1                    | 90.5                    | 885.3                    | 93                      |
| 12:30 | 36.5                    | 51.9                   | 79.5                     | 95.9                   | 98.1                   | 95.9                   | 84                     | 96.5                   | 75.6                   | 77.9                   | 68.2                    | q                       | 87.6                    | 874.7                    | 94.1                    |
| 13:00 | 36.8                    | 53                     | 76                       | 93.5                   | 95.4                   | 94                     | 88.9                   | 93.5                   | 74.1                   | 76.9                   | 67.1                    | 81.5                    | 85.7                    | 835.3                    | 93.1                    |
| 13:30 | 36.7                    | 51.8                   | 75.8                     | 91                     | 92.9                   | 92.3                   | 83.3                   | 91.4                   | 72.8                   | 74.4                   | 66.2                    | 81.8                    | 84.5                    | 798.4                    | 90.2                    |
| 14:00 | 37.2                    | 55.8                   | 72.5                     | 90                     | 91.7                   | 91.2                   | 85                     | 89.3                   | 72.8                   | 74.7                   | 66.4                    | 82.5                    | 84.9                    | 688.1                    | 89.4                    |
| 14:30 | 37.3                    | 55.3                   | 71.1                     | 87                     | 88.3                   | 88.4                   | 83.2                   | 86.6                   | 69.6                   | 73.4                   | 66                      | 81                      | 80.3                    | 657.6                    | 86.7                    |
| 15:00 | 37.5                    | 56.1                   | 64.8                     | 82.1                   | 83.5                   | 83.8                   | 80.4                   | 82                     | 66.6                   | 71.9                   | 64.4                    | 78.5                    | 77.5                    | 545.8                    | 82.4                    |
| 15:30 | 37.5                    | 49.3                   | 59.7                     | 68.8                   | 69.4                   | 70                     | 65.7                   | 68.3                   | 57.9                   | 60.2                   | 54.6                    | 65.5                    | 62.7                    | 485.2                    | 68.4                    |
| 16:00 | 37.7                    | 46.8                   | 56.7                     | 63.8                   | 64.2                   | 64.9                   | 60.5                   | 63.5                   | 53.9                   | 56.6                   | 52                      | 61.4                    | 61.4                    | 335.2                    | 63.4                    |
| 16:30 | 37.9                    | 44.1                   | 53.1                     | 56.7                   | 57.8                   | 59.4                   | 53.2                   | 59.1                   | 49.6                   | 52.7                   | 48.1                    | 53.6                    | 55                      | 233.9                    | 57.2                    |
| 17:00 | 37.4                    | 41.8                   | 50.5                     | 49                     | 49.6                   | 50.1                   | 48.4                   | 50.5                   | 43.3                   | 46.2                   | 43.6                    | 46.6                    | 48                      | 153.4                    | 49.5                    |
| 17:30 | 37.2                    | 38.7                   | 41.1                     | 41.5                   | 41.8                   | 41.4                   | 41.7                   | 42.4                   | 37.2                   | 38.9                   | 38.8                    | 40.2                    | 40.6                    | 66.5                     | 41.8                    |

**Test No.3 - U -corrugatedplate anti-parallel to airflow 20-05-22 (U = 1.5 m/s ± 0.1)**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 28.0                    | 40.3                   | 44.9                     | 48.3                   | 47.7                   | 47.8                   | 47.6                   | 47.6                   | 40.4                   | 43.7                   | 42.8                    | 43.6                    | 43.3                    | 260.8                    | 47.8                    |
| 8:00  | 29.2                    | 42.1                   | 51.2                     | 54.6                   | 54.7                   | 55.0                   | 54.4                   | 54.9                   | 45.7                   | 48.3                   | 47.8                    | 49.1                    | 51.3                    | 309.1                    | 54.72                   |
| 8:30  | 29.4                    | 50.2                   | 59.2                     | 67.5                   | 67.4                   | 66.0                   | 65.1                   | 66.1                   | 50.2                   | 54.5                   | 56.2                    | 55.3                    | 60.4                    | 403.8                    | 66.42                   |
| 9:00  | 30.1                    | 48.8                   | 61.8                     | 66.4                   | 68.3                   | 70.6                   | 68.7                   | 69.5                   | 55.1                   | 56.9                   | 57.6                    | 60.1                    | 65.1                    | 480.7                    | 68.7                    |
| 9:30  | 30.7                    | 50.0                   | 68.7                     | 74.3                   | 75.2                   | 76.9                   | 73.8                   | 76.1                   | 59.3                   | 62.6                   | 62.8                    | 65.8                    | 69.8                    | 594.4                    | 75.26                   |
| 10:00 | 32.0                    | 52.7                   | 73.2                     | 78.9                   | 80.7                   | 85.7                   | 78.5                   | 80.7                   | 63.5                   | 67.1                   | 70.7                    | 66.4                    | 74.0                    | 644.1                    | 80.9                    |
| 10:30 | 32.8                    | 57.0                   | 75.6                     | 84.2                   | 85.5                   | 90.7                   | 82.4                   | 85.6                   | 65.7                   | 68.1                   | 70.5                    | 72.8                    | 77.9                    | 750.4                    | 85.68                   |
| 11:00 | 33.2                    | 60.5                   | 76.8                     | 81.4                   | 87.3                   | 92.1                   | 82.0                   | 87.9                   | 67.8                   | 72.1                   | 69.9                    | 74.8                    | 77.2                    | 742.4                    | 86.14                   |
| 11:30 | 33.4                    | 53.1                   | 77.9                     | 88.2                   | 90.2                   | 92.5                   | 84.9                   | 88.5                   | 66.4                   | 70.5                   | 70.0                    | 73.7                    | 77.2                    | 630.4                    | 88.86                   |
| 12:00 | 33.5                    | 54.2                   | 77.8                     | 88.2                   | 90.4                   | 93.4                   | 86.1                   | 89.0                   | 67.0                   | 70.9                   | 71.1                    | 73.4                    | 77.1                    | 948.7                    | 89.42                   |
| 12:30 | 33.4                    | 53.1                   | 77.3                     | 89.0                   | 91.3                   | 94.8                   | 90.4                   | 89.9                   | 68.6                   | 71.9                   | 72.2                    | 75.6                    | 80.6                    | 845.3                    | 91.08                   |
| 13:00 | 33.6                    | 53.9                   | 77.0                     | 89.0                   | 91.4                   | 94.6                   | 86.7                   | 89.7                   | 68.7                   | 72.1                   | 73.1                    | 75.7                    | 80.5                    | 788.7                    | 90.28                   |
| 13:30 | 33.8                    | 52.0                   | 74.5                     | 79.6                   | 81.4                   | 84.2                   | 76.8                   | 80.2                   | 62.9                   | 65.8                   | 64.2                    | 68.1                    | 73.2                    | 535.7                    | 80.44                   |
| 14:00 | 34.3                    | 55.9                   | 72.0                     | 82.6                   | 83.5                   | 85.1                   | 85.2                   | 83.0                   | 64.1                   | 68.7                   | 68.8                    | 70.5                    | 72.6                    | 755.4                    | 83.88                   |
| 14:30 | 35.3                    | 53.4                   | 68.6                     | 76.7                   | 77.8                   | 80.1                   | 70.5                   | 77.1                   | 60.2                   | 64.1                   | 62.4                    | 66.4                    | 71.0                    | 425.5                    | 76.44                   |
| 15:00 | 35.3                    | 51.4                   | 66.4                     | 73.6                   | 74.3                   | 75.5                   | 70.0                   | 73.6                   | 58.0                   | 62.3                   | 60.9                    | 63.2                    | 67.3                    | 530.1                    | 73.4                    |
| 15:30 | 35.5                    | 50.9                   | 64.3                     | 70.5                   | 71.1                   | 72.6                   | 66.9                   | 70.6                   | 56.1                   | 59.9                   | 59.3                    | 61.3                    | 63.5                    | 415.3                    | 70.34                   |
| 16:00 | 35.5                    | 47.7                   | 58.8                     | 62.7                   | 63.0                   | 64.4                   | 59.8                   | 62.7                   | 51.6                   | 54.7                   | 53.3                    | 56.0                    | 57.1                    | 297.6                    | 62.52                   |
| 16:30 | 35.5                    | 45.1                   | 50.9                     | 54.2                   | 54.2                   | 54.9                   | 53.3                   | 54.2                   | 46.4                   | 48.8                   | 47.5                    | 50.2                    | 51.1                    | 150.1                    | 54.16                   |
| 17:00 | 36.6                    | 43.1                   | 47.3                     | 50.1                   | 50.0                   | 49.9                   | 50.0                   | 50.7                   | 43.6                   | 46.3                   | 45.8                    | 46.9                    | 46.8                    | 81.1                     | 50.14                   |

### Test No.3 - Trapezoidal corrugated plate 30-05-22 ( $U = 1.5 \text{ m/s} \pm 0.1$ )

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 30.3                    | 39.7                   | 42.3                     | 44.8                   | 45.7                   | 43.8                   | 48.4                   | 47.3                   | 38.2                   | 42.9                   | 42.1                    | 42.3                    | 42.4                    | 225.8                    | 46                      |
| 8:00  | 33.1                    | 42.8                   | 49.6                     | 51.9                   | 53.1                   | 52.1                   | 57.7                   | 56.1                   | 43.4                   | 49.5                   | 47.3                    | 48.8                    | 49.9                    | 322.8                    | 54.18                   |
| 8:30  | 34.2                    | 46.3                   | 56.5                     | 59.0                   | 61.5                   | 59.0                   | 66.3                   | 64.4                   | 48.2                   | 55.7                   | 55.7                    | 55.1                    | 56.7                    | 424.1                    | 62.04                   |
| 9:00  | 34.3                    | 48.7                   | 63.3                     | 66.7                   | 71.0                   | 67.4                   | 73.7                   | 72.6                   | 53.1                   | 65.3                   | 64.9                    | 60.7                    | 63.8                    | 516.9                    | 70.28                   |
| 9:30  | 36.3                    | 50.7                   | 69.4                     | 71.9                   | 77.3                   | 74.2                   | 81.2                   | 81.2                   | 57.0                   | 68.2                   | 68.9                    | 65.9                    | 70.3                    | 605.3                    | 77.16                   |
| 10:00 | 38.0                    | 53.6                   | 74.0                     | 77.4                   | 82.8                   | 79.6                   | 86.1                   | 85.9                   | 60.3                   | 72.1                   | 70.8                    | 70.5                    | 76.1                    | 684.4                    | 82.36                   |
| 10:30 | 38.0                    | 54.6                   | 76.0                     | 77.3                   | 84.6                   | 81.5                   | 87.9                   | 88.3                   | 62.4                   | 73.0                   | 71.8                    | 72.8                    | 77.8                    | 744.2                    | 83.92                   |
| 11:00 | 38.0                    | 60.1                   | 77.6                     | 82.3                   | 88.6                   | 85.7                   | 92.5                   | 91.1                   | 65.5                   | 76.5                   | 74.3                    | 75.4                    | 81.6                    | 789.4                    | 88.04                   |
| 11:30 | 38.0                    | 60.5                   | 79.1                     | 85.4                   | 93.2                   | 88.5                   | 95.2                   | 95.8                   | 67.3                   | 77.9                   | 74.4                    | 77.7                    | 82.1                    | 829.6                    | 91.62                   |
| 12:00 | 38.0                    | 61.4                   | 81.5                     | 84.4                   | 91.4                   | 87.1                   | 93.7                   | 94.2                   | 66.8                   | 76.9                   | 75.8                    | 76.7                    | 78.6                    | 834.2                    | 90.16                   |
| 12:30 | 38.0                    | 60.9                   | 80.0                     | 84.1                   | 91.4                   | 87.0                   | 94.4                   | 94.5                   | 66.1                   | 77.2                   | 75.6                    | 76.6                    | 80.2                    | 831.4                    | 90.28                   |
| 13:00 | 38.0                    | 58.7                   | 78.0                     | 82.4                   | 89.3                   | 84.6                   | 86.2                   | 92.0                   | 64.9                   | 75.9                   | 73.5                    | 69.1                    | 79.4                    | 787.2                    | 86.9                    |
| 13:30 | 38.0                    | 60.6                   | 77.8                     | 82.2                   | 89.1                   | 85.1                   | 87.0                   | 92.0                   | 65.4                   | 75.7                   | 73.6                    | 68.5                    | 86.3                    | 747.6                    | 87.08                   |
| 14:00 | 38.0                    | 61.3                   | 76.1                     | 79.9                   | 86.4                   | 82.5                   | 80.0                   | 89.2                   | 64.2                   | 74.1                   | 73.0                    | 70.4                    | 77.9                    | 684.1                    | 83.6                    |
| 14:30 | 38.0                    | 58.4                   | 73.9                     | 77.6                   | 83.3                   | 80.3                   | 80.3                   | 85.9                   | 62.7                   | 72.5                   | 70.9                    | 70.1                    | 74.0                    | 625.9                    | 81.48                   |
| 15:00 | 38.0                    | 59.8                   | 71.9                     | 73.9                   | 78.9                   | 75.8                   | 73.4                   | 81.3                   | 60.2                   | 69.3                   | 66.9                    | 65.4                    | 70.4                    | 526.4                    | 76.66                   |
| 15:30 | 38.0                    | 56.6                   | 68.5                     | 68.3                   | 71.8                   | 69.5                   | 73.8                   | 73.7                   | 56.4                   | 63.8                   | 65.2                    | 64.1                    | 65.1                    | 400.8                    | 71.42                   |
| 16:00 | 38.0                    | 52.9                   | 64.5                     | 66.3                   | 68.1                   | 65.4                   | 68.4                   | 68.5                   | 54.4                   | 60.4                   | 58.2                    | 60.6                    | 61.3                    | 300.8                    | 67.34                   |
| 16:30 | 38.0                    | 52.8                   | 57.7                     | 65.9                   | 65.9                   | 65.3                   | 65.1                   | 64.9                   | 52.7                   | 57.7                   | 53.8                    | 60.5                    | 58.5                    | 200.4                    | 65.42                   |
| 17:00 | 38.0                    | 48.9                   | 54.1                     | 58.2                   | 58.0                   | 57.3                   | 57.4                   | 56.3                   | 48.6                   | 52.6                   | 48.9                    | 54.0                    | 52.2                    | 125.5                    | 57.44                   |
| 17:30 | 38.0                    | 46.8                   | 49.3                     | 50.1                   | 49.7                   | 49.2                   | 51.2                   | 50.3                   | 44.3                   | 47.4                   | 45.8                    | 48.2                    | 47.2                    | 80.3                     | 50.1                    |

### Test No.4 - Flat plate 06-05-22 ( $U = 2 \text{ m/s} \pm 0.1$ )

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 22.3                    | 28                     | 30.1                     | 30.3                   | 31.5                   | 31.7                   | 30.9                   | 32.5                   | 26.4                   | 28.8                   | 28.3                    | 28.9                    | 29.4                    | 229.8                    | 31.38                   |
| 8:00  | 22.5                    | 31                     | 34.6                     | 35.9                   | 38.7                   | 38.1                   | 37.2                   | 38.5                   | 30.8                   | 33                     | 31.7                    | 35.1                    | 35.5                    | 308.9                    | 37.68                   |
| 8:30  | 24.7                    | 33                     | 38.9                     | 39.2                   | 43.1                   | 43.3                   | 40.6                   | 42.9                   | 34.4                   | 36                     | 34.8                    | 38.5                    | 39.6                    | 342.3                    | 41.82                   |
| 9:00  | 24.6                    | 33                     | 39.1                     | 40.1                   | 43.9                   | 44.4                   | 41.2                   | 43.5                   | 35.2                   | 37.4                   | 36                      | 39.1                    | 40                      | 346.2                    | 42.62                   |
| 9:30  | 24.3                    | 34                     | 40.9                     | 41.6                   | 46.2                   | 47                     | 42.9                   | 46.1                   | 37.1                   | 39                     | 37.4                    | 40.9                    | 42.3                    | 384.5                    | 44.76                   |
| 10:00 | 24.8                    | 39                     | 48.4                     | 50.6                   | 58.7                   | 58.9                   | 53.2                   | 58.2                   | 43.6                   | 46                     | 44.5                    | 48.7                    | 51.1                    | 636.7                    | 55.92                   |
| 10:30 | 25.5                    | 41                     | 55.2                     | 58.1                   | 68                     | 69.1                   | 61.5                   | 68                     | 50                     | 52.7                   | 49.8                    | 55.7                    | 59.5                    | 788.2                    | 64.94                   |
| 11:00 | 26.9                    | 42                     | 59.9                     | 60                     | 70.8                   | 70.6                   | 62.9                   | 70.1                   | 50.5                   | 53.3                   | 48.6                    | 58.5                    | 62.1                    | 761.4                    | 66.88                   |
| 11:30 | 27.1                    | 43                     | 61.2                     | 62.9                   | 73.4                   | 73.5                   | 63.6                   | 72.7                   | 52.3                   | 55.2                   | 50.4                    | 58.4                    | 65.2                    | 851.3                    | 69.22                   |
| 12:00 | 29.2                    | 44                     | 62.9                     | 64                     | 74.3                   | 75.1                   | 59.6                   | 73.9                   | 53.3                   | 55.5                   | 50.5                    | 60.4                    | 66.5                    | 875.7                    | 69.38                   |
| 12:30 | 29.4                    | 47                     | 63.8                     | 68.5                   | 80.2                   | 80.9                   | 65.4                   | 79.5                   | 58                     | 60.1                   | 55.4                    | 65                      | 74.7                    | 884.3                    | 74.9                    |
| 13:00 | 29.7                    | 46                     | 62                       | 65.3                   | 76.2                   | 77.1                   | 64.7                   | 75.6                   | 55.8                   | 58.4                   | 53.8                    | 62.2                    | 70.5                    | 844.6                    | 71.78                   |
| 13:30 | 29.7                    | 49                     | 60.5                     | 69.9                   | 78.5                   | 80.1                   | 67.7                   | 77.9                   | 57                     | 60.8                   | 55.5                    | 66.5                    | 69.7                    | 764.3                    | 74.82                   |
| 14:00 | 29.8                    | 45                     | 60.3                     | 61.6                   | 70.7                   | 72.4                   | 59.9                   | 69.6                   | 52.9                   | 56                     | 51.6                    | 60.4                    | 63.2                    | 666.5                    | 66.84                   |
| 14:30 | 29.6                    | 43                     | 55.5                     | 59.5                   | 67.8                   | 69.7                   | 59                     | 67.1                   | 52.2                   | 54.6                   | 50.9                    | 59                      | 65.4                    | 540.8                    | 64.62                   |
| 15:00 | 30.1                    | 43                     | 52.5                     | 53.1                   | 59.5                   | 61.3                   | 52.3                   | 58.9                   | 46.8                   | 49.6                   | 46.6                    | 53.3                    | 53.9                    | 432.4                    | 57.02                   |
| 15:30 | 30.4                    | 42                     | 50.6                     | 54.2                   | 59.2                   | 60.9                   | 50.7                   | 58.1                   | 46.6                   | 49.5                   | 46.6                    | 53.5                    | 53.3                    | 365.5                    | 56.62                   |
| 16:00 | 30.8                    | 40                     | 46.4                     | 46                     | 52.9                   | 55                     | 44.4                   | 51.8                   | 42.5                   | 45.1                   | 43.1                    | 48.6                    | 48                      | 325.3                    | 50.02                   |
| 16:30 | 29.5                    | 35                     | 41.7                     | 41.5                   | 45.2                   | 46.9                   | 41.7                   | 45.1                   | 38.1                   | 42.6                   | 39.7                    | 41.7                    | 43.1                    | 226.8                    | 44.08                   |
| 17:00 | 29.3                    | 33                     | 38                       | 38.1                   | 40.2                   | 42.3                   | 37.3                   | 40.4                   | 35.1                   | 38.4                   | 36.5                    | 38.1                    | 38.6                    | 132.1                    | 39.66                   |
| 17:30 | 29.3                    | 32                     | 35.2                     | 35.4                   | 36.2                   | 37.2                   | 36                     | 35.5                   | 32                     | 34.8                   | 34.8                    | 37.7                    | 35                      | 84.5                     | 36.06                   |

**Test No.4 - U -corrugatedplate parallel to airflow 06-05-22 (U = 2 m/s ± 0.1)**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 22.3                    | 30                     | 34.6                     | 37.5                   | 40                     | 36.9                   | 38                     | 39.6                   | 31.5                   | 33.9                   | 32.6                    | 33.5                    | 34.1                    | 268.2                    | 38.4                    |
| 8:00  | 22.5                    | 31.7                   | 40                       | 42.4                   | 44.7                   | 40.9                   | 41.8                   | 42.8                   | 33.3                   | 34.5                   | 33.4                    | 38.1                    | 38.8                    | 324.1                    | 42.52                   |
| 8:30  | 24.7                    | 33                     | 42.1                     | 46.6                   | 48.2                   | 45.6                   | 44.5                   | 47.1                   | 37.2                   | 38.3                   | 36.5                    | 42.3                    | 41.1                    | 354.8                    | 46.4                    |
| 9:00  | 24.6                    | 34                     | 42.5                     | 46.7                   | 48.6                   | 46.7                   | 44.9                   | 47.4                   | 38.1                   | 39.3                   | 37                      | 41.8                    | 42.7                    | 354.6                    | 46.86                   |
| 9:30  | 24.3                    | 34.8                   | 44.8                     | 49.6                   | 51.3                   | 49.4                   | 47.3                   | 50                     | 40                     | 41.4                   | 38.5                    | 44.2                    | 44.9                    | 384.4                    | 49.52                   |
| 10:00 | 24.8                    | 38.7                   | 53.2                     | 62                     | 65                     | 61.8                   | 59.5                   | 63.3                   | 48.1                   | 49                     | 45.5                    | 53.5                    | 54.2                    | 645.7                    | 62.32                   |
| 10:30 | 25.5                    | 39.3                   | 60.2                     | 71.2                   | 75.2                   | 71.7                   | 67.5                   | 73.6                   | 55                     | 56.4                   | 51                      | 60                      | 63.4                    | 788.7                    | 71.84                   |
| 11:00 | 26.9                    | 40                     | 64                       | 74.8                   | 78.6                   | 75.7                   | 71.6                   | 76.4                   | 57.8                   | 59                     | 52.8                    | 62.9                    | 66.8                    | 758.9                    | 75.42                   |
| 11:30 | 27.1                    | 41.3                   | 63.7                     | 76.3                   | 80.1                   | 78                     | 71.2                   | 77.4                   | 58.9                   | 59.5                   | 54                      | 64.5                    | 68.2                    | 858.9                    | 76.6                    |
| 12:00 | 29.2                    | 42.2                   | 64.5                     | 78.4                   | 81.2                   | 80.1                   | 71.1                   | 78.8                   | 60                     | 60.6                   | 54.5                    | 70.2                    | 69.6                    | 866.2                    | 77.92                   |
| 12:30 | 29.4                    | 42.8                   | 66.2                     | 81.4                   | 84.3                   | 82.7                   | 72.2                   | 80.6                   | 61.6                   | 63.5                   | 56.3                    | 68.1                    | 69.9                    | 877.8                    | 80.24                   |
| 13:00 | 29.7                    | 46.3                   | 65.7                     | 80                     | 82.4                   | 81.7                   | 68.2                   | 79.4                   | 62                     | 63.7                   | 56.1                    | 67.5                    | 70                      | 823.5                    | 78.34                   |
| 13:30 | 29.7                    | 48.6                   | 67.2                     | 83.8                   | 85.1                   | 83.9                   | 76.3                   | 82.1                   | 63                     | 70.1                   | 59.9                    | 73                      | 73.7                    | 736.7                    | 82.24                   |
| 14:00 | 29.8                    | 41                     | 62.9                     | 72.6                   | 75.1                   | 75.5                   | 61.3                   | 72.6                   | 58.2                   | 59.8                   | 53.4                    | 65                      | 64.5                    | 640.3                    | 71.42                   |
| 14:30 | 29.6                    | 40.3                   | 63.2                     | 69                     | 71.5                   | 72.3                   | 62.1                   | 69.5                   | 56.4                   | 58.4                   | 52.1                    | 63.8                    | 62                      | 524.6                    | 68.88                   |
| 15:00 | 30.1                    | 40                     | 56.3                     | 62.3                   | 63.6                   | 64.3                   | 57.6                   | 61.7                   | 50.3                   | 52.9                   | 47.1                    | 60.4                    | 55.4                    | 423.6                    | 61.9                    |
| 15:30 | 30.4                    | 40.6                   | 51.1                     | 62.9                   | 63                     | 64.4                   | 57.7                   | 61.7                   | 50.7                   | 53.6                   | 48.2                    | 61.7                    | 55.7                    | 393.8                    | 61.94                   |
| 16:00 | 30.8                    | 39.1                   | 49.5                     | 56.9                   | 55.4                   | 57.3                   | 50.6                   | 54.2                   | 45.4                   | 47.7                   | 44.2                    | 52.1                    | 49.4                    | 310.4                    | 54.88                   |
| 16:30 | 29.5                    | 32.2                   | 45.4                     | 48.6                   | 49                     | 48.2                   | 42.2                   | 49                     | 41.2                   | 43.1                   | 39.8                    | 44.2                    | 44                      | 205.3                    | 47.4                    |
| 17:00 | 29.3                    | 32.8                   | 38.8                     | 40.3                   | 40.4                   | 40.6                   | 38.7                   | 40.3                   | 35.7                   | 37.2                   | 35.7                    | 42.7                    | 39.1                    | 118.7                    | 40.06                   |
| 17:30 | 29.3                    | 32.1                   | 35.8                     | 36.8                   | 36.8                   | 36.3                   | 36.1                   | 36.8                   | 32.4                   | 33.9                   | 34.1                    | 36.1                    | 25.8                    | 75.1                     | 36.56                   |

**Test No.4 - U -corrugatedplate anti-parallel to airflow 24-05-22 (U = 2 m/s ± 0.1)**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 23.5                    | 33.4                   | 38.5                     | 39.4                   | 39.5                   | 38.9                   | 39.8                   | 39.8                   | 33.3                   | 35.9                   | 35.9                    | 35.9                    | 35.4                    | 259.7                    | 39.48                   |
| 8:00  | 24.2                    | 34.2                   | 44.7                     | 48.0                   | 48.9                   | 48.5                   | 45.9                   | 47.6                   | 37.3                   | 40.5                   | 40.0                    | 40.8                    | 42.0                    | 337.2                    | 47.78                   |
| 8:30  | 25.1                    | 35.8                   | 48.3                     | 54.4                   | 56.0                   | 56.8                   | 53.9                   | 55.5                   | 42.5                   | 45.6                   | 46.0                    | 47.3                    | 49.3                    | 462.9                    | 55.32                   |
| 9:00  | 26.7                    | 38.8                   | 57.5                     | 60.2                   | 62.0                   | 64.4                   | 59.9                   | 61.4                   | 46.6                   | 49.3                   | 50.1                    | 51.9                    | 55.4                    | 548.3                    | 61.58                   |
| 9:30  | 26.9                    | 40.7                   | 63.2                     | 65.9                   | 68.1                   | 71.4                   | 64.8                   | 65.9                   | 50.1                   | 52.5                   | 52.7                    | 55.6                    | 60.8                    | 622.3                    | 67.22                   |
| 10:00 | 27.1                    | 42.9                   | 65.8                     | 70.5                   | 72.8                   | 76.1                   | 70.0                   | 71.0                   | 53.1                   | 56.2                   | 56.2                    | 59.4                    | 63.0                    | 715.2                    | 72.08                   |
| 10:30 | 28.6                    | 43.9                   | 67.7                     | 71.9                   | 76.3                   | 80.6                   | 71.1                   | 75.0                   | 55.5                   | 58.2                   | 57.6                    | 62.2                    | 66.6                    | 778.8                    | 74.98                   |
| 11:00 | 29.8                    | 45.8                   | 69.5                     | 75.5                   | 77.8                   | 83.4                   | 72.7                   | 75.1                   | 56.3                   | 58.7                   | 58.5                    | 62.8                    | 67.9                    | 810                      | 76.9                    |
| 11:30 | 31.4                    | 46.8                   | 71.1                     | 78.8                   | 81.7                   | 86.4                   | 77.0                   | 78.6                   | 57.5                   | 62.2                   | 59.6                    | 64.6                    | 69.4                    | 884.3                    | 80.5                    |
| 12:00 | 32.9                    | 47.0                   | 75.1                     | 81.5                   | 83.9                   | 87.5                   | 78.6                   | 80.1                   | 59.2                   | 62.6                   | 61.1                    | 66.2                    | 71.1                    | 874.6                    | 82.32                   |
| 12:30 | 34.1                    | 48.9                   | 76.2                     | 89.7                   | 91.3                   | 90.4                   | 81.4                   | 90.3                   | 66.2                   | 79.1                   | 65.3                    | 75.0                    | 74.6                    | 868.7                    | 88.62                   |
| 13:00 | 34.2                    | 54.2                   | 77.1                     | 99.7                   | 101.2                  | 100.8                  | 89.9                   | 103.4                  | 77.6                   | 90.6                   | 80.2                    | 86.1                    | 88.6                    | 862.2                    | 99                      |
| 13:30 | 35.2                    | 53.5                   | 75.7                     | 81.7                   | 84.8                   | 89.9                   | 77.0                   | 82.6                   | 62.2                   | 64.9                   | 64.7                    | 69.0                    | 72.5                    | 811                      | 83.2                    |
| 14:00 | 35.4                    | 52.4                   | 72.5                     | 78.7                   | 81.7                   | 86.0                   | 72.8                   | 80.0                   | 60.8                   | 63.7                   | 63.5                    | 67.6                    | 70.9                    | 721.3                    | 79.84                   |
| 14:30 | 35.4                    | 51.9                   | 70.8                     | 76.4                   | 78.7                   | 82.9                   | 68.5                   | 77.1                   | 58.9                   | 61.9                   | 62.8                    | 66.0                    | 67.8                    | 686.5                    | 76.72                   |
| 15:00 | 35.6                    | 43.5                   | 68.0                     | 65.5                   | 68.2                   | 73.5                   | 60.6                   | 66.0                   | 53.6                   | 55.3                   | 57.2                    | 58.6                    | 62.2                    | 573.1                    | 66.76                   |
| 15:30 | 35.7                    | 45.2                   | 63.7                     | 62.3                   | 68.1                   | 71.8                   | 58.9                   | 67.2                   | 52.5                   | 56.0                   | 55.1                    | 58.2                    | 62.3                    | 477.3                    | 65.66                   |
| 16:00 | 36.2                    | 43.9                   | 57.4                     | 58.1                   | 58.8                   | 63.4                   | 58.0                   | 61.7                   | 49.3                   | 52.2                   | 51.9                    | 54.2                    | 56.9                    | 382.6                    | 60                      |
| 16:30 | 36.5                    | 44.9                   | 50.9                     | 52.4                   | 53.3                   | 54.9                   | 48.3                   | 55.4                   | 42.6                   | 48.5                   | 48.8                    | 49.9                    | 51.3                    | 291.8                    | 52.86                   |
| 17:00 | 36.3                    | 42.3                   | 47.1                     | 49.5                   | 49.2                   | 49.3                   | 49.6                   | 47.6                   | 40.3                   | 42.8                   | 53.7                    | 44.8                    | 47.3                    | 191.7                    | 49.04                   |
| 17:30 | 35.6                    | 40.9                   | 43.2                     | 42.6                   | 43.1                   | 43.5                   | 44.2                   | 42.1                   | 38.1                   | 39.9                   | 39.4                    | 39.9                    | 41.8                    | 113.3                    | 43.1                    |

**Test No.4 - Trapezoidal corrugated plate 31-05-22 ( $U = 2 \text{ m/s} \pm 0.1$ )**

| Time  | T <sub>in</sub><br>(°C) | T <sub>1</sub><br>(°C) | T <sub>out</sub><br>(°C) | T <sub>3</sub><br>(°C) | T <sub>4</sub><br>(°C) | T <sub>5</sub><br>(°C) | T <sub>6</sub><br>(°C) | T <sub>7</sub><br>(°C) | T <sub>8</sub><br>(°C) | T <sub>9</sub><br>(°C) | T <sub>10</sub><br>(°C) | T <sub>11</sub><br>(°C) | T <sub>12</sub><br>(°C) | I<br>(w/m <sup>2</sup> ) | T <sub>ap</sub><br>(°C) |
|-------|-------------------------|------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------------|
| 7:30  | 30.1                    | 39.3                   | 45.4                     | 45.2                   | 48.4                   | 46.9                   | 50.0                   | 50.0                   | 39.5                   | 44.6                   | 43.7                    | 42.8                    | 43.0                    | 291.6                    | 48.1                    |
| 8:00  | 32.3                    | 38.8                   | 50.6                     | 49.9                   | 52.7                   | 53.2                   | 55.3                   | 54.7                   | 41.7                   | 48.7                   | 46.0                    | 49.0                    | 50.5                    | 392.3                    | 53.16                   |
| 8:30  | 33.2                    | 41.3                   | 57.9                     | 58.9                   | 62.4                   | 61.6                   | 62.4                   | 64.9                   | 48.3                   | 55.0                   | 55.9                    | 54.6                    | 56.1                    | 487.2                    | 62.04                   |
| 9:00  | 35.2                    | 45.2                   | 63.0                     | 64.9                   | 70.6                   | 71.3                   | 69.6                   | 72.5                   | 53.5                   | 60.5                   | 61.0                    | 60.5                    | 63.5                    | 590.7                    | 69.78                   |
| 9:30  | 36.3                    | 45.6                   | 68.4                     | 64.2                   | 71.2                   | 72.0                   | 69.4                   | 74.4                   | 55.4                   | 61.2                   | 60.3                    | 62.5                    | 68.4                    | 687.4                    | 70.24                   |
| 10:00 | 36.5                    | 47.7                   | 69.3                     | 69.3                   | 76.1                   | 79.1                   | 73.5                   | 79.8                   | 57.4                   | 64.7                   | 62.0                    | 65.7                    | 69.5                    | 740.5                    | 75.56                   |
| 10:30 | 38.0                    | 47.9                   | 72.8                     | 63.4                   | 69.7                   | 72.4                   | 65.7                   | 73.6                   | 55.6                   | 60.2                   | 58.9                    | 62.1                    | 66.7                    | 822.3                    | 68.96                   |
| 11:00 | 38.1                    | 53.5                   | 77.0                     | 79.2                   | 85.9                   | 88.5                   | 88.2                   | 90.1                   | 63.8                   | 74.0                   | 70.6                    | 75.9                    | 78.8                    | 842.8                    | 86.38                   |
| 11:30 | 38.2                    | 52.0                   | 78.1                     | 74.9                   | 83.1                   | 86.2                   | 82.7                   | 85.5                   | 62.5                   | 70.4                   | 67.8                    | 72.5                    | 76.4                    | 858.9                    | 82.48                   |
| 12:00 | 38.4                    | 53.3                   | 79.2                     | 77.0                   | 84.0                   | 86.5                   | 85.0                   | 86.9                   | 61.9                   | 71.5                   | 67.9                    | 72.9                    | 77.0                    | 856.7                    | 83.88                   |
| 12:30 | 38.8                    | 57.3                   | 80.2                     | 85.6                   | 92.4                   | 92.5                   | 91.1                   | 94.2                   | 66.7                   | 78.2                   | 75.1                    | 77.9                    | 82.7                    | 828.4                    | 91.16                   |
| 13:00 | 39.0                    | 57.1                   | 80.0                     | 89.5                   | 95.2                   | 95.5                   | 94.7                   | 97.5                   | 68.7                   | 81.5                   | 80.1                    | 80.9                    | 84.4                    | 806.1                    | 94.48                   |
| 13:30 | 38.6                    | 53.0                   | 76.5                     | 76.9                   | 82.6                   | 84.1                   | 83.6                   | 83.8                   | 61.7                   | 70.0                   | 67.1                    | 71.0                    | 74.7                    | 695.4                    | 82.2                    |
| 14:00 | 38.6                    | 55.9                   | 74.6                     | 73.3                   | 78.7                   | 80.1                   | 72.2                   | 80.2                   | 60.8                   | 67.6                   | 65.1                    | 67.4                    | 70.9                    | 676.9                    | 76.9                    |
| 14:30 | 38.6                    | 52.8                   | 72.4                     | 71.0                   | 76.3                   | 79.7                   | 68.3                   | 79.2                   | 60.1                   | 65.3                   | 63.6                    | 65.3                    | 69.8                    | 571.1                    | 74.9                    |
| 15:00 | 39.0                    | 57.1                   | 70.3                     | 73.2                   | 77.4                   | 78.0                   | 72.2                   | 78.6                   | 59.2                   | 67.6                   | 64.9                    | 66.0                    | 70.1                    | 516.3                    | 75.88                   |
| 15:30 | 39.0                    | 56.0                   | 66.2                     | 67.2                   | 71.8                   | 72.4                   | 71.0                   | 73.8                   | 57.1                   | 64.9                   | 62.8                    | 64.6                    | 68.4                    | 374.4                    | 71.24                   |
| 16:00 | 39.0                    | 53.8                   | 62.1                     | 63.4                   | 64.8                   | 65.7                   | 69.5                   | 68.1                   | 54.5                   | 61.2                   | 59.0                    | 63.5                    | 60.4                    | 274.8                    | 66.3                    |
| 16:30 | 39.2                    | 52.8                   | 56.8                     | 58.2                   | 59.2                   | 59.5                   | 60.6                   | 59.5                   | 50.0                   | 54.4                   | 53.3                    | 57.2                    | 55.0                    | 192.3                    | 59.4                    |
| 17:00 | 39.4                    | 49.9                   | 52.7                     | 53.1                   | 53.3                   | 52.8                   | 55.0                   | 53.8                   | 47.7                   | 50.6                   | 48.9                    | 52.3                    | 50.1                    | 140.3                    | 53.6                    |
| 17:30 | 39.3                    | 49.1                   | 45.7                     | 49.4                   | 49.3                   | 48.6                   | 51.0                   | 49.9                   | 45.6                   | 47.7                   | 46.7                    | 48.9                    | 48.1                    | 76.9                     | 49.64                   |

# Appendix C

## Theoretical results

### Test No.1 - Flat plate

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 65.8                | 29.3               | 36.52         | 80.65              | 0.002 | 0.5   | 1008           | 0.0011 | 40.493         | 638   | 0.5            | 13%    |
| 12:00 | 82.1                | 32.5               | 49.64         | 99.23              | 0.002 | 0.5   | 1010           | 0.0011 | 55.150         | 862.0 | 0.5            | 13%    |
| 16:00 | 52.7                | 32.0               | 20.68         | 58.21              | 0.002 | 0.5   | 1007           | 0.0011 | 22.907         | 255.0 | 0.5            | 18%    |

### Test No.1 - U -corrugatedplate parallel to airflow

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I   | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-----|----------------|--------|
| 9:00  | 66.6                | 29.3               | 37.32         | 79.38              | 0.002 | 0.5   | 1008           | 0.0011 | 41.380         | 615 | 0.5            | 13%    |
| 12:00 | 80.4                | 32.8               | 47.63         | 97.69              | 0.002 | 0.5   | 1009           | 0.0011 | 52.865         | 895 | 0.5            | 12%    |
| 16:00 | 56.3                | 32.0               | 24.29         | 61.68              | 0.002 | 0.5   | 1008           | 0.0011 | 26.933         | 263 | 0.5            | 20%    |

### Test No.1 - U -corrugatedplate anti-parallel to airflow

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 75.5                | 29.1               | 46.35         | 84.36              | 0.002 | 0.5   | 1009           | 0.0011 | 51.444         | 549.6 | 0.5            | 19%    |
| 12:00 | 83.2                | 33.2               | 49.96         | 101.24             | 0.002 | 0.5   | 1010           | 0.0011 | 55.506         | 842.1 | 0.5            | 13%    |
| 16:00 | 74.3                | 35.6               | 38.67         | 82.34              | 0.002 | 0.5   | 1009           | 0.0011 | 42.920         | 375.8 | 0.5            | 23%    |

### Test No.1 - Trapezoidal corrugated plate

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 70.3                | 30.3               | 39.98         | 81.54              | 0.002 | 0.5   | 1009           | 0.0011 | 44.374         | 532.8 | 0.5            | 17%    |
| 12:00 | 83.4                | 32.1               | 51.29         | 103.32             | 0.002 | 0.5   | 1010           | 0.0011 | 56.983         | 860.6 | 0.5            | 13%    |
| 16:00 | 72.7                | 34.4               | 38.28         | 88.24              | 0.002 | 0.5   | 1009           | 0.0011 | 42.487         | 370.4 | 0.5            | 23%    |

### Test No.2 - Flat plate

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 63.4                | 25.1               | 38.32         | 69.95              | 0.002 | 1     | 1008           | 0.0023 | 88.841         | 717   | 0.5            | 25%    |
| 12:00 | 72.2                | 29.0               | 43.21         | 88.69              | 0.002 | 1     | 1009           | 0.0023 | 100.277        | 841.8 | 0.5            | 24%    |
| 16:00 | 49.6                | 30.9               | 18.66         | 57.32              | 0.002 | 1     | 1007           | 0.0023 | 43.218         | 250.7 | 0.5            | 34%    |

**Test No.2 - U -corrugatedplate parallel to airflow**

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 62.7                | 25.1               | 37.55         | 74.22              | 0.002 | 1     | 1008           | 0.0023 | 87.056         | 680.8 | 0.5            | 26%    |
| 12:00 | 74.0                | 31.5               | 42.51         | 89.32              | 0.002 | 1     | 1009           | 0.0023 | 98.653         | 797.2 | 0.5            | 25%    |
| 16:00 | 55.2                | 30.9               | 24.32         | 56.34              | 0.002 | 1     | 1007           | 0.0023 | 56.328         | 245.8 | 0.5            | 46%    |

**Test No.2 - U -corrugatedplate anti-parallel to airflow**

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 73.3                | 32.1               | 41.22         | 79.63              | 0.002 | 1     | 1009           | 0.0023 | 95.659         | 534.9 | 0.5            | 36%    |
| 12:00 | 85.1                | 37.5               | 47.61         | 102.3              | 0.002 | 1     | 1010           | 0.0023 | 110.598        | 806.5 | 0.5            | 27%    |
| 16:00 | 71.5                | 39.3               | 32.24         | 69.92              | 0.002 | 1     | 1009           | 0.0023 | 74.819         | 325.8 | 0.5            | 46%    |

**Test No.2 - Trapezoidal corrugated plate**

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 64.1                | 32.3               | 31.75         | 69.32              | 0.002 | 1     | 1008           | 0.0023 | 73.609         | 518.3 | 0.5            | 28%    |
| 12:00 | 84.1                | 38.4               | 45.67         | 97.62              | 0.002 | 1     | 1010           | 0.0023 | 106.091        | 851.7 | 0.5            | 25%    |
| 16:00 | 69.9                | 39.5               | 30.41         | 78.33              | 0.002 | 1     | 1009           | 0.0023 | 70.572         | 400.2 | 0.5            | 35%    |

**Test No.3 - Flat plate**

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 60.5                | 31.2               | 29.33         | 78.35              | 0.002 | 1.5   | 1008           | 0.0034 | 100.520        | 488.8 | 0.5            | 41%    |
| 12:00 | 79.2                | 36.5               | 42.71         | 94.23              | 0.002 | 1.5   | 1009           | 0.0034 | 146.521        | 846.6 | 0.5            | 35%    |
| 16:00 | 57.4                | 37.7               | 19.66         | 59.34              | 0.002 | 1.5   | 1008           | 0.0034 | 67.379         | 279.2 | 0.5            | 48%    |

**Test No.3 - U -corrugatedplate parallel to airflow**

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 62.5                | 31.2               | 31.29         | 74.21              | 0.002 | 1.5   | 1008           | 0.0034 | 107.237        | 535   | 0.5            | 40%    |
| 12:00 | 85.1                | 36.5               | 48.62         | 98.62              | 0.002 | 1.5   | 1010           | 0.0034 | 166.961        | 885.3 | 0.5            | 38%    |
| 16:00 | 62.1                | 37.7               | 24.35         | 71.22              | 0.002 | 1.5   | 1008           | 0.0034 | 83.452         | 270.2 | 0.5            | 62%    |

**Test No.3 - U -corrugatedplate anti-parallel to airflow**

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 67.4                | 30.1               | 37.25         | 72.45              | 0.002 | 1.5   | 1008           | 0.0034 | 127.663        | 480.7 | 0.5            | 53%    |
| 12:00 | 84.8                | 33.5               | 51.32         | 95.32              | 0.002 | 1.5   | 1010           | 0.0034 | 176.233        | 720.1 | 0.5            | 49%    |
| 16:00 | 64.5                | 35.5               | 28.99         | 67.85              | 0.002 | 1.5   | 1008           | 0.0034 | 99.355         | 287.6 | 0.5            | 69%    |

### Test No.3 - Trapezoidal corrugated plate

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-<br>m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-----------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 69.1                | 34.3               | 34.77         | 78.62              | 0.002 | 1.5       | 1009           | 0.0034 | 119.282        | 490.2 | 0.5            | 49%    |
| 12:00 | 86.2                | 38.0               | 48.19         | 94.62              | 0.002 | 1.5       | 1010           | 0.0034 | 165.484        | 773.2 | 0.5            | 43%    |
| 16:00 | 67.4                | 38.0               | 29.36         | 71.32              | 0.002 | 1.5       | 1008           | 0.0034 | 100.623        | 328.8 | 0.5            | 61%    |

### Test No.4 - Flat plate

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-<br>m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-----------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 43.9                | 24.6               | 19.32         | 47.86              | 0.002 | 2         | 1007           | 0.0046 | 89.494         | 346.2 | 0.5            | 52%    |
| 12:00 | 67.9                | 29.2               | 38.65         | 73.51              | 0.002 | 2         | 1008           | 0.0046 | 179.212        | 875.7 | 0.5            | 41%    |
| 16:00 | 48.9                | 30.8               | 18.12         | 64.21              | 0.002 | 2         | 1007           | 0.0046 | 83.935         | 325.3 | 0.5            | 52%    |

### Test No.4 - U -corrugatedplate parallel to airflow

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-<br>m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-----------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 45.8                | 24.6               | 21.23         | 57.26              | 0.002 | 2         | 1007           | 0.0046 | 98.342         | 354.6 | 0.5            | 55%    |
| 12:00 | 68.7                | 29.2               | 39.52         | 79.32              | 0.002 | 2         | 1009           | 0.0046 | 183.428        | 866.2 | 0.5            | 42%    |
| 16:00 | 54.3                | 30.8               | 23.51         | 58.12              | 0.002 | 2         | 1007           | 0.0046 | 108.903        | 280.4 | 0.5            | 78%    |

### Test No.4 - U -corrugatedplate anti-parallel to airflow

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-<br>m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-----------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 64.3                | 26.7               | 37.62         | 67.23              | 0.002 | 2         | 1008           | 0.0046 | 174.436        | 538.3 | 0.5            | 65%    |
| 12:00 | 81.0                | 32.9               | 48.11         | 85.62              | 0.002 | 2         | 1010           | 0.0046 | 223.519        | 820.6 | 0.5            | 54%    |
| 16:00 | 64.0                | 36.2               | 27.8          | 64.77              | 0.002 | 2         | 1008           | 0.0046 | 128.903        | 321.9 | 0.5            | 80%    |

### Test No.4 - Trapezoidal corrugated plate

| Time  | T <sub>out</sub> °C | T <sub>in</sub> °C | $\Delta T$ °C | T <sub>ap</sub> °C | Ad    | U-<br>m/s | C <sub>P</sub> | m'     | Q <sub>u</sub> | I     | A <sub>c</sub> | $\eta$ |
|-------|---------------------|--------------------|---------------|--------------------|-------|-----------|----------------|--------|----------------|-------|----------------|--------|
| 9:00  | 66.4                | 35.2               | 31.24         | 73.44              | 0.002 | 2         | 1008           | 0.0046 | 144.854        | 538.7 | 0.5            | 54%    |
| 12:00 | 84.0                | 38.4               | 45.64         | 89.11              | 0.002 | 2         | 1010           | 0.0046 | 212.043        | 856.7 | 0.5            | 50%    |
| 16:00 | 68.0                | 39.0               | 28.99         | 69.22              | 0.002 | 2         | 1008           | 0.0046 | 134.421        | 274.8 | 0.5            | 98%    |

## Comparative Analysis of Thermal Performance in Dual-Flow Solar Air Heaters Utilizing Diverse Absorber Plates

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### ABSTRACT

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#### Keywords:

*solar air heater, dual-flow, flat plate, corrugated plate, trapezoidal plate, computational fluid dynamics, thermal performance*

This study undertakes an experimental and computational evaluation of a dual-flow solar air heater (SAH) equipped with three distinct types of absorber plates: flat, trapezoidal, and U-corrugated. Experiments were conducted under actual outdoor weather conditions in Baghdad, Iraq (33.31°N, 44.36°E) during varying days in April and May 2022. The collector, oriented south (surface azimuth angle = zero due south) and tilted at an angle of 30° from the horizontal, was scrutinized under four different airflow rates: 0.0011, 0.0023, 0.0036, and 0.0046 kg/s. Computational simulations of the four absorber plates were performed using ANSYS Fluent software to ascertain and validate thermal efficiencies and performance characteristics. Findings indicate that at an airflow rate of 0.0046 kg/s, the thermal efficiencies of the SAHs with flat, U-corrugated, and trapezoidal plates were 43%, 51%, and 54% respectively. Additionally, a shift from parallel to anti-parallel airflow direction resulted in an increased thermal efficiency from 51% to 56%. It was determined that the optimal configuration was achieved with the U-corrugated plate in an anti-parallel airflow. The average efficiencies at the maximum airflow rate of 0.0046 kg/s were reported as 42.80% for the flat plate, 51.33% for the U-corrugated plate with parallel airflow, 54.38% for the trapezoidal plate with anti-parallel airflow, and 55.53% for the U-corrugated plate with anti-parallel airflow. Finally, a favorable alignment between the experimental and simulated results was observed, with an average discrepancy of 5.7% in thermal efficiency.

## 1. INTRODUCTION

Solar energy, a globally available renewable resource, holds great promise for a clean energy future. One method of harnessing this energy is through solar heaters, which convert solar energy into usable thermal power. However, the poor convection coefficient between the absorber plate's surface and the stream in a solar air heater (SAH) poses a significant challenge. Extensive research has been undertaken to identify the most efficient conventional and modified SAH designs that can suit a variety of needs [1]. Among a plethora of designs, U-corrugated and V-corrugated absorbers are often preferred due to their efficiency in energy capture. Several studies have explored the efficiency of these absorber geometries. Metwally et al. [2] examined a corrugated channel heater alongside five standard configurations and found that the ribbed conduit design outperformed the others, enhancing efficiency by 15%-43% at a solar irradiance of 950 W/m<sup>2</sup> and a flow rate of 0.01-0.1 kg/s. Similarly, Liu et al. [3] and Gao et al. [4] reported superior performance of V-corrugated and corrugated absorbers over flat plate heaters. Karim and Hawlader [5] and Choudhury and Garg [6] reached analogous conclusions in their experimental investigations. Certain parameters enhance the efficiency of U-corrugated solar heaters, as demonstrated by Gao et al. [7]. They derived that the height ratio and geometric ratio needed to exceed two and

one, respectively, and the inclination angle needed to be less than 40° to minimize heat loss due to natural convection. Furthermore, they found that employing U-corrugated plates increased turbulence, facilitating heat transfer within the airflow duct [4]. Solar heaters with specific design features have also been studied. Forson et al. [8] reported an enhancement in thermal efficiency with an increase in the depth ratios of single-pass solar air heaters (SPSAHs) and double-pass solar air heaters (DPSAHs). Similarly, the introduction of fins to the absorber surface has been shown to significantly improve the performance of DPSAHs [9]. The efficiency of SAHs with V-corrugated absorbers in single- and double-pass modes was found to be superior to that of flat plate SAHs [10]. The influence of solar irradiance and mass flow rates on the efficiency of finned double-pass SAHs was investigated by Fudholi et al. [11]. They discovered that the heater's maximum efficiency was attained at a mass flow rate of 0.09 kg/s and that a solar irradiance of 425-790 W/m<sup>2</sup> could provide a potential energy improvement of 740-1,070 W. Further modifications to the design of SAHs have been explored as well. The staggered baffles in a DPSAH was investigated by Ho et al. [12], who reported that the baffled expanded fins induced a turbulent flow pattern and enhanced the thermal efficiency of the DPSAH. A variety of SAH designs have been investigated in the literature, with corrugated and V-corrugated absorbers often emerging as

# CERTIFICATE OF ATTENDANCE

INTERNATIONAL AEGEAN SCIENTIFIC RESEARCH SYMPOSIUM 2021, DECEMBER 25TH -  
26TH, 2021 / ONLINE



This is to certify that

**Layth Thamer ZUBAIRI**

Attended and Presented Paper Entitled

**Hydrogen Production, Storage and Evaluation of Solar Energy  
Contribution**

ULUSLARARASI EGE BİLİMSSEL ARAŞTIRMALAR SEMPOZYUMU 2021, 25-26  
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***4<sup>th</sup> International Conference on Sustainable Engineering Techniques (ICSET 2022)***

Baghdad, Iraq, 5-6 October, 2022

Letter of Acceptance and Invitation

Ref: 148 Date: 4 / 8 / 2022

Paper ID: 210

Paper Title:

***Experimental and numerical investigation of double pass flow flat plate solar air heater***

Dear Layth Thamer Zubairi , Wisam A. M. Al-Shohani , Merdin Danişmaz ,  
Nabil J.Yasin

With heartiest congratulations I am pleased to inform you that based on the recommendations of the reviewers; your paper identified above has been accepted for publication and oral presentation by the *4<sup>th</sup> International Conference on Sustainable Engineering Techniques (ICSET 2022)*. Your paper will be published in the *AIP Conference Proceedings*.

Herewith, the Conference Organizing Committee sincerely invites you to present your paper at the conference to be held at the Middle Technical University / Engineering Technical College, Baghdad, Iraq, 5- 6 October, 2022.

We look forward to your participation in the ICSET 2022.

Yours sincerely,

Prof. Dr. Nabil Jamil Yasin

ICSET 2022 Organizing Committee, Baghdad, Iraq.

<https://icset4.tecb.mtu.edu.iq/>



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| Articles and Papers                                |                                                                                                                                                                                                                                                                                                                                                                   |
|----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Articles in International Refereed Journals</b> |                                                                                                                                                                                                                                                                                                                                                                   |
| 1.                                                 | Layth Thamer Zubairi, Merdin Danişmaz, Nabil J. Yasin , Wisam A. <sup>M</sup> . Al-Shohani. (2023). Comparative Analysis of Thermal Performance in Dual-Flow Solar Air Heaters Utilizing Diverse Absorber Plates. <i>International Journal of Heat and Technology</i> . <a href="https://doi.org/10.18280/ijht.410423">https://doi.org/10.18280/ijht.410423</a> . |
| 2.                                                 | Merdin Danismaz, Layth Thamer Zubairi, “Hydrogen Production, Storage and Evaluation of Solar Energy Contribution”, <i>Gelenbevi Scientific Research Journal (GSR Journal)</i> .                                                                                                                                                                                   |
| 3.                                                 | Layth Thamer Zubairi, Wisam A. M. Al-Shohani, Merdin Danismaz, Nabil J. Yasin. “Experimental and Numerical Investigation of Double Pass Flow Flat Plate Solar Air Heater”, 4th-ICSET 2022.                                                                                                                                                                        |