T.C.
MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN
PURE AND APPLIED SCIENCES

EXPERIMENTAL ANALYSIS OF THERMOSYPHON SOLAR HOT WATER HEATER INCLUDING SIMULATION MODEL VALIDATION

Murat ASLAN

THESIS
FOR THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

SUPERVISOR
Asist. Prof. Emre ALPMAN
Prof. Dr. Ing. Wilfried ZÖRNER

İSTANBUL 2011

T.C.
MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN
PURE AND APPLIED SCIENCES

EXPERIMENTAL ANALYSIS OF THERMOSYPHON SOLAR HOT WATER HEATER INCLUDING SIMULATION MODEL VALIDATION

Murat ASLAN
(524609002)

THESIS
FOR THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

SUPERVISOR
Asist. Prof. Emre ALPMAN
Prof. Dr. Ing. Wilfried ZÖRNER

İSTANBUL 2011

ACKNOWLEDGEMENT

This thesis was carried out at the Centre of Excellence for Renewable Energy Research at Ingolstadt University of Applied Sciences.

I would like to thank Prof. Wilfred Zörner and Sebastian Brandmayr for their excellent support and guidance. I also would like to thank Hermann Riess for his support and help.

I would like to thank Dr. Christoph Trinkl, Holger Müller, Christoph Reiter, Matthias Sonnleitner and Georg Häring for their friendship.

CONTENTS

PAGE

ÖZET

SİMULASYON MODEL OLMAK ÜZERE TERMOSİFON TİP GÜNEŞLİ SU ISITMA SİSTEMİNİN DENEYSEL ANALİZİ

Termosifon tip güneşli su ısıtma sistemleri dünyada yaygın olarak kullanılmaktadır. Özellikle ılıman iklimlerde, Akdeniz çevresindeki ülkelerde günlük sıcak su ihtiyacını karşılamasından dolayı tercih sebebidir. Diğer bir tercih sebebi ise sistemin yapısının teknik olarak basit olmasıdır. Pompaya ihtiyaç yoktur. Çalışma prensibi yoğunluk farkına dayanır. Kollektör içinde güneş radyasyonu esnasında ısınan akışkan yoğunluk farkından dolayı kollektörün üst kısmına yerleştirilen depolama tankına doğru hareket eder. Depolama tankında, akışkan ile kullanılabilir su arasında ısı transferi olduktan sonra soğuyan akışkan tankın alt tarafından kollektöre geri dönmektedir. Böylece kapalı bir çevrim oluşmaktadır.

Bu tez çalışması, termosifon tip güneşli su ısıtma sisteminin deneysel olarak optimizasyonunu içermektedir. Bu anlamda, kollektör ve depolama tankı üzerinde laboratuvar ortamında testler yapılmıştır. Kollektör testleri; absorban plaka içindeki akış dağılımının incelenmesi ve kollektör verimin incelenmesi testlerinden oluşmaktadır. Depolama tankı testleri ise; sıcak su verimi testlerinden oluşmaktadır. Ayrıca, depolama tankı çalışması, bilgisayar ortamında bir simulasyon programı kullanılarak, testlerden elde edilen bulguların doğrulamasını içermektedir.

Absorban plaka içindeki akış dağılımı, farklı debilerde ve giriş-çıkış konfigürasyonlarında, termografik bir kamera ile görüntülenmiştir. Elde edilen görüntülerde plaka içindeki akışın zayıf olduğu kısımlar incelenerek absorban plaka için optimum bir giriş-çıkış konfigürasyonu belirlenmiştir.

Kollektör verimi testlerinde bir solar simulator kullanılarak farklı debilerde verim eğrileri elde edilmiştir. Sonuç olarak, debinin, kollektör verimi üzerinde bir etkisi olmadığı görülmüştür.

Depolama tankı testlerinde, değişik şekillerde difüzör kullanılarak, depolama tankı içindeki sıcak su verimi incelenmiş ve optimum bir difuzör şekli belirlenmiştir. Elde edilen bulgular, bir simulasyon programı ile bilgisayar ortamında yapılan simulasyon çalışmalarıyla karşılaştırılıp bir doğrulama sağlanmıştır.

Aralık, 2011 **Murat ASLAN**

ABSTRACT

EXPERIMENTAL ANALYSIS OF THERMOSYPHON SOLAR HOT WATER HEATER INCLUDING SIMULATION MODEL VALIDATION

Thermosyphon solar hot water heaters are used all over the world. Especially, around the Mediterranean Sea, countries use thermosyphon systems due to their technically less complex structure compared to pumped systems and production of daily hot water is sufficient. There is no need to a pump because of its working principle. During the hours of sunshine, fluid within the collector is heated by solar radiation. The heated fluid becomes less dense than the fluid in the storage tank and flows through the collector risers and connecting pipes into the storage tank. In the storage tank there is a heat transfer between the tap water and the heated fluid. The cooled down fluid sinks down to the collector inlet. Hence, a continual circulation is created.

In this study, an optimisation of the thermosyphon system is aimed. Laboratory testing of the collector prototype and the storage tank were studied.

The collector tests include; a determination of the flow distribution inside the absorber plate and the efficiency curve. The flow distribution inside the absorber plate was visualised by a thermographic camera at the different flow rates and inlet-outlet configurations. By inspecting the flow distribution records an optimum inlet-outlet configuration was determined. Efficiency curve tests were carried out at different flow rates. As a result, it was observed that the flow rate does not have an influence on the collector performance.

Laboratory testing of the storage tank includes thermal stratification of water inside the tank. The storage tank studies also include a simulation validation of the results obtained from the tests. In the storage tank tests, the thermal stratification of the storage tank was observed using different diffuser shapes. An optimum diffuser shape was determined. Also, by using a computer based simulation, the storage tank test results were validated.

December, 2011 **Murat ASLAN**

SYMBOLS

a_1 : Linear Heat Loss Coefficient (W/mK)
a_2 : Parabolic Heat Loss Coefficient (W/m^{2}K)
A : Cross Sectional Area (m^2)
D : Diameter (m)
G : Irradiance, Incident Solar Flux (W/m^2)
ΔH : Height Difference between Collector and Storage Tank (m)
μ : Dynamic Viscosity (Ns/ m^2)
η : Efficiency (%)
η_0 : Zero Loss Efficiency (%)
Q : Flow Rate (m^3/s)
ρ : Density (kg/m^3)
Re : Reynolds Number
T_a : Ambient Air Temperature (˚C)
T_{in} : Inlet Temperature of Collector (˚C)
T_m : Mean Fluid Temperature (K)
T_{out} : Outlet Temperature of Collector (˚C)
T_{red} : Reduced Temperature (m^{2}K/W)
V : Velocity (m/s)

ABBREVIATIONS

CFD **:** Computational Fluid Dynamics
ICS **:** Integrated Collector Storage Systems
PV **:** Photovoltaic
SWH **:** Solar Water Heater
PP **:** Polypropylene
EPDM **:** Artificial Rubber
PVC **:** Polyvinylchloride
HDPE **:** High Density Polyethylene

FIGURES

PAGE NUMBER

TABLES

PAGE NUMBER

I. Introduction and Aim

Nowadays, renewable energies are very popular because they are clean and non-polluting. The countries which are in conformity with the Kyoto agreement need these energy sources in order to reduce CO_2 and other gaseous emissions.

Lots of studies have been carried out by universities and companies in order to reduce initial and maintenance costs and to increase the reliability and efficiency of the renewable energy systems.

“In developed countries, energy consumption in the building sector represents a major part of the total energy budget. In the European Union this is approximately equal to 40 % of the total energy consumption (Argiriou et al., 1997, Kalogirou, 2008). A considerable percentage of this amount is spent for hot water production. One way to reduce this amount of energy is to employ solar energy.” (Kalogirou, 2008)

Lots of countries have a high solar irradiation suitable for hot water production. Especially, the countries around the Mediterranean Sea show a high potential for the use of solar energy.

Thermosyphon systems or gravity or natural circulation systems are popular solar thermal application for hot water production. They are technically less complex and more cost effective than pumped system. “90 % of solar domestic hot water systems installed worldwide are thermosyphon systems” (Meyer J.P, 2006, Brandmayr and Zörner, 2007). “In the past, these systems have not been an object to research and development activities” (Brandmayr and Zörner, 2007).

“In spite of this lack of research, thermosyphon systems are currently becoming more and more interesting for Central European manufacturers of solar thermal components and systems. These manufacturers are confronted with increasingly saturated local markets and therefore look for possibilities in export, mainly concerning regions around the Mediterranean Sea. In these regions thermosyphon systems respond to the customers’ demands in an ideal manner, because the production of daily hot water is sufficient and there is no need for house heating. Thermosyphon systems replace the commonly used electrical water heaters” (Brandmayr and Zörner, 2007).

Figure I.1 Markets for Thermosyphon Systems around the Mediterranean Sea

This thesis is a part of research project on thermosyphon systems carried out at Ingolstadt University. "The research project is intended to develop a technically and aesthetically optimised thermosyphon system according to the two contradictory trends observed on the global thermosyphon market. On the one hand, it is necessary to reduce costs. On the other hand, the target markets are affected by permanently growing living standard, hence an increasing demand for comfort which results in higher requirements regarding system performance and storage. Additionally, design and aesthetics are equally becoming more and more important" (Brandmayr and Zörner, 2007).

The target of this research project is the development of a thermosyphon domestic hot water system that outperforms the state of the art systems at reduced production costs.

The goal of this thesis is the optimisation and simulation of storage tanks as well as the experimental optimisation of a solar collector.

II. General Background

II.I. Solar Energy Applications

Solar energy is used for lots of applications such as power production by photovoltaic (PV) or solar thermal systems. PV systems convert solar radiation directly into electrical current for power generation. Solar energy applications generally can be classified as shown in figure II.1.

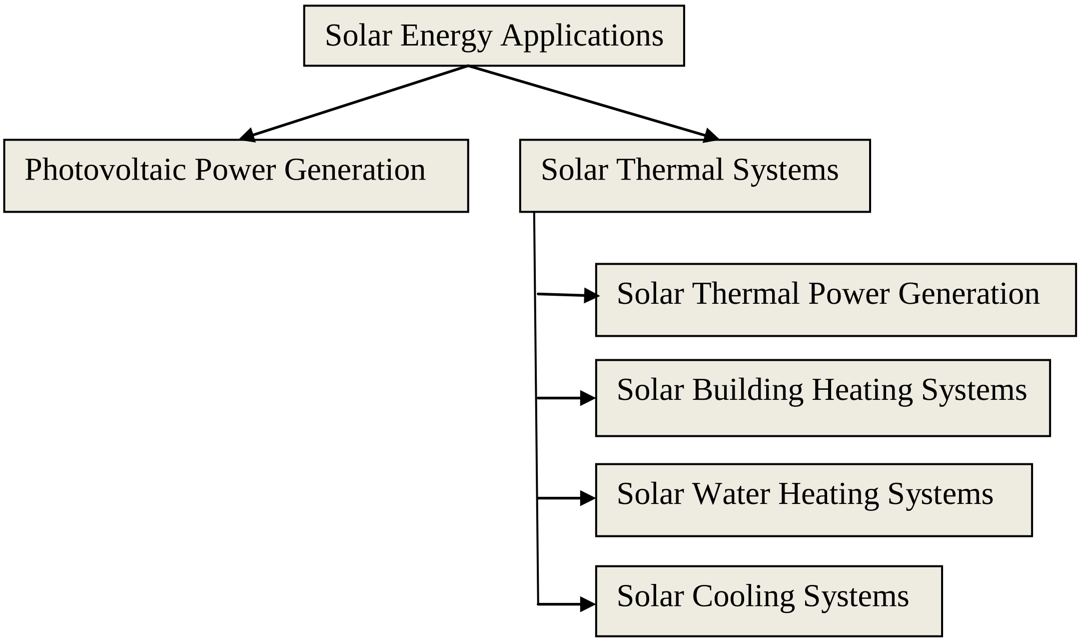


Figure II.1 Solar Energy Applications

II.2. Solar Water Heating Systems

Today, several million houses all over the world use solar water heating systems. These systems are a cost-effective and a reliable choice for hot water production.

A solar thermal system generally consists of one or more solar collectors, a storage tank and the connecting pipes between the collector and storage tank. The fluid inside the collector is heated by the sun and pumped to the storage tank in order to heat the domestic water inside the storage tank.

There are two type solar water heating system: direct and indirect system. In direct system, potable water is heated directly in the collector and pumped to the storage tank. In indirect system, the heat is absorbed by a heat transfer fluid inside the absorber and transferred to the heat exchanger (storage tank). In the storage tank the heat is transferred from heat transfer fluid to the potable, domestic or service water.

The heat transfer fluid is transported either naturally (passive) or by forced circulation (active systems). Natural circulation occurs by natural convection (thermosyphoning), whereas forced circulation systems use pumps or fans in case of solar air heaters.

There are five types of solar energy systems to heat domestic and service hot water as shown in figure II.2.

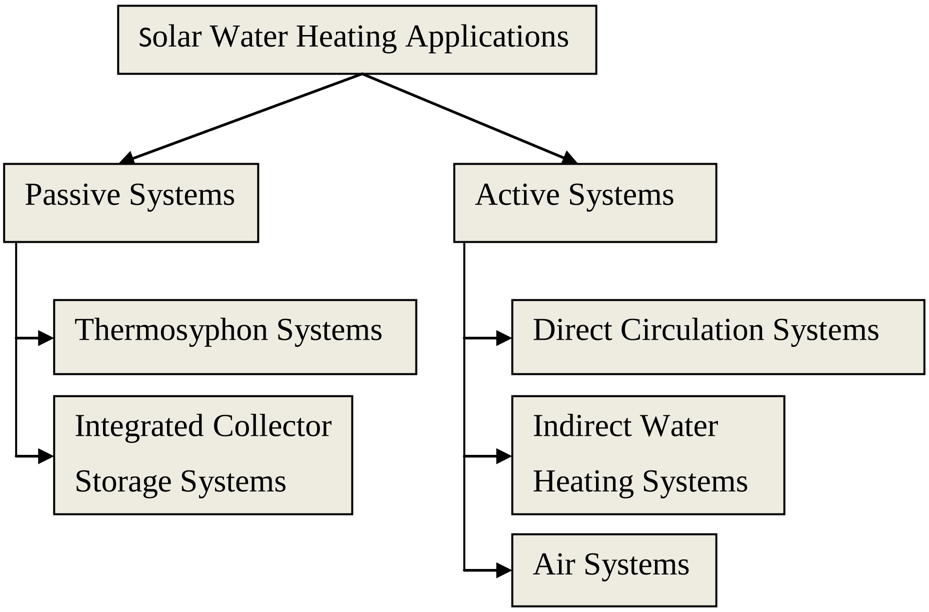


Figure II.2 Solar Water Heating Applications

II.3. Solar Thermal Collectors

The main part of a solar water heater (SWH) is the solar collector. It is special kind of heat exchanger. A collector absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a heat transfer fluid (water, non freezing liquid or air) inside the absorber. The main applications of solar thermal collectors are shown in figure II.3.

The solar collectors are exposed to all weather conditions. Due to this reason several protection measures against freezing and overheating have to be taken.

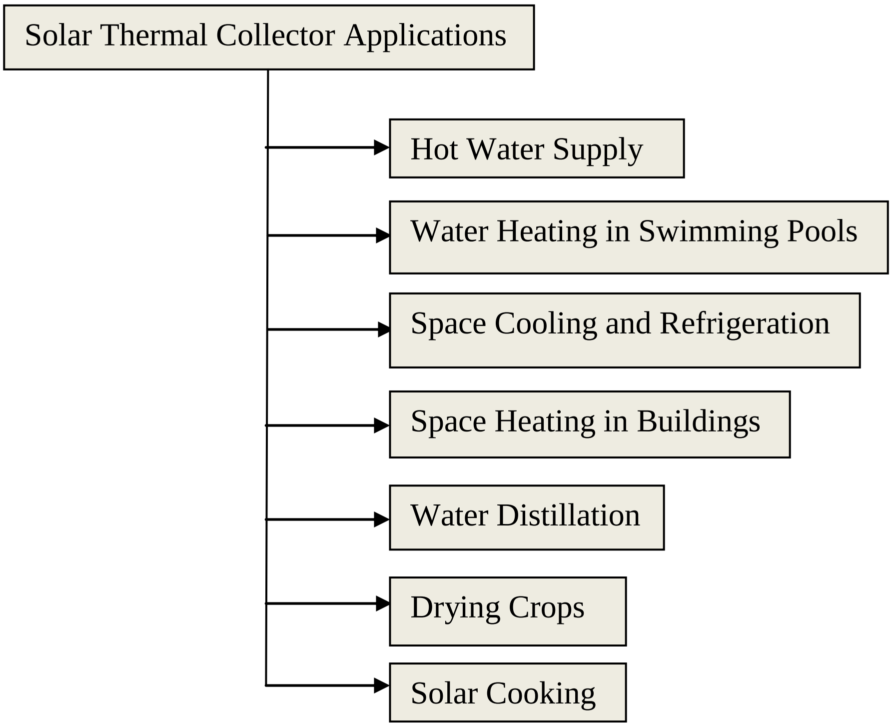


Figure II.3 Solar Thermal Collector Applications

There are two types of solar collectors: non-concentrating or stationary and concentrating collectors. Evacuated tube collectors and flat plate collectors are stationary collectors. Concentrating collectors use a mirrored surface to collect the sun light and concentrate it on a receiving surface. Examples are parabolic dishes and parabolic troughs.

Solar collectors can also be divided according to the temperature level produced: low-temperature collectors, medium temperature collectors and high-temperature collectors. Flat-plate collectors and evacuated tube collectors are used for low–temperature applications, like domestic hot water supply. Concentrating collectors are used for medium and high temperature applications like solar thermal power generation. Figure II.4 shows the classification of the solar collectors.

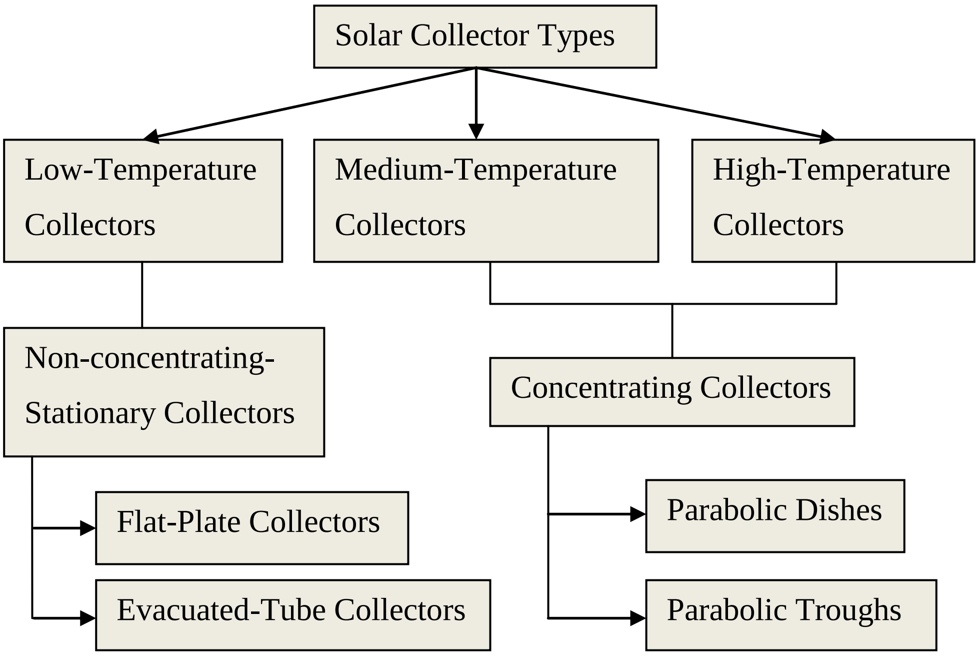


Figure II.4 Solar Collector Types

II.4. Flat-Plate Collectors

The major applications of flat-plate collectors are solar water heating, building heating, air conditioning and low temperature process heat.

When the solar radiation passes through a transparent cover and impinges on the absorber surface, a large amount of this energy is absorbed by the absorber plate and transferred to the fluid in the absorber. This heated fluid is pumped to the storage tank. A typical flat-plate collector is as shown in the figure II.5.

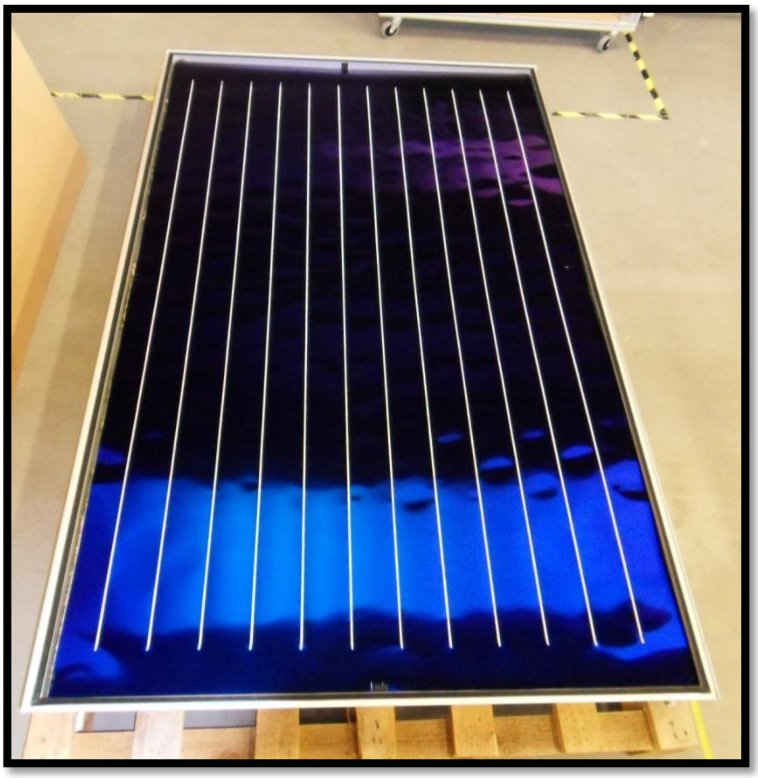


Figure II.5 Typical Flat-Plate Collector

A flat-plate collector generally consists of the following components as shown in figure II.6:

- Glazing: One or more sheets of glass or other radiation-transmitting materials
- Absorber plates: Flat, corrugated or grooved plates are attached to tubes, fins or passages. The plate may be integral with tubes.
- Tubes, fins or other passages: To conduct the heat transfer fluid from the inlet to the outlet. The tubes can be welded to the absorbing plate or be an integral part of the plate. Copper is commonly used as a tube material.
- Headers or manifolds: To discharge the fluid. Copper is also used for the header material.
- Insulation: To minimise the heat loss from the back and sides of the collector.
- Container or casing: To surround the other mentioned components and keep them free from dust, moisture, etc.

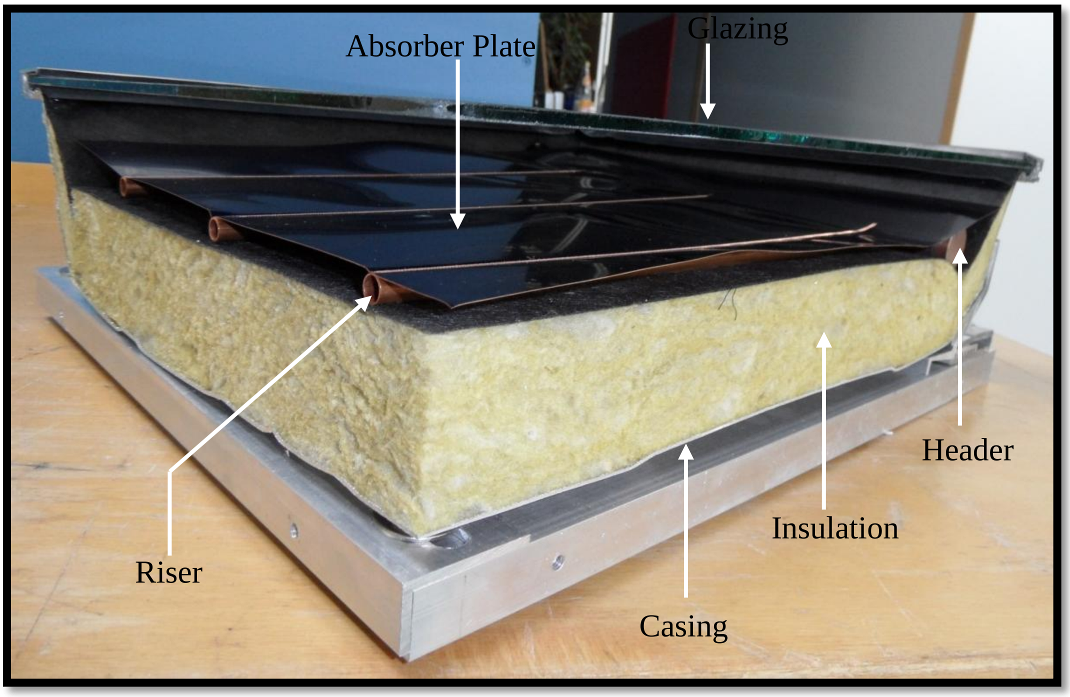


Figure II.6 Components of a Flat-Plate Collector

The backside of the absorber plate and side of the casing should be well insulated to reduce conduction losses.

A transparent cover (glazing) is used to reduce convection losses from the absorber plate. It also reduces radiation losses from the collector. Glass is generally used as transparent cover. It has high transmittance to solar short wave radiation, but it is nearly opaque to long wave thermal radiation emitted by the absorber plate as shown in figure II.7.

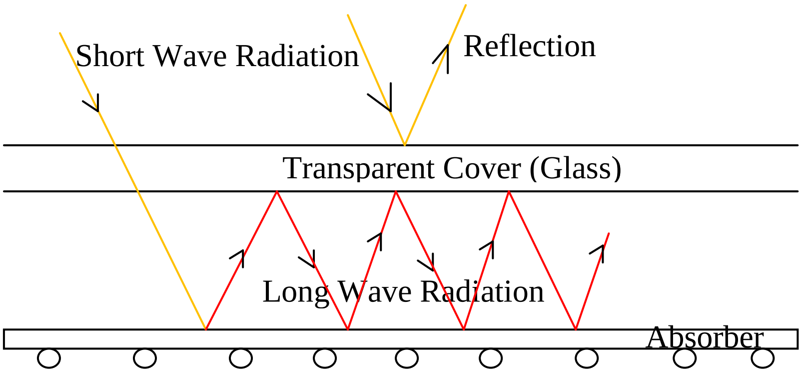


Figure II.7 Radiation on a Flat-Plate Collector

Some of the short wave radiation is reflected from the transparent cover and some is transmitted by the transparent cover as can be seen in figure II.7. Transmitted short wave radiation is absorbed by the absorber sheet. Some of the absorbed radiation is emitted as long wave radiation (sensed as heat) by the absorber sheet. This emitted radiation is not transmitted by the transparent cover because of its opaque property. Hence, the heat is preserved between the transparent cover and the absorber sheet.

Solar energy applications depend on the radiation. For most of solar energy applications, only thermal radiation is important. Thermal radiation is the electromagnetic energy that is propagated through space at the speed of light.

The spectrum of electromagnetic radiation is divided into wavelength bands as shown in figure II.8. Solar energy applications are in the ultraviolet to near-infrared range from 0.29 to approximately 25 μm. This includes the visible spectrum (light being a particular portion of the electromagnetic spectrum which the human eye responds).

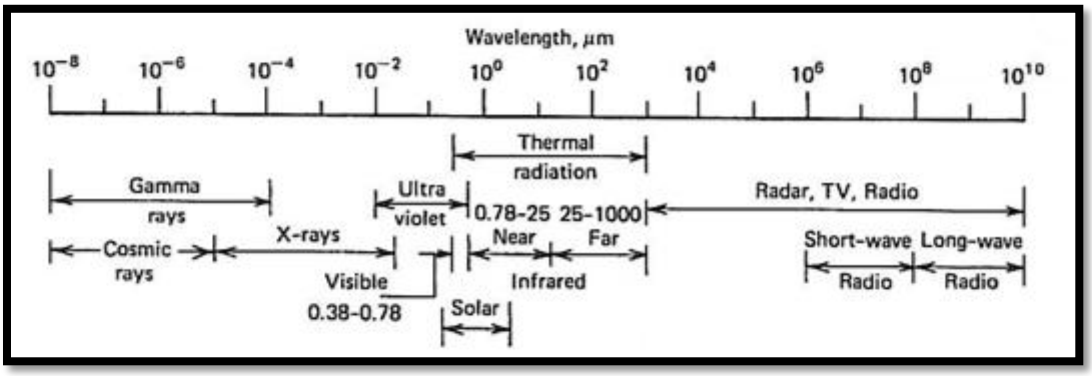


Figure II.8 Spectrum of Electromagnetic Radiation (Duffie and Beckman, 2006)

II.4.1 Glazing Material

The glazing material should minimise the heat losses from the top of the collector. It should transmit as much solar irradiation as possible.

Glass is widely used to glaze solar collectors because it can transmit as much as 90 % of the incoming shortwave solar irradiation and it transmits none of the long wave radiation emitted outward by the absorber plate. Glass with low iron content has a relatively high transmittance for solar radiation (approximately 0.85-0.90 at normal incidence), but its transmittance is essentially zero for the long wave thermal radiation (5-50 μm) emitted by the heated surfaces.

II.4.2 Absorber Plate

The transmitted sun-light is absorbed by the absorber sheet. The absorbtance of the absorber surface for short wave solar radiation depends on the nature and colour of coating, and the incident angle (Kalogirou, 2004).

Black colour has high absorbtivity, approximately 95 %. However, it has also high emissivity, approximately 92 %. The black surface will lose energy through radiation due to its high emissivity. So, it is not a good choice as an absorber coating. An ideal surface should have high absorbtivity and low emissivity. Nowadays, selective coatings have an absorbtivity of 95 % and an emissivity of 5 %.

The selectivity is achieved by polishing a metal surface and coating it with a thin surface layer, which is transparent to long wave radiation but has high absorbtance for shorter wavelength solar radiation. Surface layers made of nickel or chrome have been found to be quite suitable as selective surfaces.

Generally, copper, aluminium and stainless steel are used as absorber materials. Copper and aluminium have a higher thermal conductivity than stainless steel. Aluminium has high thermal conductivity, low density and low weight. It is easy to process, but it has a low corrosion resistance. Copper has a high thermal conductivity, good corrosion resistance, high durability and it is easy to process. But it has high density, high weight and it is expensive. Stainless steel has high durability and corrosion resistance. It has low thermal conductivity and high density, and it is expensive. Due to economic reasons aluminium sheet is used instead of copper. But, copper is still used as the tube material due to its higher thermal conductivity and better corrosion resistance.

II.5.Thermosyphon Solar Water Heaters

Thermosyphon solar water heaters are natural circulation systems. They generally consist of three major parts: the solar thermal collector, a storage tank and the interconnecting pipes between collector and storage. Thermosyphon systems operate because of the difference in density between hot and cold fluid. The storage tank should be above the collector. The upper outlet of the collector should be connected to the top of the storage tank and lower part of the storage tank to the collecor inlet (bottom) to obtain the natural circulation. Hence, there will be a circulation from the collector to the storage tank as shown in figure II.9.

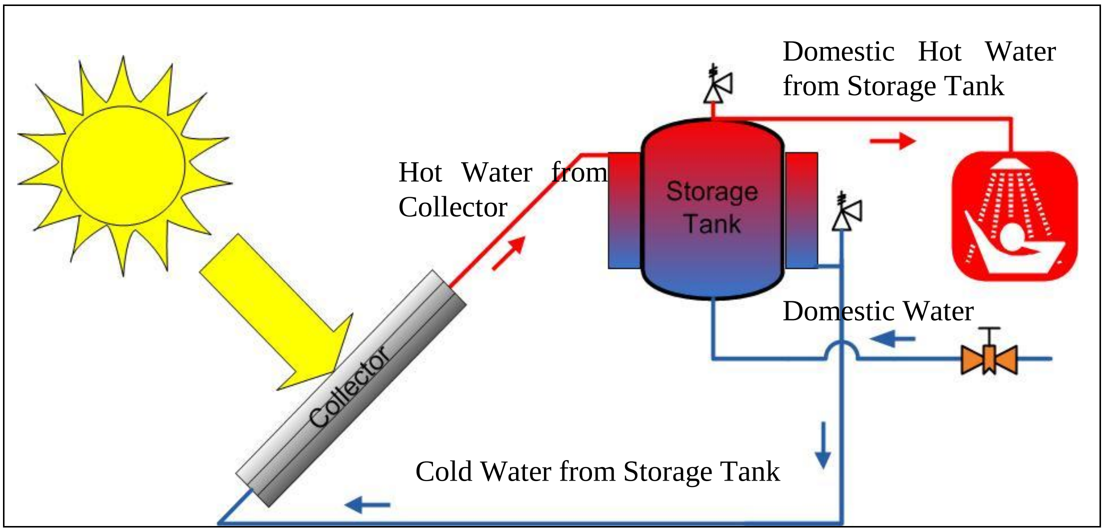


Figure II.9 Function Principle of Thermosyphon System

The flow rate of a natural circulation thermosyphon system varies throughout day and year depending on the absorbed radiation.

To ensure a constant hot water quality, it is possible to include electric back up heater for periods with adverse weather.

State of the art thermosyphon systems show a lot of technical problems:

1) The first problem is reverse thermosyphoning, which occurs in times of hot storage tank and low irradiation, e.g. during night. In case of reverse thermosyphoning, hot water from storage flows back into the collector working as a heat exchanger to the colder surrounding. Hence, the system gets cooled down during night.
2) The second problem is the storage tank design. While tapping water from the storage, the stratification within the tank is destroyed. This fact slows down the temperature sensitive flow rates in such a system and therefore has a negative effect on the daily system performance.
3) The third problem is overheating, as high efficient collectors designed for pumped systems are combined with simple storage cylinders in order to build up a thermosyphon system. During summer times these systems are able to reach storage temperatures of well above 100°C and therefore become a danger to users, as they might scald themselves while tapping water. (Brandmayr, 2009)

II.6. Market Analysis

II.6.1. Europe

It is the European Union's aim to increase the solar thermal collector area currently installed in its member countries to a total capacity of 70,000 MW by 2010 (Brandmayr, 2009).

Towards the end of 2005, the total capacity of all European solar thermal systems was about 11,175 MW, which equals only about 16 % of the target of the EU (Brandmayr, 2009).

Apart from Europe's three main solar thermal markets - Germany (47 %), Austria (12 %) and Greece(11 %) – which together represent about 70 % of the entire European market in 2005, markets like Spain, Italy or France are becoming more and more important (Brandmayr, 2009).

Especially France, without its overseas, had a market growth of about 134 % in 2005. The reason for this development is the so called 'sun plan'. France, according to the words of its industrial minister, wants to be Europe's leading market for solar thermal applications by 2010 (Brandmayr, 2009).

Spain had a market growth of only 19 % and stayed below the European average in 2005. But in September 2006, a law came into force which makes it necessary for almost all newly built houses to produce 30…70 % of needed hot water by solar energy. With this legal obligation, Spain serves as a pioneer within Europe (Brandmayr, 2009).

II.6.2. North Africa and Middle East

Mowing away from the European solar thermal market and focusing on the North African market, only little financial possibilities can be found on the inhabitant's side. But especially these economically weak countries are ideal for the use of solar thermal applications (Brandmayr, 2009).

Tunisia has an annual amount of sunshine hours of about 2,800 - 3,200 at an ambient temperature of about 20 °C. These prevailing conditions make all Northern African countries like Tunisia, Algeria, Libya, Morocco and Egypt ideal markets for the most simple solar-thermal water heaters of all the thermosyphon systems (Brandmayr, 2009).

In the Middle East, especially Israel attracts attention due to its high density of thermosyphon solar hot water heaters. One reason for this has been the legal restraint, introduced in 1980, to install solar thermal water heaters when building a new house. Meanwhile solar thermal applications are accepted (Brandmayr, 2009).

II.6.3 Turkey

Turkey is located in a relatively advantageous geographical location which has a high amount of solar radiation.

With an average of 2640 sunshine hours per year, Turkey could be ready to generate about 380 billion kWh of solar electricity per year. But today 67% of the energy used in Turkey is imported in form of oil, coal or natural gas. The public authorities and political decision-makers prefer fossil and nuclear energy forms (Grunwald, 2010). However, due to the Kyoto protocol the Turkish government has taken some decisions. These are:

- ✓ Renewable energy usage will be 30% in 2020.
- ✓ Natural gas usage will decrease below 30%.
- ✓ Wind power installed capacity will be 20GW in 2020. (Gülbahar, 2010)

II.7. State of The Art

II.7.1. Collectors

Thermosyphon systems outside of China commonly use flat plate collectors. Only a few manufacturers include, in most cases, non-pressurised systems with evacuated tube collectors in their programme (Brandmayr and Zörner, 2007).

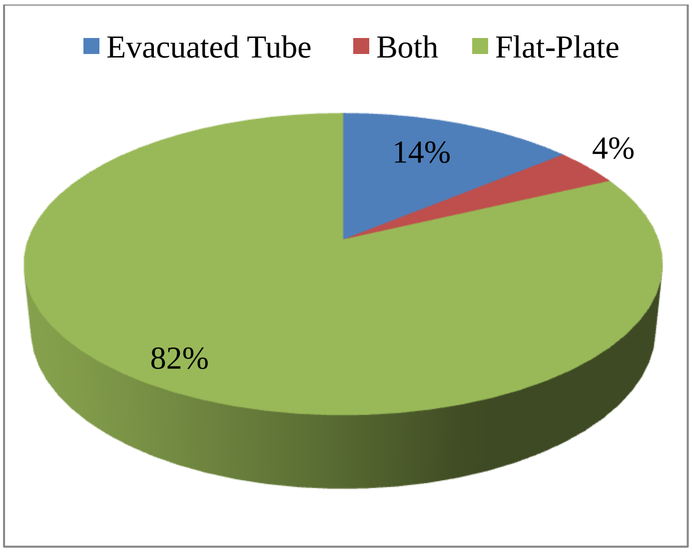


Figure II.10 Collector Types Used for Thermosyphon Systems (Brandmayr and Zörner, 2007)

In contrast to the rest of the world, solely thermosyphon systems with evacuated tubes are sold in China. There are two main reasons for this:

- ✓ Evacuated tubes are produced at very low cost within China.
- ✓ In China, most of the thermosyphon systems sold are non-pressurised systems, with only a single hydraulic circuit. In these systems, collector and storage make up one unit as the evacuated tubes are plugged into the storage tank especially perforated for this sake which is cheap to produce. (Brandmayr and Zörner, 2007)

Regarding flat-plate collector thermosyphon systems many manufacturers have different absorber coatings according to the climatic and the customer's demands in their programme. In most cases, the same system is available with a solar black painted absorber or a selective coated absorber. Nowadays, most manufacturers of thermosyphon systems use ultrasonic welded absorbers for their high standard products. Together with laser welded absorbers they make up more than 75 % of the used production techniques (Brandmayr, 2009).

II.7.2. Storage Tank

Regardless of the collector type used, horizontally installed storage tanks are mostly used (94% market share), vertically oriented storage tank are an exception (figure II.11) (Brandmayr, 2009).

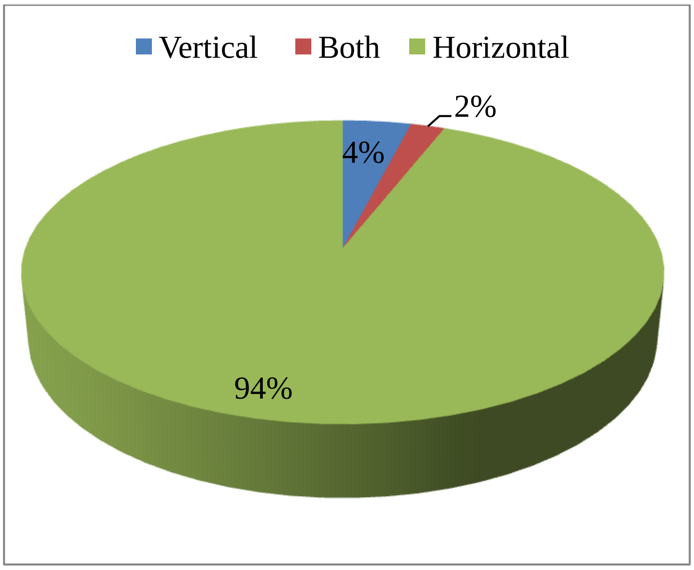


Figure II.11 Storage Tank Position (Brandmayr, 2009)

The aesthetic advantage of horizontal storage tanks is that these systems can be built optically compact (figure II.13) and they can be installed easier on an inclined roof. However, standing storage tanks (vertical storage tank) have an advantage of good temperature stratification due to long path (figure II.12) (Brandmayr, 2009).

Figure II.12 Thermosyphon System with Vertical Storage Tank in Turkey (Brandmayr, 2009)

Figure II.13 Thermosyphon System with Horizontal Storage Tank in Gran Canary (ESTIF, 2010)

II.8. Literature Review

Gupta and Garg (1968) made an investigation on solar water heaters with natural circulation in order to determine design studies for various system parameters like circulating pipe diameter and layout, collector configuration, absorber length/breadth ratio and tank/height ratio. For their experimental trials they used a single pass circuit thermosyphon system filled with water. The observations had been firstly taken for a clear day and later for cloudy day.

The temperature increase between inlet and outlet of a collector in a thermosyphon system was observed to be nearly constant during times of sunshine.

The distance between the collector's top header and cold water outlet (storage tank bottom) was varied from -0.3 to +0.6 m. The minus sign indicates that the collector's top level is higher than the tank bottom.

They examined the circulation pipe of nominal diameters 25 and 19 mm. In both cases, the mean tank temperatures are same irrespective of the connecting pipe diameters. However, flow conditions are faster for the pipe with bigger diameter and, consequently, the temperature difference between tank top and bottom is reduced compared to the smaller diameter pipe.

Norton and Probert (1983) compared the different type of solar energy water heaters:

1. Pumped systems with single tank direct liquid system,
2. Double tank direct liquid system,
3. Single tank indirect liquid system,
4. Double tank indirect liquid system,
5. Double tank indirect air system, and
6. Thermosyphon system with single tank liquid system.

They observed that direct systems outperformed than indirect systems and the best performance was obtained from a thermosyphon unit. Their study also showed that the system efficiency decreased with the addition of a second storage tank.

They made studies in New Zealand. There were wide variations in the chosen collector areas and this made direct comparisons of performances difficult. Nevertheless, they observed that thermosyphon systems were at least as effective as the pumped systems.

They also made a study in Germany. An indirect solar energy system for hot water production was monitored from 1979 to 1981. It was concluded that an indirect thermosyphon system can be as efficient as an indirect pumped system under climatic conditions of Central Europe.

Morrison and Braun (1984) developed a numerical simulation model for themosyphon solar water heaters and they compared the simulation results obtained from two locations. They examined the characteristics of a vertical and a horizontal tank thermosyphon system. They compared the performance of pumped and thermosyphon system and they observed that both systems have a similar performance when the systems are operated at a daily load volume to daily collector flow rate of 1. However, thermosyphon systems perform better than pumped systems with a high flow rate due to the better thermal stratification in the storage tank.

They observed that horizontal tank systems do not perform as well as vertical tank systems due to short conduction path in horizontal tanks. The effect of conduction in horizontal tanks can be reduced by using a two tank system if both tanks are combined end to end in one horizontal package in order to reduce the heat losses.

Vaxman and Sokolov (1986) simulated the insulation thickness of pipes on the overall performance of thermosyphon systems. The simulation is based on the numerical solution of the energy and momentum equations for the various systems components.

They observed that the reverse flow is decreasing with the increase of the upper pipe insulation at zero height difference (ΔH) between collector and tank. Even small insulation of the upper pipe will reduce the efficiency losses.

An increase in ΔH results in an increase of the flow friction and therefore will be associated with a decrease of the flow rate. This, in turn, causes both a decrease in the collector efficiency during radiation periods and a decrease in reverse flow during periods of insufficient radiation. So an optimal value of ΔH has to be determined. They observed if energy is drawn from the system during periods of reverse flow conditions, the system performance can be optimized by $\Delta H > 0$. The results indicated that this height should be in the range of 30-80 cm.

Another study on reverse circulation was made by Morrison (1986). Morrison used a numerical model of thermosyphon circulation to determine the conditions under which reverse flow occurs. To keep the heat loss due to reverse flow on clear nights below 20 W the top of the collector must be located 50 mm below the tank if both ends of the collector loop are at the bottom of the tank. If there is a 1 m separation between the ends of the collector loop at the tank, a separation of 250 mm is needed between the bottom of the tank and the top of the collector.

Consul, Rodrıguez, Perez-Segarra, Soria (2004) studied the thermal stratification of a storage tank. The transient thermal behavior of a storage tank was simulated numerically. The influence of the inlet mass flow rate on the degree of thermal stratification during *unloading process* was analyzed.

They used coupled parallel computers (Beowulf clusters) as a tool for virtually prototyping thermal storage tanks. A horizontal tank was simulated. The tank was considered to have an initial constant temperature of 42°C. Cold water (20°C) was injected from left side of the tank. Four mass flow rates were considered: 0.0167, 0.025, 0.05, and 0.1 kg/s.

They observed that for the three first flow rates (0.0167, 0.025, 0.05 kg/s) the tank is properly stratified as the process evolves. For the highest mass flow rate

(0.1 kg/s), the temperature profile at the bottom of the tank differs considerably from the ideal situation due to high momentum of the flow rate causing a sudden mixing with the bottom fluid layer. The best results were obtained for the mass flow rate of 0.025 kg/s, even when mixing due to the inlet stream is expected to be lower for the smallest mass flow rate of 0.0167 kg/s.

The solar collectors and the associated piping must be designed to avoid damage from freezing and boiling. Low ambient temperatures during periods of no solar radiation can result in plate temperatures below 0 °C. According to Duffie and Beckman (2006) five approaches have been developed to protect collectors against by freezing.

1. Antifreeze solutions can be used in the collector loop with a heat exchanger between the collector and the storage tank. Ethylene glycol-water and propylene glycol-water solutions are common antifreeze liquids.
2. Air can be used as the heat transfer fluid in the collector heat exchanger loop. And also hence, leakage and boiling will not be problem.
3. Circulation of warm water from the tank through the collector loop to keep it from freezing can be made. But then thermal losses from the system are significantly increased.
4. Draining water from the collectors when they are not operating.
5. To design the collector plate and piping so that it will withstand occasional freezing.

If no energy is withdrawn from the system or a circulating pump should not operate during times of high radiation, the plate temperature may exceed 100 °C and overheating problems occurs. According to Duffie and Beckman antifreeze solutions can be used in collector loops in order to elevate boiling points. And other approaches are to use pressure relief valves and vent tanks to relieve excess pressure.

There are lots of studies made up to now. The reverse thermosyphoning, overheating and stratification in the storage tank are mainly concerning parameters on the overall design of the thermosyphon system.

Reverse thermosyphoning can be eliminated by arranging the distance between the collector and the storage tank or by using non return valves.

Overheating problem can be eliminated by using pressure relief valves to relieve excess pressure from the system. The other choice is also to use the antifreeze fluids in the collector loop.

Stratification in the storage tank is the other problem in the system. Vertical storage tanks have an advantage of long path inside the tank according to the horizontal tank.

III. Studies

This study includes the optimization of thermosyphon system experimentally with a simulation validation. Collector efficiency tests and improvement of the stratification inside the horizontal mantle storage tank are the concerning studies of this thesis.

The experimental analysis of thermosyphon hot water system which includes infrared tests of absorber, thermal efficiency tests of collector and mixing tests of storage tank are aimed. Infrared tests are study of flow distribution inside the absorber. Thermal efficiency tests are to study the collector efficiency using a solar simulator. Mixing tests are aiming at improving thermal stratification of the storage tank. The mixing tests are simulated using a CFD (computational fluid dynamics) program, STAR CCM+.

III.1. Infrared Tests

The aim of this study is to experimentally see the flow distribution and thermal behaviour of the absorber. The influence of flow distribution at different flow rates and collector tilt angles was investigated. The flow distribution is important for the collector efficiency. It should be homogeneous in order to obtain a higher collector efficiency.

Infrared photography was used to visualise the flow distribution inside the absorber. A thermographic camera or an infrared camera is a device that forms an image using infrared radiation, similar to a common camera that forms an image using visible light. An infrared camera can show areas with very low flow rates and even dead water zones.

The experimental set up is as shown in figure III.1. Firstly, there is cold water inside the absorber. The hot water inside the storage tank heated by a chiller is pumped into the absorber.

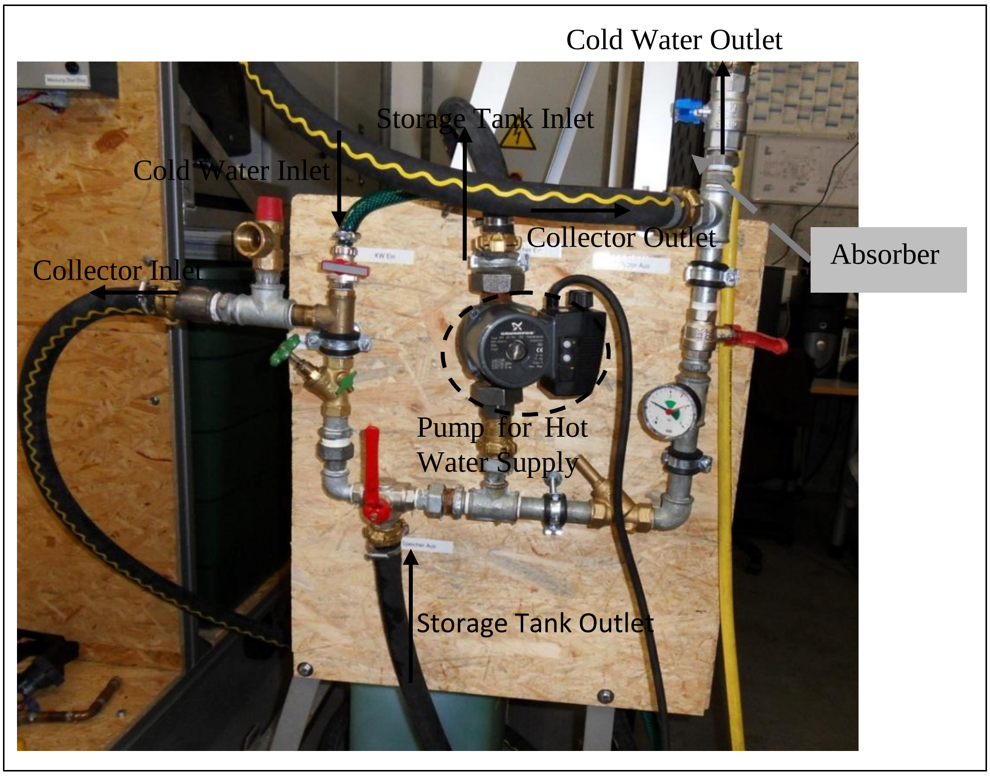


Figure III.1 Infrared Test Experimental Set Up

The absorber fluid is water which is circulated through the absorber by a pump.

Studies were carried out with two different type of absorber. One is a volumetric absorber (plastic pool absorber) and the other is a sheet pipe absorber.

III.1.1. Pool Absorber

There are thermosyphon systems available using a simple volumetric pool absorber as energy source. In order to test the behaviour of volumetric absorbers a pool absorber was investigated.

Pool absorbers are low-cost products which provide efficiency solar heating wherever temperature level needed. The main areas of use are in private, public and commercial swimming pools.

Unglazed pool absorbers have no housing and no thermal insulation. Such absorbers obtain only a low efficiency since these are affected by wind conditions. Their optical efficiencies measured at medium collector temperature which is equivalent to ambient temperature are higher than the efficiencies of flat-plate or vacuum tube collectors.

There are two types of pool absorbers: tube and absorber mats. For tube absorbers tubes are laid out in parallel. For absorber mats, channels are structurally interconnected with each other resulting in plates with different dimensions.

Absorber mats and tubes are often made of plastic materials. Standard materials are PP (polypropylene), EPDM (artificial rubber), PVC (polyvinylchloride) and HDPE (high density polyethylene). It is essential that the material used is not toxic and UV-resistant.

For the tests an absorber mats was used which allowed volumetric flow. The sample additionally provided the possibility to realise different connections for the tests.

Tests were made at the vertical position at temperature ranges between 50-60 °C. According to the flow distribution the hot flow emits long wave infrared radiation. This radiation is detected by an infrared camera and produces an image of the heat distribution in the channels of the absorber mat. Finally, the water leaves the absorber at the outlet and returns to the temperature control unit.

The first test was made at flow rate of 500 l/h at 55 °C. Water enters the absorber from left bottom pipe and leaves the absorber from right top pipe as shown in figure III.2. The absorber was at vertical position.

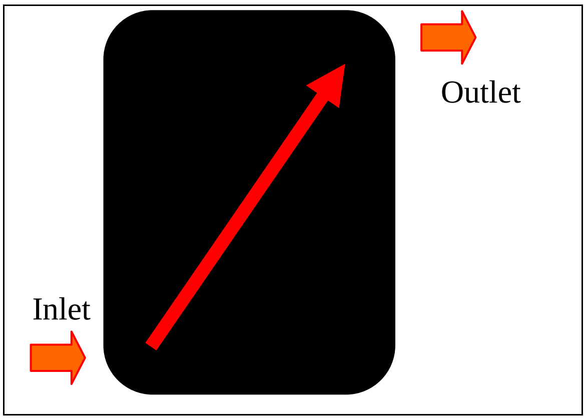
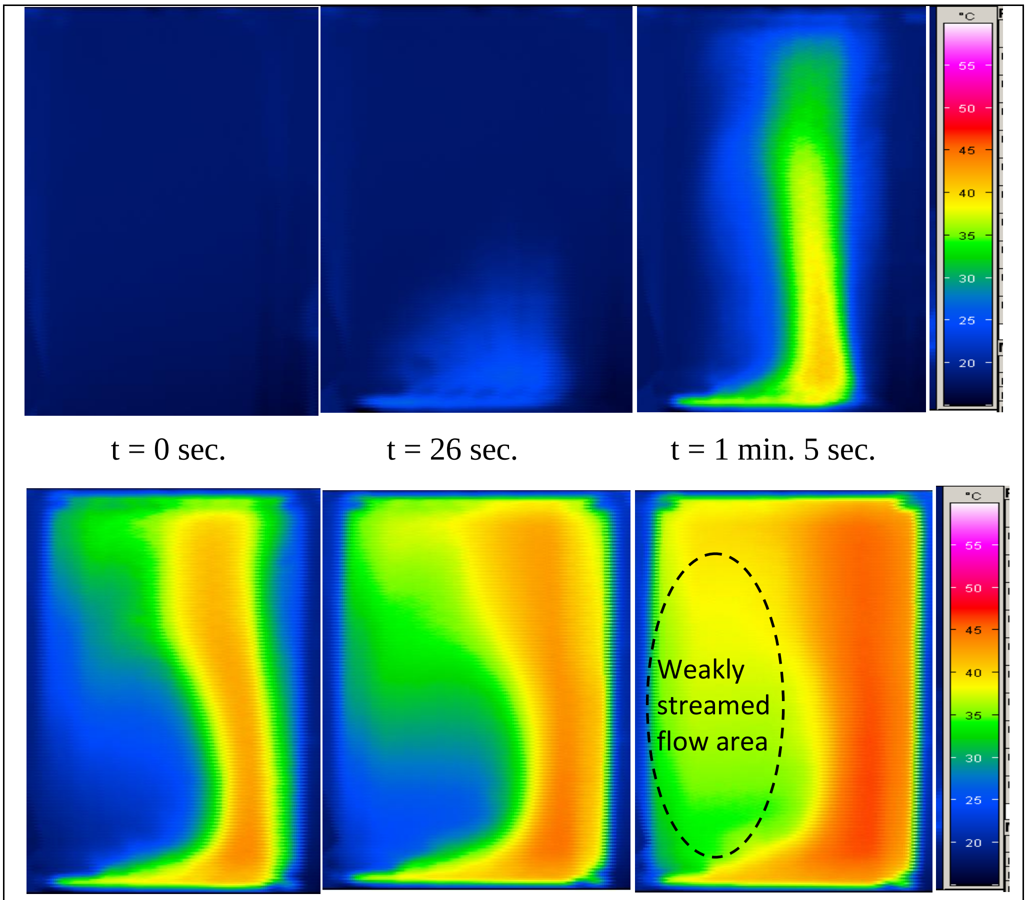


Figure III.2 Inlet-Outlet Configuration of Absorber



t = 0 sec. t = 26 sec. t = 1 min. 5 sec.

t = 2 min. 10 sec. t = 3 min. 15 sec. t = 6 min. 30 sec.

Figure III.3 Infrared Sequences of Volumetric Absorber at Flow Rate of 500 l/h

It can be seen that after 6 minutes flow becomes developed flow in figure III.3. And temperature distribution can clearly be seen. At the right side of the absorber the temperature distribution is satisfactory. But at the left side the temperature distribution is not as good as the right side and flow is weakly streamed.

The second test was made at flow rate of 500 l/h. The absorber was at vertical position. Water enters the absorber from bottom right side and leaves the absorber from top left side as shown in figure III.4.

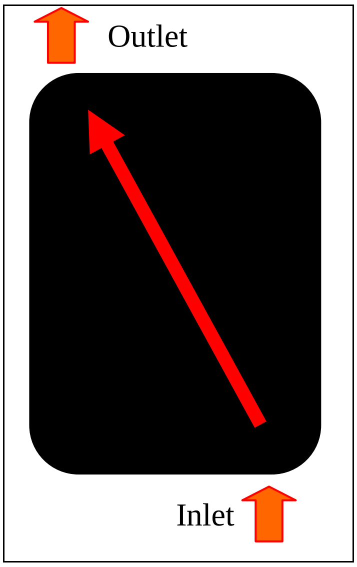
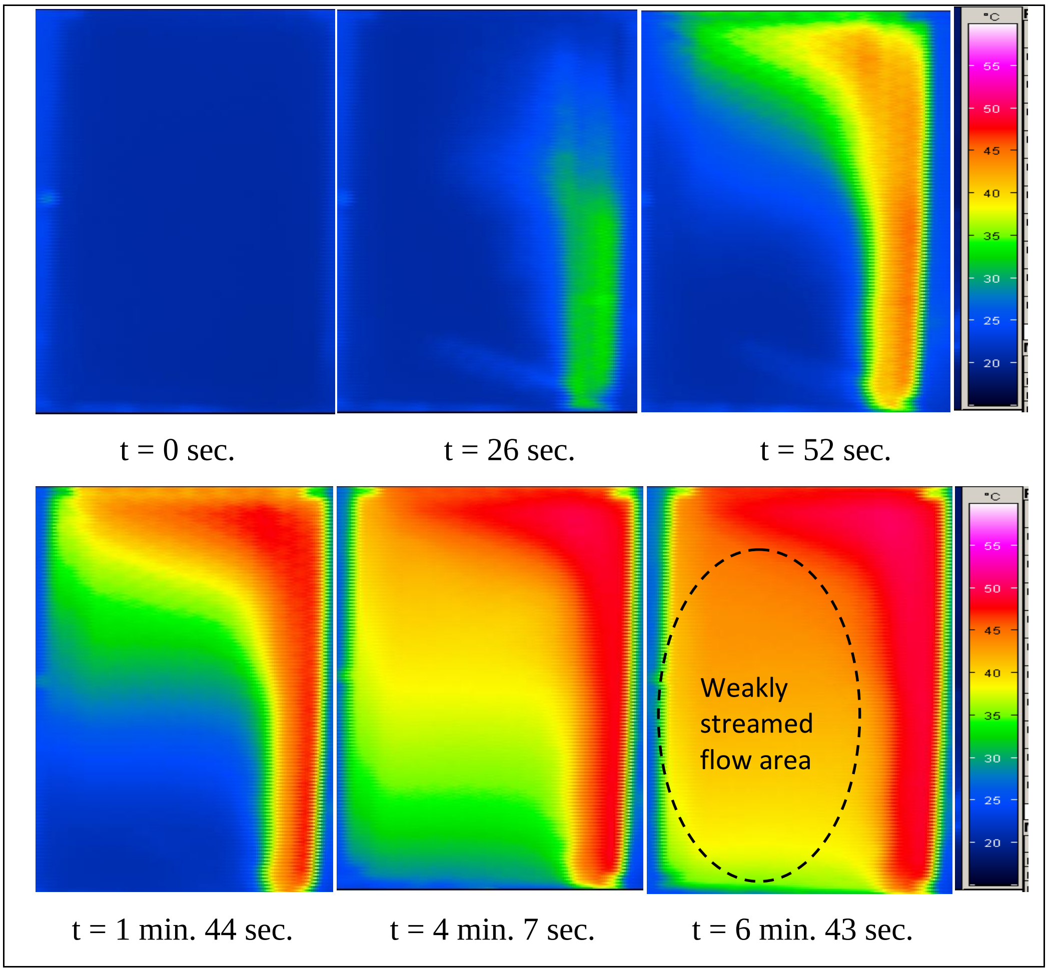


Figure III.4 Inlet-Outlet Configuration of Absorber



t = 0 sec. t = 26 sec. t = 52 sec.

t = 1 min. 44 sec. t = 4 min. 7 sec. t = 6 min. 43 sec.

Figure III.5 Infrared Sequences of Volumetric Absorber at Flow Rate of 500 l/h

It can be seen that after 6 minutes flow becomes developed flow in figure III.5. The temperature distribution can clearly be seen. At the right and the top side of the absorber the temperature distribution is satisfactory. But at the left and the bottom side is not as good as the right side and the flow is weakly streamed. Weakly streamed flow area is less at the first condition than at the second condition.

The third test was made at flow rate of 500 l/h at 50 °C. Water enters to absorber from bottom left and leaves the absorber from top left as shown in figure III.6.

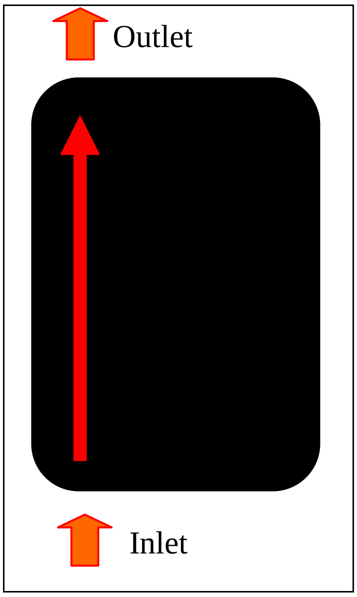
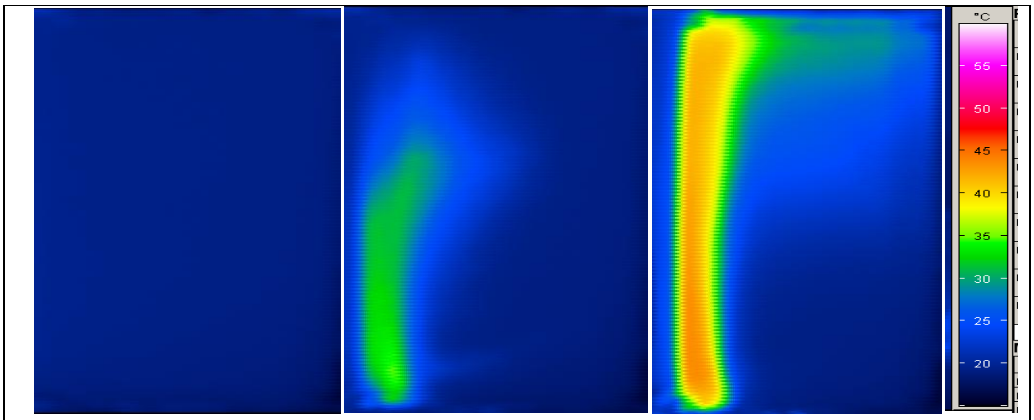
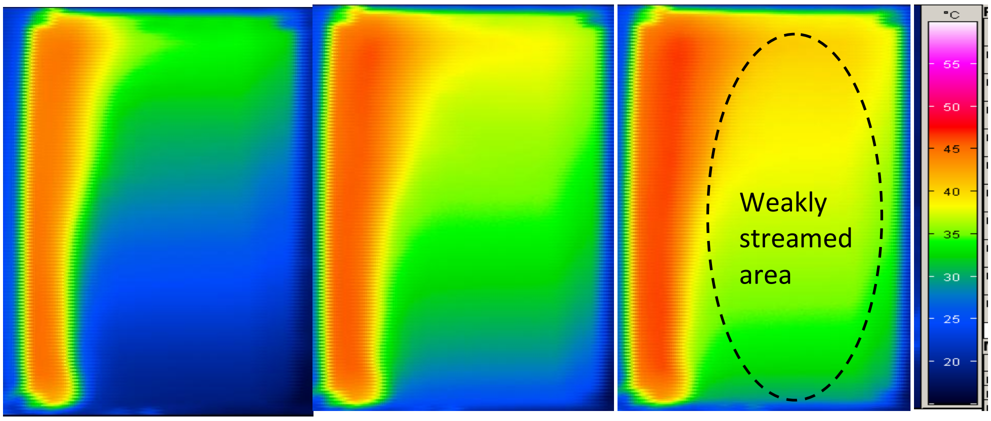


Figure III.6 Inlet-Outlet Configuration of Absorber



t = 0 sec. t = 1min. t = 2 min. 30 sec.



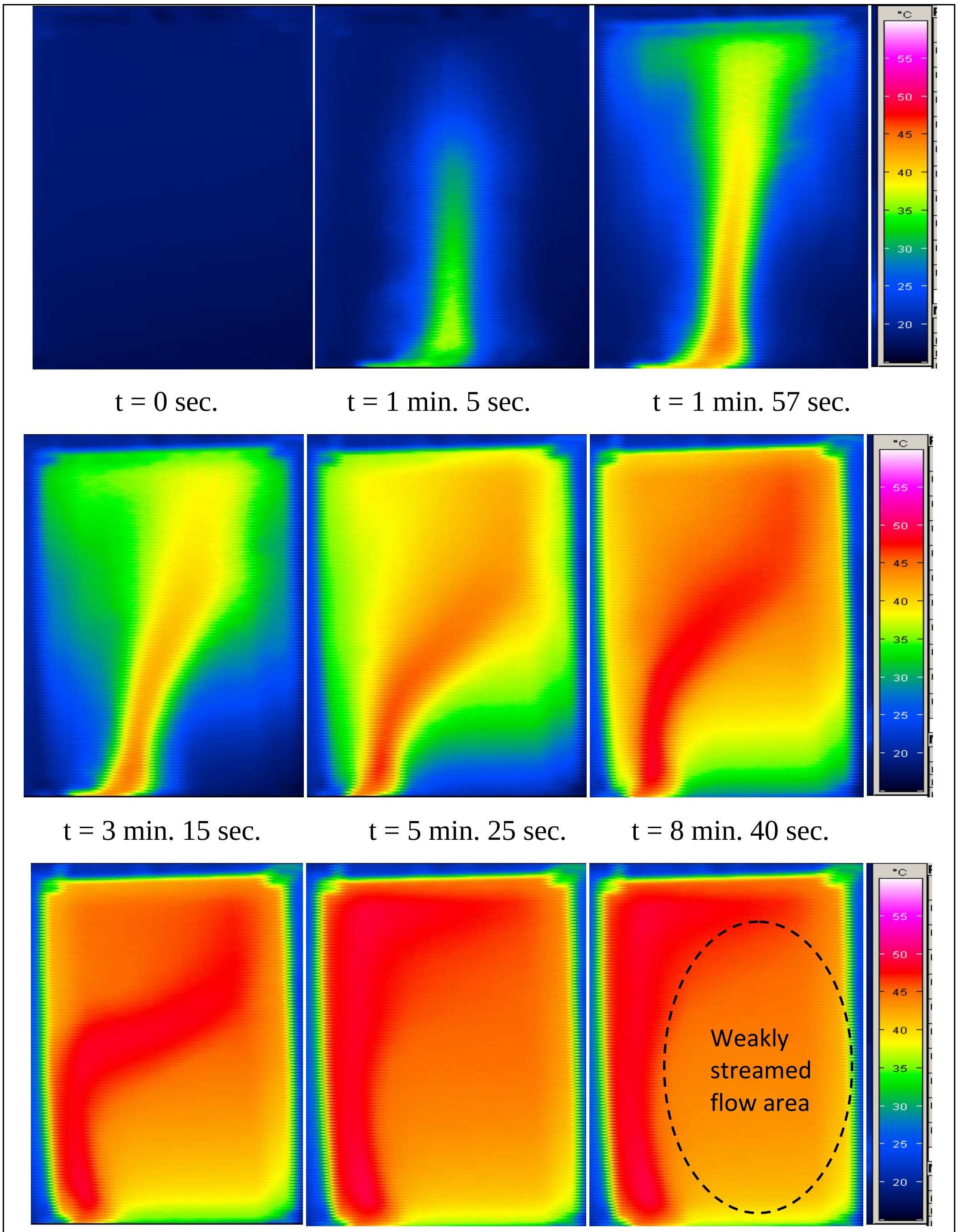
t = 5 min. t = 10 min. t = 15 min.

Figure III.7 Infrared Sequences of Volumetric Absorber at Flow Rate of 500 l/h

It can be seen that after 5 minutes flow becomes developed flow in figure III.7. The temperature distribution can clearly be seen. At the left side of absorber a better temperature distribution is obtained but at the right side the temperature distribution is not as good as at the left side and the flow is weakly streamed. Weakly streamed flow area is less at first and second configuration than third condition.

The first, the second and the third tests show that first configuration has the best flow stream inside the absorber and less weakly streamed area than the other configurations. So, the first configuration would be more efficient for a thermosyphon system.

The fourth test was made according to the first condition as shown in the figure III.2 at flow rate of 350 l/h at 60 °C.



t = 0 sec. t = 1 min. 5 sec. t = 1 min. 57 sec.

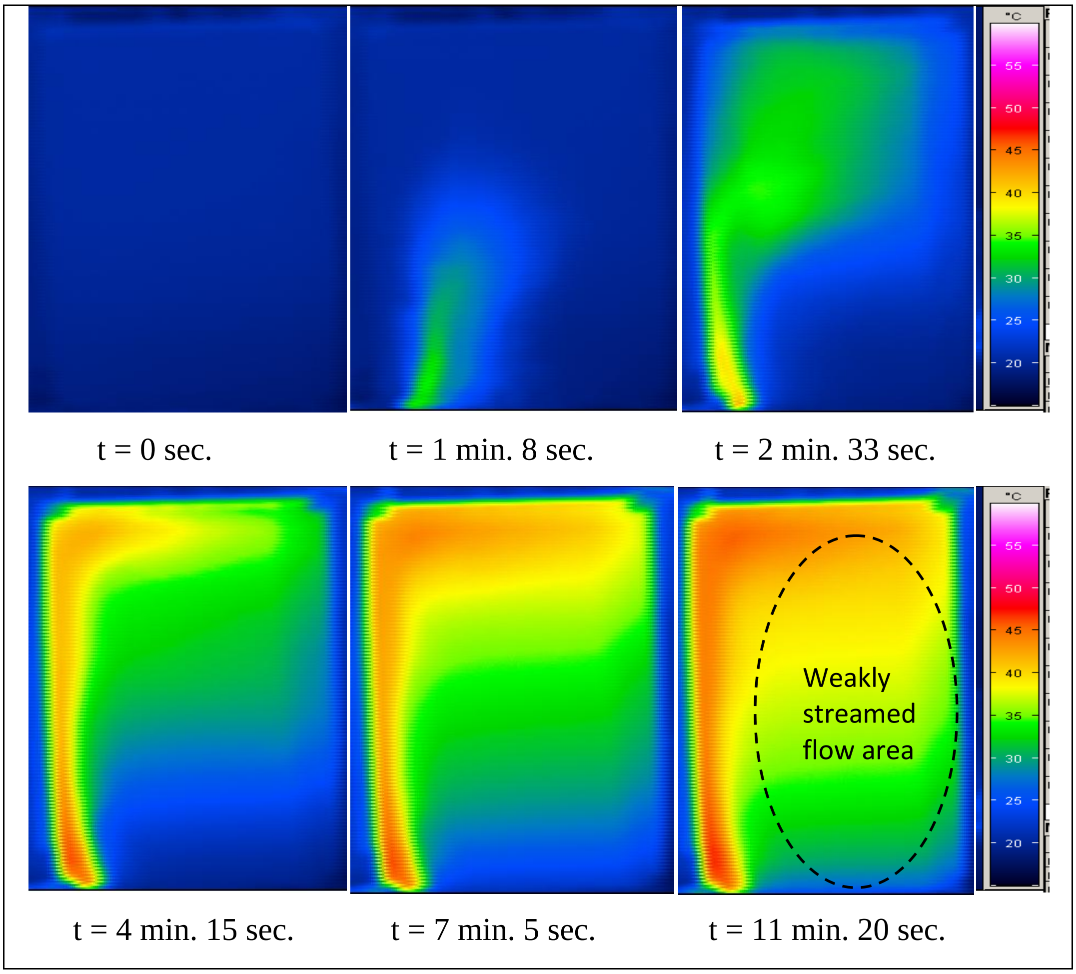
t = 3 min. 15 sec. t = 5 min. 25 sec. t = 8 min. 40 sec.

t = 13 min. t = 17 min. 20 sec. t = 22 min. 58 sec.

Figure III.8 Infrared Sequences of Volumetric Absorber at Flow Rate of 350 l/h

It can be seen that flow stream is initially like an S-shape at the middle of the absorber and after 17 minutes the flow becomes developed flow at the left side of the absorber and the absorber is full in figure III.8. The temperature distribution can clearly be seen.

The fifth test was also made according to the first condition at a flow rate of 200 l/h at 60 °C.



t = 0 sec.   t = 1 min. 8 sec.   t = 2 min. 33 sec.

t = 4 min. 15 sec.   t = 7 min. 5 sec.   t = 11 min. 20 sec.

Figure III.9 Infrared Sequences of Volumetric Absorber at Flow Rate of 200 l/h

It can be seen that the flow stream is collected at the left side of the absorber. After 11 minutes flow becomes developed flow and the absorber is full of hot water in figure III.9. The temperature distribution can clearly be seen. At the left and the top side of the absorber a better temperature distribution is obtained but at the right and the bottom side the temperature distribution is not as good as the left side and flow is weakly streamed.

The tests which are made were at vertical position. The best flow configuration was determined and effects of flow rates were observed. It can be seen that as the flow rate decreases homogeneous flow inside the absorber decreases.

In the volumetric absorber tests the flow distribution inside the absorber at the different flow rates was observed. Better flow distribution was obtained at the first configuration as shown in the figure III.2 at flow rate of 350 l/h. But the configuration does not also have a good flow distribution. There are weakly streamed areas. So, a design improvement can be made for the volumetric absorber in order to obtain a better flow distribution.

III.I.2. Sheet Pipe Absorber

The sheet pipe absorber made from aluminium sheet and aluminium tubes as shown in figure III.10 was tested at different flow rates. The absorber is selectively coated. The absorber has aperture area of 2.3 m^2. 12 risers are connected to headers.

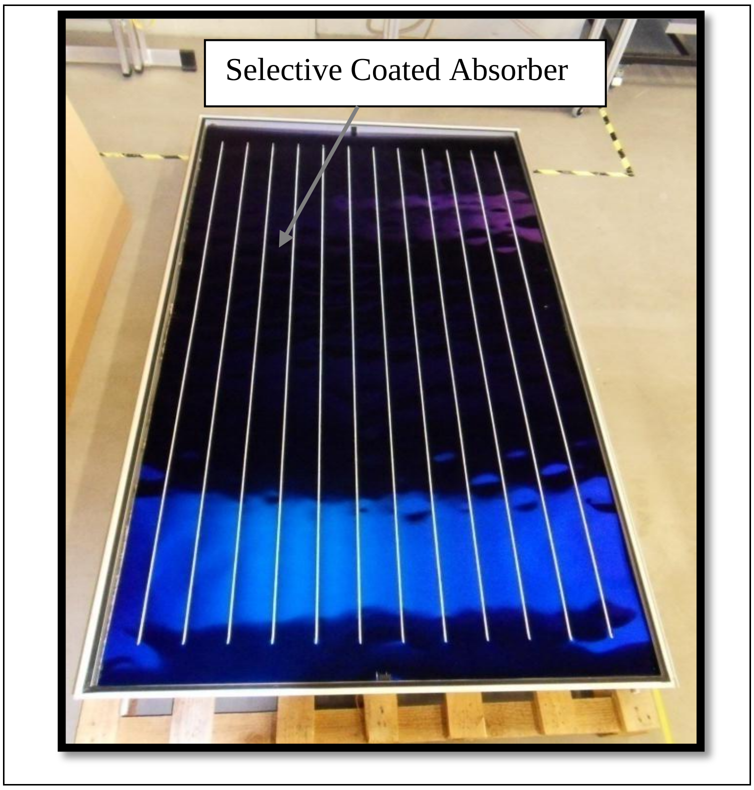


Figure III.10 Sheet Pipe Absorber

Before starting the infrared test tubes were painted with black paint as shown in figures III.11 and III.12 in order to obtain better visualisation of flow stream inside the absorber.

Figure III.11 Tubes with Black Paint

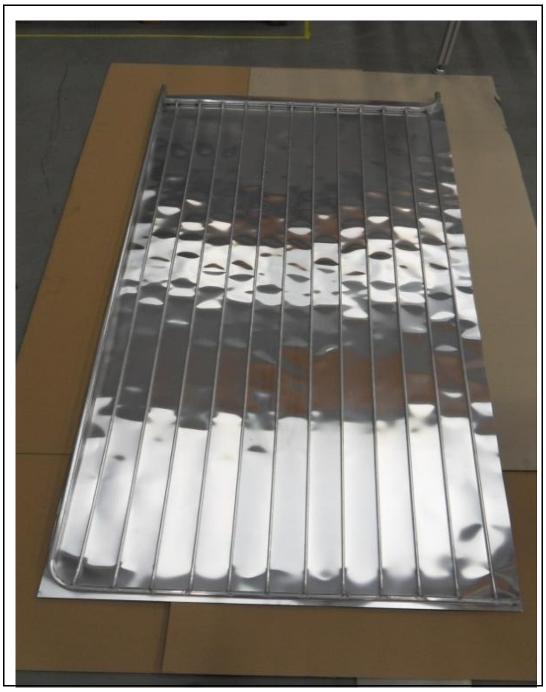


Figure III.12 Tubes without Black Paint

Figure III.13 shows the inlet-outlet configuration of the sheet pipe absorber.

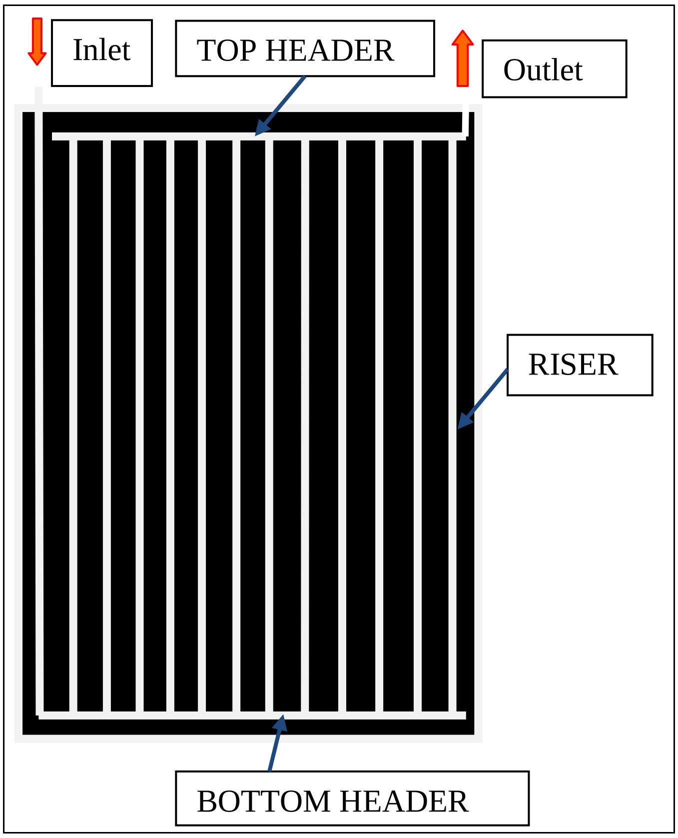
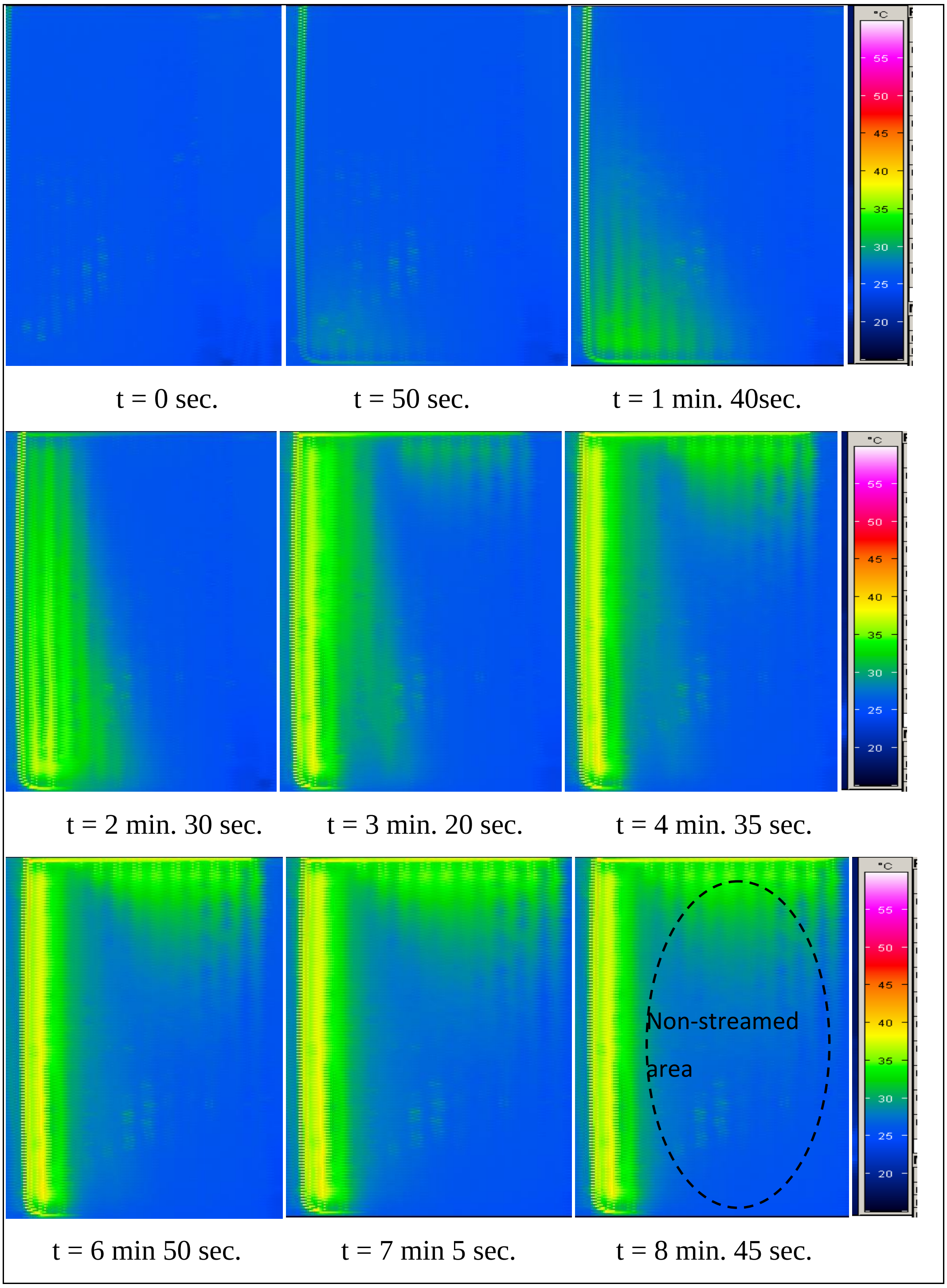


Figure III.13 Inlet-Outlet Configuration of Sheet Pipe Absorber

The infrared tests with the sheet pipe absorber were made at vertical position at a temperature range of 50-65 °C.

The first test was made at a flow rate of 20 l/h at 65 °C.



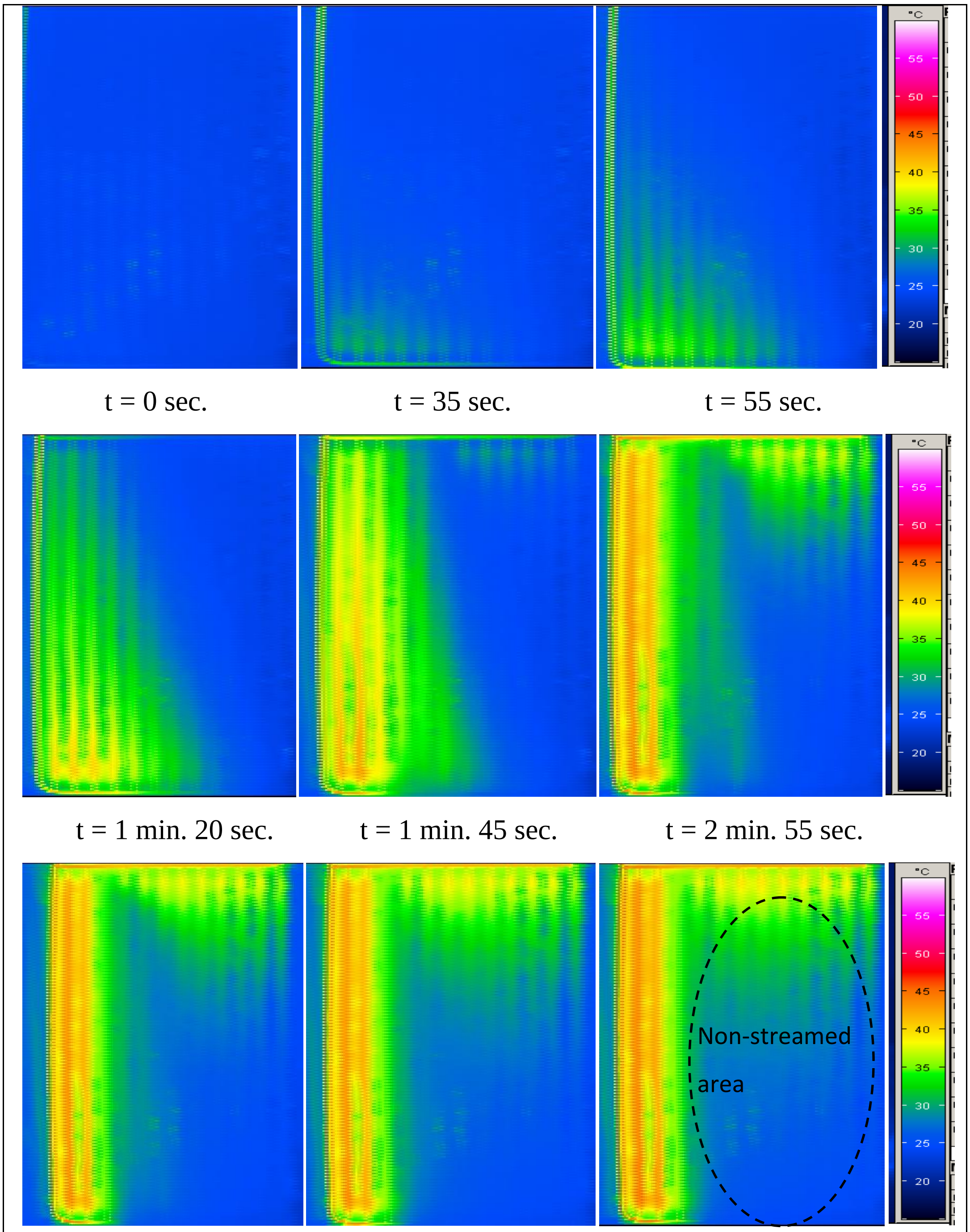
t = 0 sec. t = 50 sec. t = 1 min. 40sec.

t = 2 min. 30 sec. t = 3 min. 20 sec. t = 4 min. 35 sec.

t = 6 min 50 sec. t = 7 min 5 sec. t = 8 min. 45 sec.

Figure III.14 Infrared Sequences of Sheet Pipe Absorber at Flow Rate of 20 l/h

The second test was made at a flow rate of 40 l/h at 65 °C.



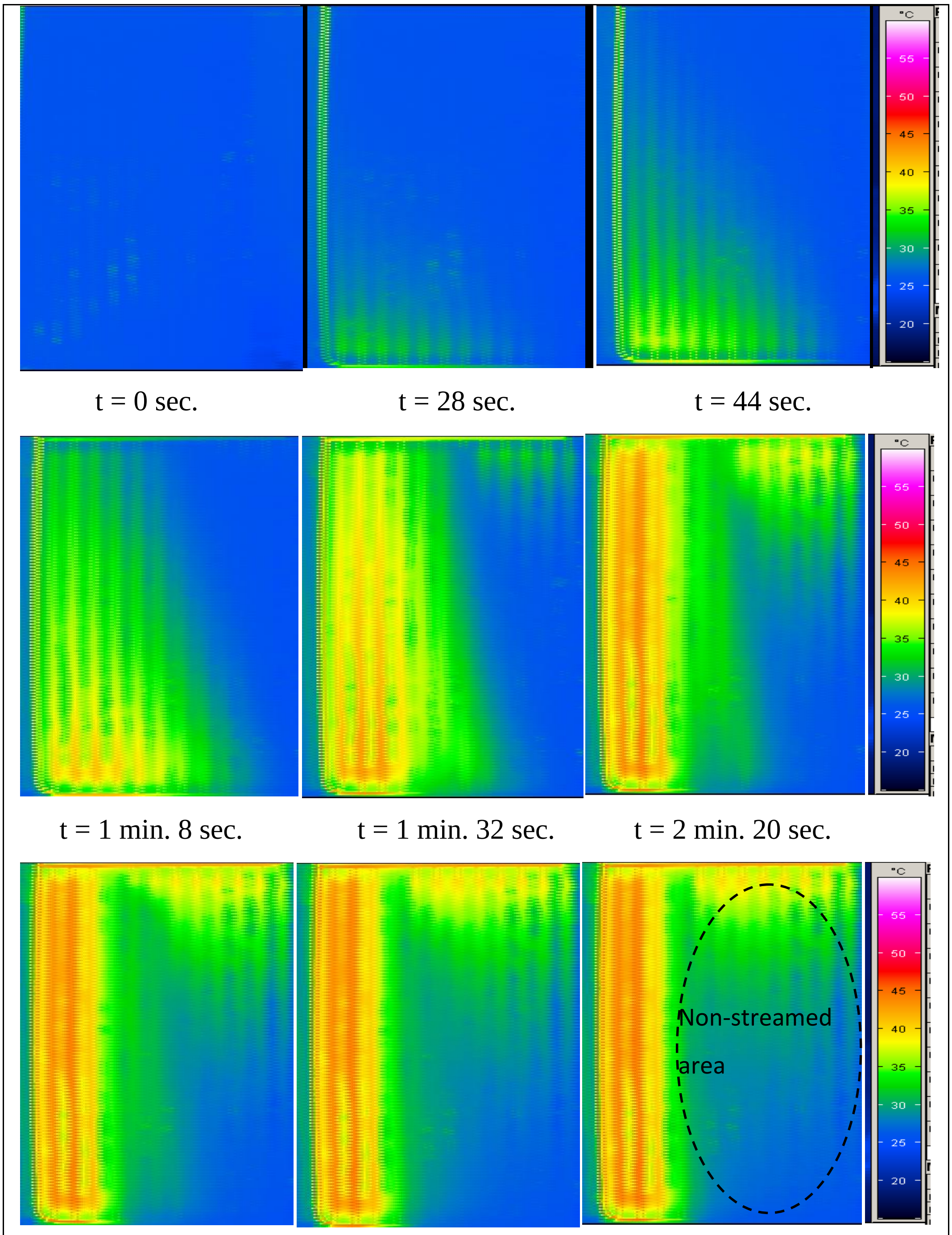
t = 0 sec. t = 35 sec. t = 55 sec.

t = 1 min. 20 sec. t = 1 min. 45 sec. t = 2 min. 55 sec.

t = 4 min. 10 sec. t = 6 min. 15 sec. t = 8 min. 45 sec.

Figure III.15 Infrared Sequences of Sheet Pipe Absorber at Flow Rate of 40 l/h

The third test was made at a flow rate of 60 l/h at 65 °C.



t = 0 sec. t = 28 sec. t = 44 sec.

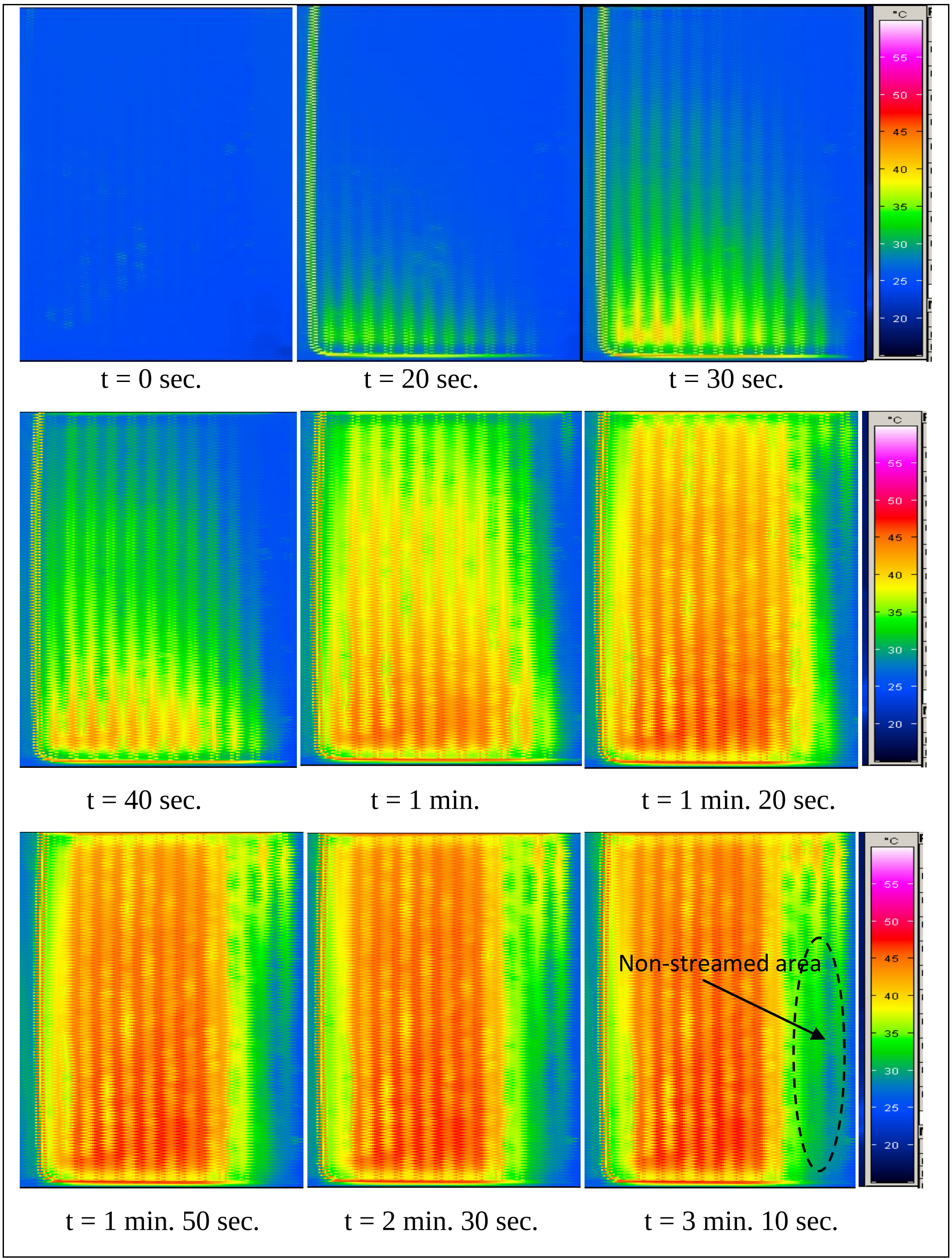
t = 1 min. 8 sec. t = 1 min. 32 sec. t = 2 min. 20 sec.

t = 3 min. 20 sec. t = 5 min. t = 7 min.

Figure III.16 Infrared Sequences of Sheet Pipe Absorber at Flow Rate of 60 l/h

In the first, second and third tests the flow distribution is poor as can be seen in the figures III.14, III.15, III.16. There are only a few risers with flow. The heated regions at the top of risers are due to convection.

The fourth test was made at a flow rate of 120 l/h at 65 °C.


t = 0 sec. t = 20 sec. t = 30 sec.

t = 40 sec. t = 1 min. t = 1 min. 20 sec.

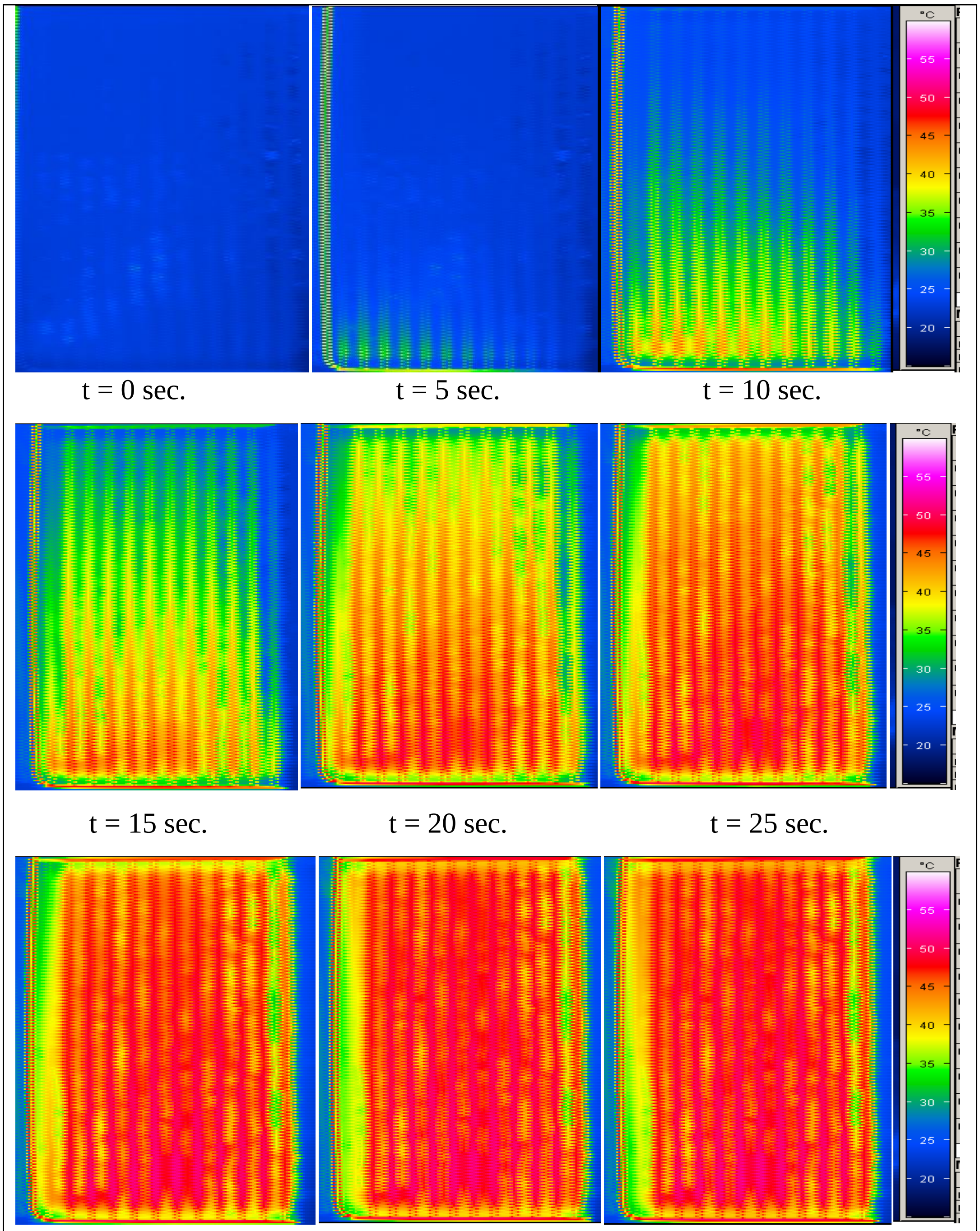
t = 1 min. 50 sec. t = 2 min. 30 sec. t = 3 min. 10 sec.

Figure III.17 Infrared Sequences of Sheet Pipe Absorber at Flow Rate of 120 l/h

It can be seen that during one minute the flow distribution is not same at the risers in figure III.17. Flow stream is less at the first riser, at the second riser it is the higher and after that it is decreasing through the last riser. After one minute fifty seconds flow distribution is homogeneous through all risers except the last three.

The flow distribution at the first riser is weakly streamed. The heated regions at the top of the last two risers are due to convection.

The fifth test was made at a flow rate of 240 l/h at 65 °C.



t = 0 sec. t = 5 sec. t = 10 sec.

t = 15 sec. t = 20 sec. t = 25 sec.

t = 35 sec. t = 50 sec. t = 75 sec.

Figure III.18 Infrared Sequences of Sheet Pipe Absorber at Flow Rate of 240 l/h

It can be seen that during fifteen seconds the flow distribution is not same at the risers in figure III.18. Flow stream is less at the first riser, at the second riser it is the higher and after that it is decreasing through the last riser. After fifty seconds the flow distribution is homogeneous at all risers except the first riser.

The tests with sheet pipe absorber at the different flow rates show that 240 l/h flow rate has the best homogeneous flow inside the absorber. 120 l/h flow rate is better than the flow rates of 20 l/h, 40 l/h and 60 l/h.

The sheet pipe absorber has also a better flow distribution than volumetric pool absorber. There are large weakly streamed regions inside the pool absorber. A new improvement can be made to obtain a good flow distribution for the pool absorber.

III.2 Thermal Performance Test

The basic target of thermal performance test is the determination of the collector efficiency by measurements under specific conditions. The thermal performance test was made by using a solar simulator.

III.2.1 Testing Procedure

9 temperature sensors were inserted on the collector. Two of them are on the casing, three are on the inlet riser and four are on the absorber plate. At these regions temperatures were measured. Position of the temperature sensors on the collector is shown in figure III.19.

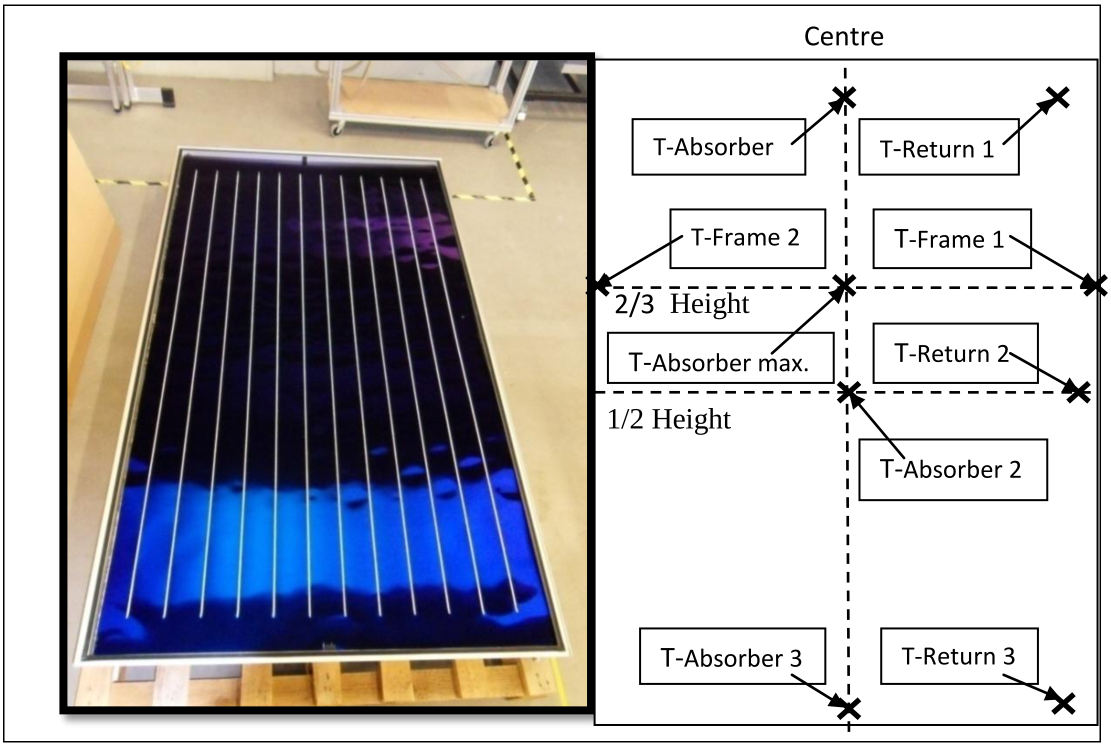


Figure III.19 Measurement Points

The heat fluid is circulated from the top to the bottom of the collector. During the test following measurements are taken:

- ✓ Global solar irradiation at the collector aperture
- ✓ Air speed parallel to the collector aperture
- ✓ Surrounding air temperature
- ✓ Temperature of the heat transfer fluid at the collector inlet
- ✓ Temperature of the heat transfer fluid at the collector outlet
- ✓ Flow rate of the heat transfer fluid

The measurements are collected to produce a set of data points.

The experimental set up is shown in figure III.20. Solar radiation is measured by a pyranometer on the plane of the collector.

Figure III.20 Solar Simulator Experimental Set Up

III.2.2 Computation of Collector Efficiency

The instantaneous efficiency of solar collector is defined as the ratio of the actual useful extracted power to the solar energy intercepted by the collector.

The collector efficiency measurements are carried out according to the standard DIN EN 12975-2.

$$\eta = \eta_0 - a_1\frac{(Tm-Ta)}{G} - a_2G(\frac{Tm-Ta}{G})^2 \qquad \text{(III.1)}$$

η : Efficiency

η_0 : Zero loss efficiency

a_1 : Linear heat loss coefficient, W/mK

T_m : Mean fluid temperature, K

G : Irradiance, incident solar flux, W/m^2

a_2 : Parabolic heat loss coefficient, W/m^{2}K^2

The instantaneous efficiency η (eta) is presented graphically as a function of the reduced temperature difference T_{red} as shown in figure III.21.

$$T_{red} = \frac{Tm - Ta}{G} \qquad (III.2)$$

T_{red} : Reduced temperature, m^{2}K/W

$$T_m = \frac{Tout - Tin}{2} \qquad (III.3)$$

T_{out} : Outlet temperature of collector, ˚C

T_{in} : Inlet temperature of collector, ˚C

T_a : Ambient air temperature, ˚C

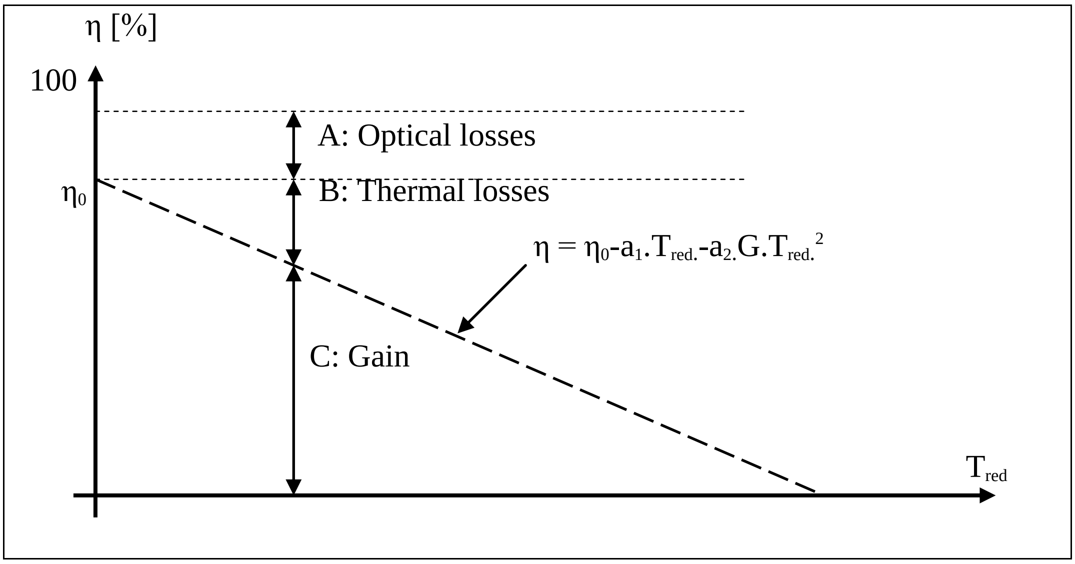


Figure III.21 Representation of Efficiency Curve

III.2.3 Tests

Thermal performance tests were made at flow rates of 60 l/h, 0.02 kg/sm^2, 280 l/h. The influence of different flow rates on thermal performance of collector was observed.

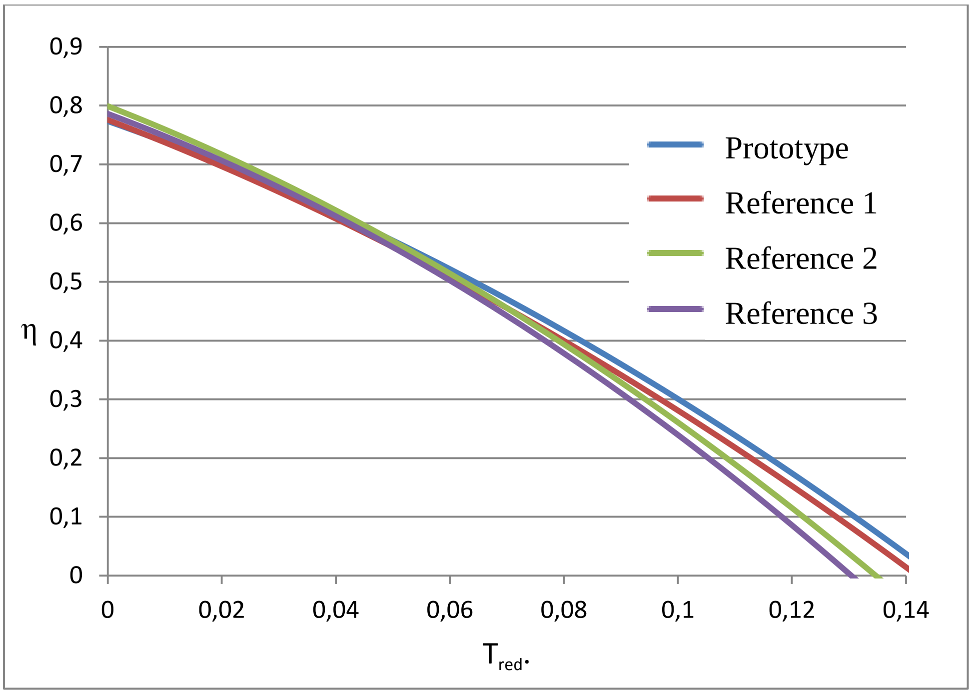


Figure III.22 Efficiency Curve at Mass Flow Rate of 0.02 kg/sm^2

Table III.1 Measurement Results of Thermal Efficiency Tests

Prototype Collector	Flow Rate		
	60 l/h	170 l/h	280 l/h
η_0	0.787	0.773	0.773
a_1	-3.744	-3.716	-3.235
a_2	-0.013	-0.015	-0.016

Figure III.22 shows the efficiency curve of four collectors at 0.02 kg/sm^2 mass flow rate. It can be seen that all collectors have nearly the same efficiency.

It can also be seen in table III.1 that efficiency results of the prototype collector at different flow rates are nearly same.

In the infrared tests the flow distribution inside the absorber was observed to find the best flow rate which has homogeneous flow distribution. But, here, in the thermal performance test it was observed that the flow rate does not have an effect on the collector efficiency.

III.3. Mixing Test

The first step of this study was the collector tests. The second step is the storage tank tests experimentally with simulation validation.

The aim of this test is to increase the thermal stratification efficiency by improving a new diffuser shape. Test equipment is a horizontal mantle (double walled) storage tank with the entry and exit parts at the bottom of the storage tank as shown in figure III.23 and its diffuser. The storage tank has a volume of 165 l.

A mantle heat exchanger is easy to construct, provides large heat transfer area and with appropriate design can promote thermal stratification in the storage tank. The primary advantage of a mantle heat exchanger is that it has low friction resistance to thermosyphon circulation and maintains the simplicity of the thermosyphon concept (Morrison, Rosengarten, Behnia, 1999).

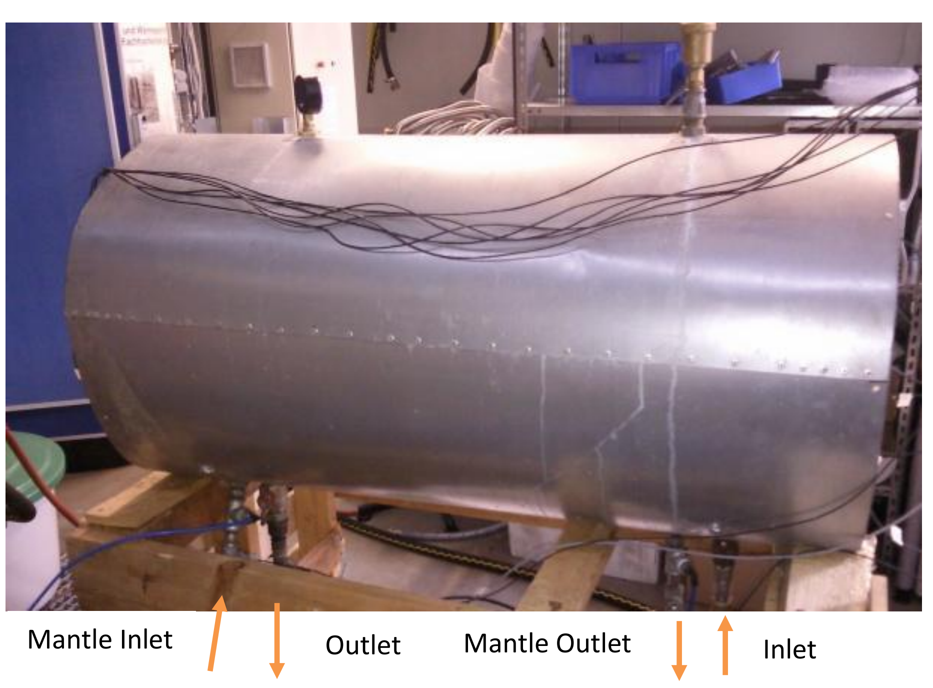


Figure III.23 Horizontal Mantle Storage Tank

The degree of stratification inside the tank depends on the design of the tank, design of the tank; the size, location, and design of the inlets and outlets; as well as the flow rates of the entering and leaving streams. It is possible to design tanks with low inlet and outlet velocities that will be highly stratified. (Duffie and Beckman, 2006)

Figure III.24 shows a general draw off curve. The blue curve is the real curve and the black curve is the ideal curve. The aim is to make the real curve as near as possible to the ideal curve. Hence, the thermal stratification inside the storage tank will increase.

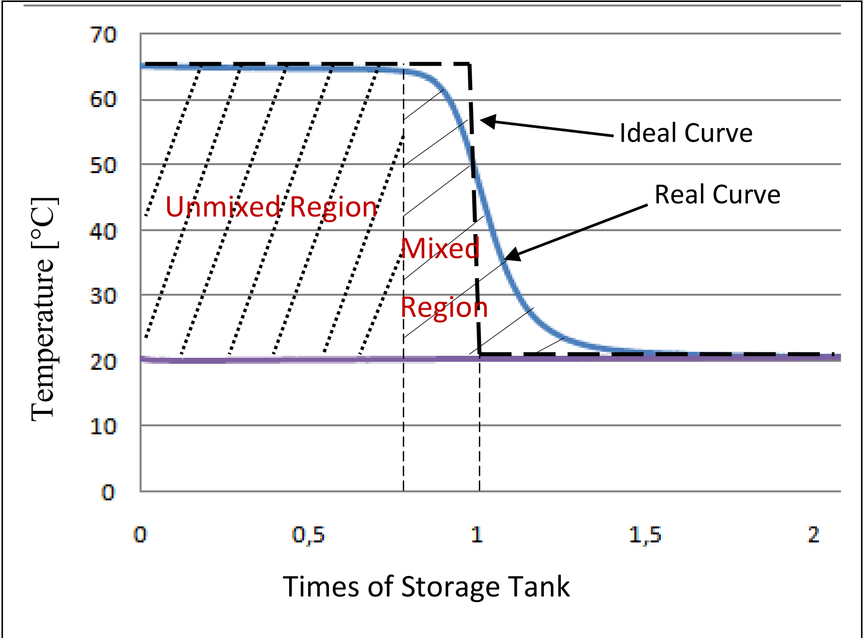


Figure III.24 A General Draw off Curve

III.3.1.Heating up Process and Testing

Before starting the test the water inside the tank is heated to 67 °C. In order to obtain this process hot water from solar collector was circulated in to the mantle of the tank and the water inside the tank was also circulated by another cycle to obtain a homogeneous flow inside the tank. The test is started after the water temperature inside the tank is reached homogeneously at 67 °C. The testing rig is shown in figure III.25.

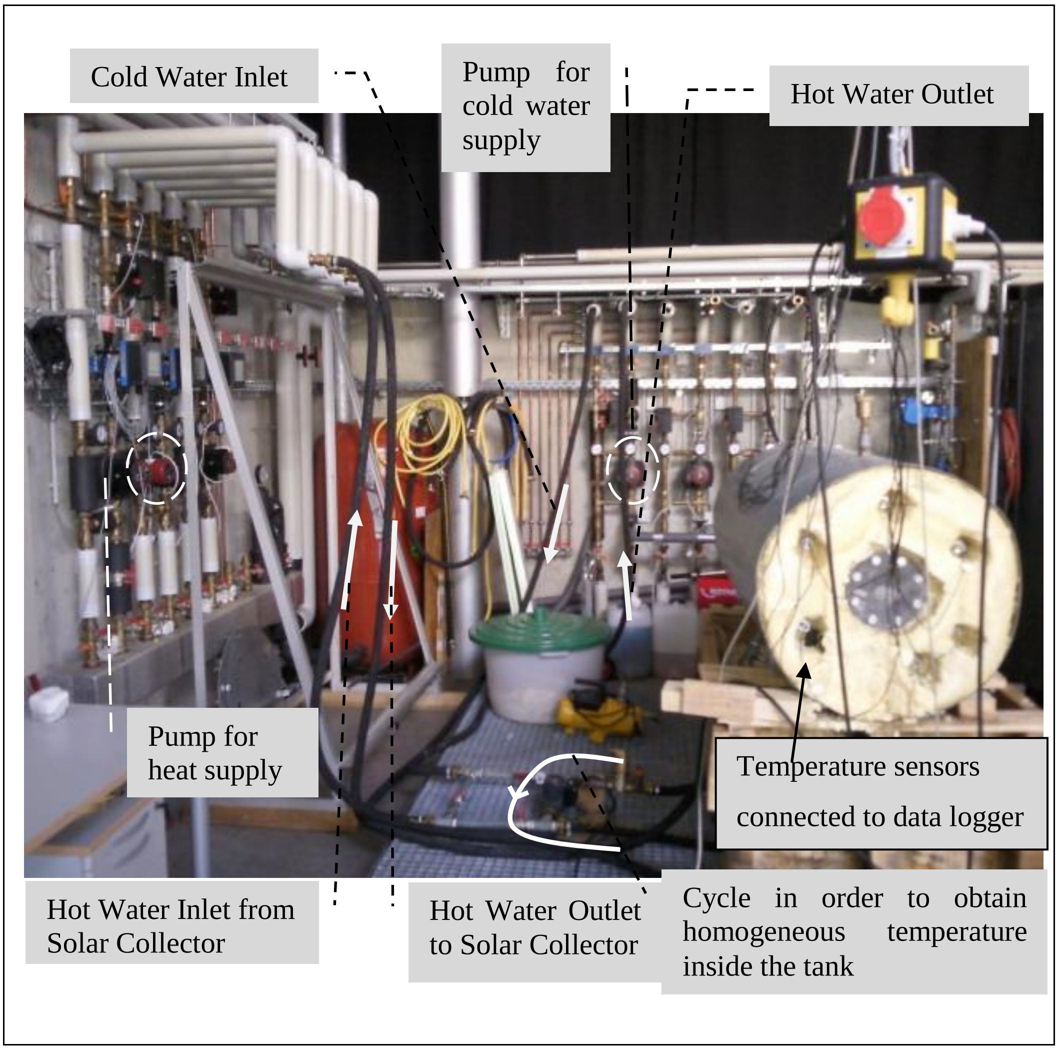


Figure III.25 Experimental Set Up of Mixing Test

Firstly, draw off curves were obtained as the mantle region of tank was full with 67 °C hot water in order to see the influence of mantle. And secondly, draw off curves were obtained as the mantle region was empty.

There are temperature sensors on the right and left sides of the storage tank in order to monitor the water temperature in the top, middle and bottom regions of the tank. These temperature sensors are connected to data logger which stores the temperature data during the test as shown in figure III.26.

1: Cold Water Temperature, °C
2: Hot Water Temperature, °C
3: Flow Rate of Cold Water to The Storage Tank Inside, lt/h
4: Collector Inlet, °C
5: Collector Outlet, °C
6: Flow Rate of Hot Water to The Mantel Inside, lt/h
7:Storage Tank Top Region, °C
8: Storage Tank Middel Region, °C
9: Storage Tank Bottom Region, °C

Figure III.26 Data Logger

III.3.2 Test Results

Firstly, thermal stratification inside the storage tank was observed with hot water inside the mantle. Secondly, after the best thermal stratification was obtained the test was made by a simulation model.

III.3.2.1 Test Results with Hot Water inside the Mantle

Test parameters are:

Tank Volume = 165 l
Flow Rate = 550 – 650 l/h (According to ISO 9452-2)
Hot Water = 65 - 67°C (inside the storage tank and mantle)
Cold Water = 15 - 18°C (entering into the storage tank)

The first test was made without diffuser inside the storage tank. The test result is as shown in the figure III.27.

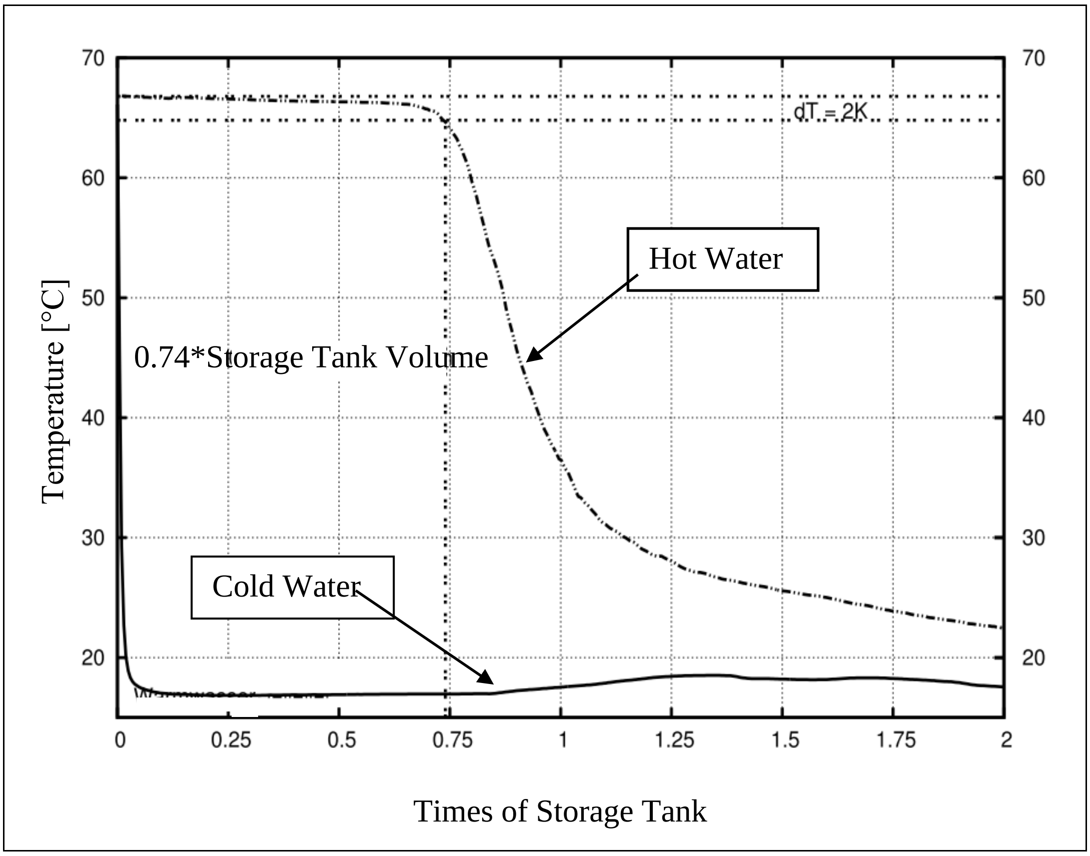


Figure III.27 Draw off Curve without Diffuser

The second test was made with original diffuser as shown in the figure III.28.

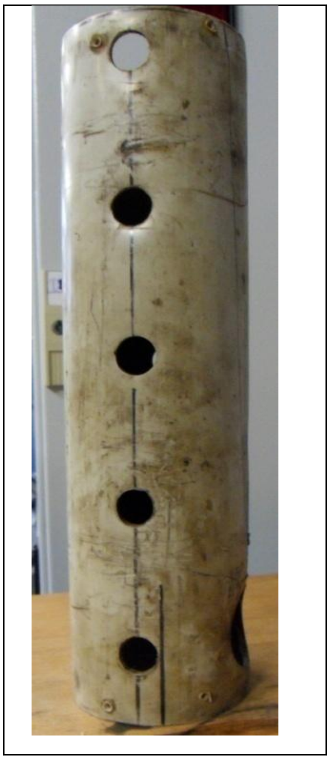


Figure III.28 Original Diffuser

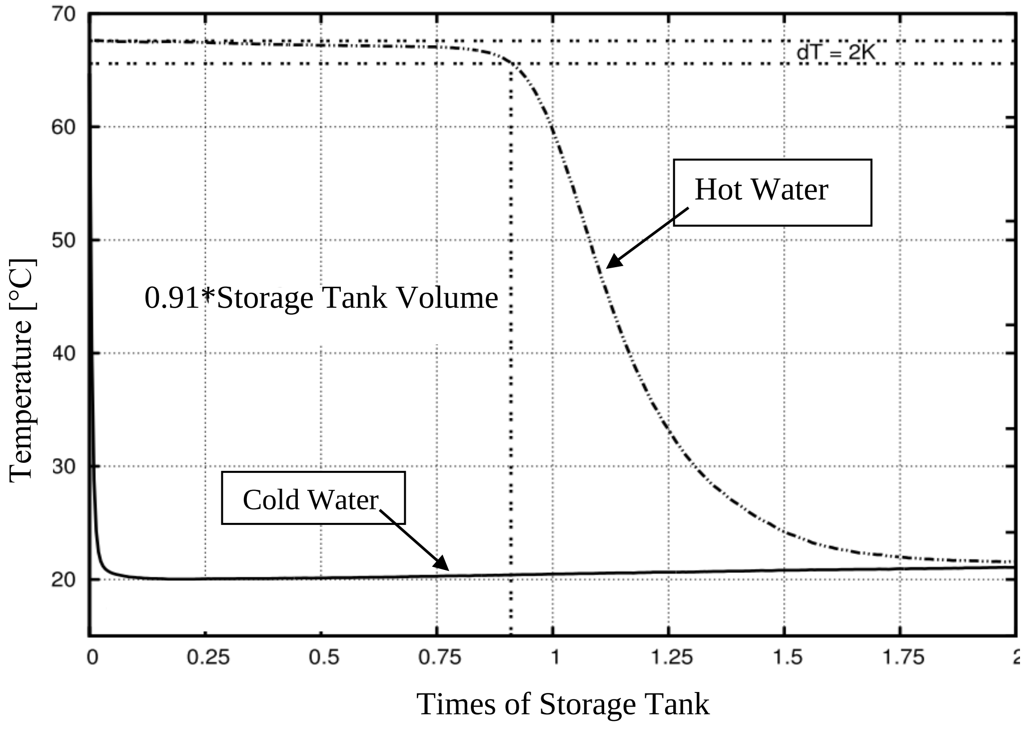


Figure III.29 Draw off Curve with Original Diffuser

The third test was made with a slotted diffuser. There is a slot at the bottom of the diffuser as shown in figure III.30 in order to deliver the cold water to the bottom region of the tank. Hence, the cold water can be kept at the bottom region of the tank as long as possible.

Figure III.30 Slotted Diffuser

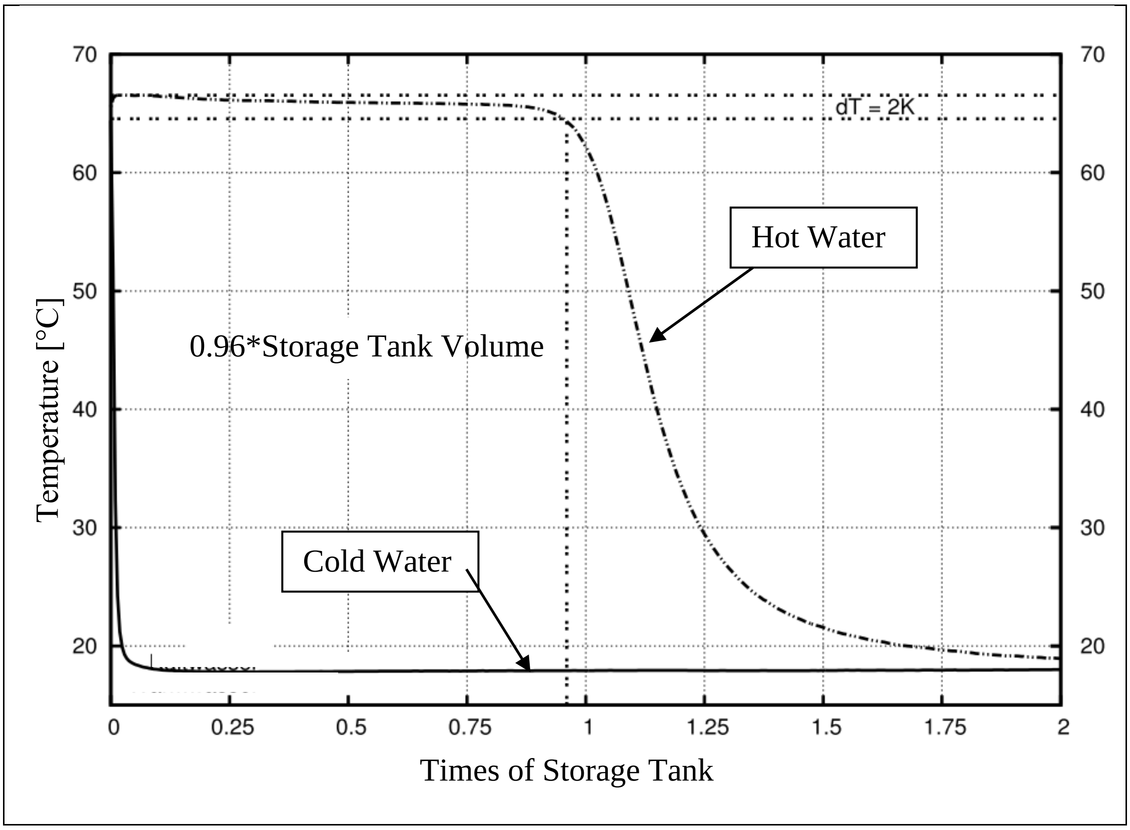


Figure III.31 Draw off Curve with Slotted Diffuser

The fourth test was made with a conical diffuser as shown in figure III.32.

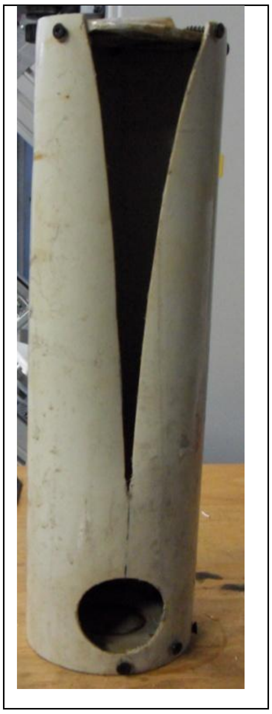


Figure III.32 Conical Diffuser

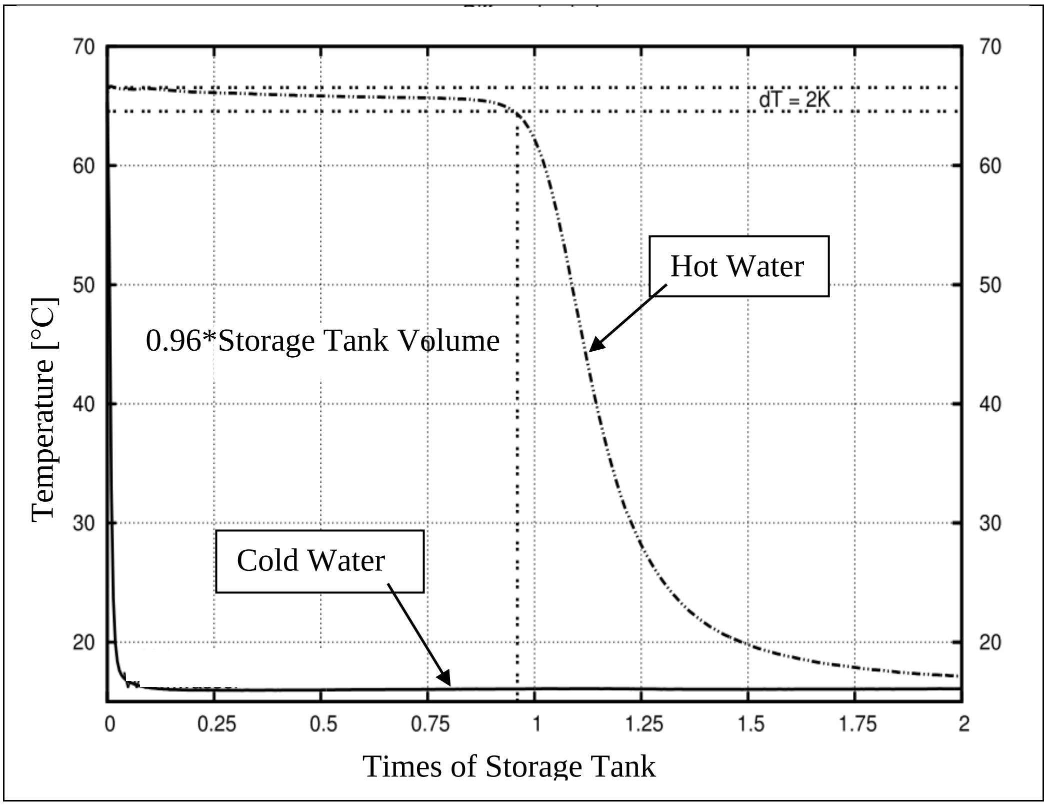


Figure III.33 Draw off Curve with Conical Diffuser

The tests show that the slotted and the conical diffuser have the best thermal stratification inside the storage tank as can be seen in figures III.27, III.29, III.31 and III.33. However, a slotted diffuser is easier to manufacture than a conical diffuser.

III.3.2.2 Test Results without Hot Water inside the Mantle

This test just was made for the slotted diffuser due to its high thermal stratification. The test was also made without hot water inside the mantle in order to make easier the simulation modelling of the test. Test parameters are:

Flow rate: 520 l/h

Water temperature inside the tank: 65 °C

Cold water temperature: 20.3 °C

The test result is as shown in figure III.34.

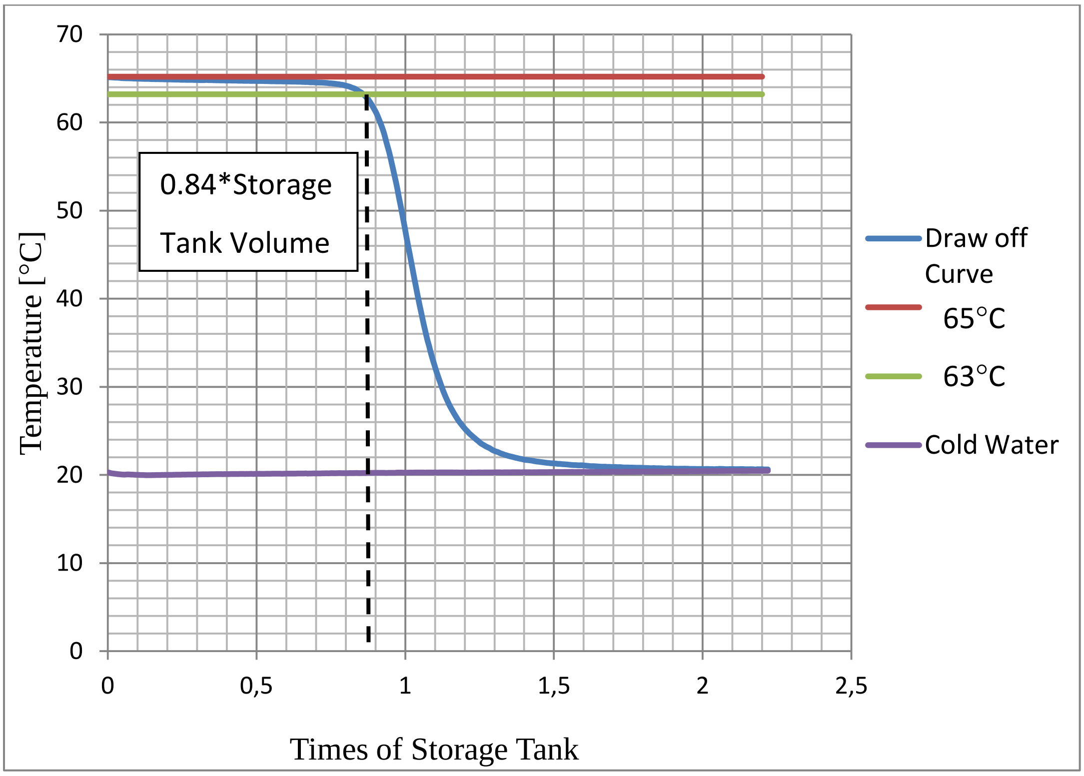


Figure III.34 Draw off Curve with Slotted Diffuser

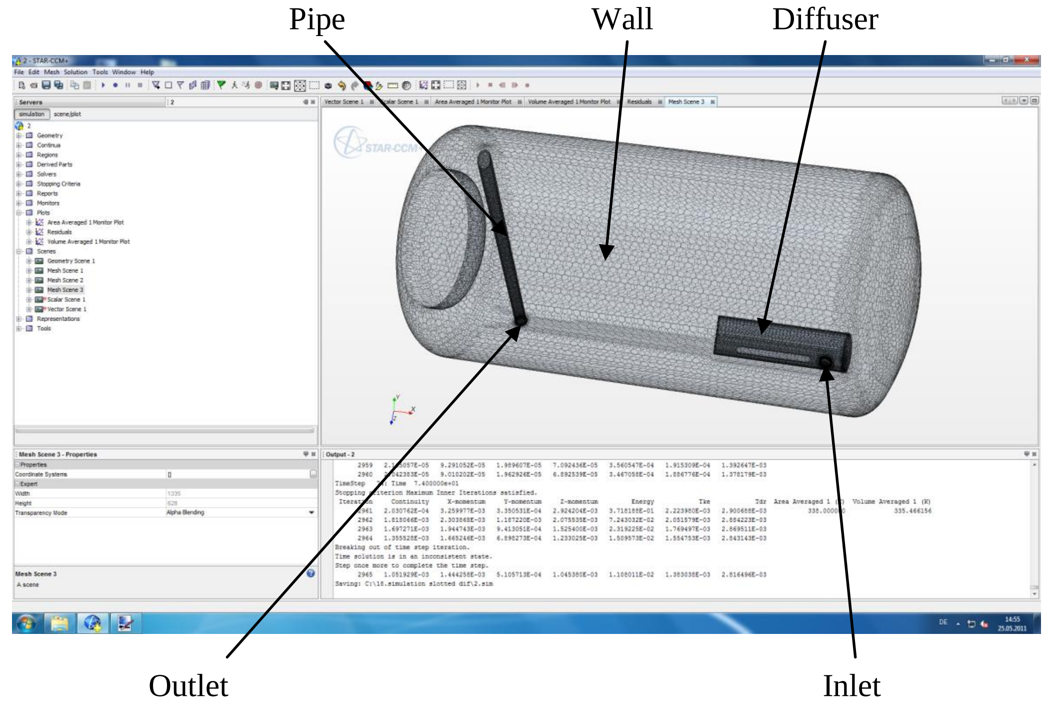
III.3.2.3 Simulation

Tests were also made by using a CFD program. The simulations are carried out by STAR CCM+ 5.06, a CFD software package of the CD Adapco Group.

Firstly, the storage tank was drawn in CATIA V5 afterwards that the CAD part was exported from the CAD software to the simulation environment where it is prepared for simulation. The file format used for transfer is the STP which converts the 3D body by creating a volume based on surfaces.

The transferred geometry was meshed as shown in figure III.35. Firstly, a surface mesh was generated by a grid of polygons on the surface of the geometry. Secondly, volume mesh was generated. Due to the complex shape of storage tank it was separated to three regions: wall, pipe and diffuser. Hence, each region was meshed at different mesh sizes in order to obtain optimum mesh size.

To achieve an acceptable cell quality, the size of the cells has to be reduced, while the numbers of cells were increased.



```
      2959   2.1[illegible]5057E-05   9.291052E-05   1.989607E-05   7.092436E-05   3.560547E-04   1.915309E-04   1.392647E-03
      2960   2.042383E-05   9.010202E-05   1.962926E-05   6.892539E-05   3.467058E-04   1.886776E-04   1.378179E-03
TimeStep   74: Time  7.400000e+01
Stopping criterion Maximum Inner Iterations satisfied.
 Iteration     Continuity     X-momentum     Y-momentum     Z-momentum         Energy            Tke            Tdr  Area Averaged 1 (K)  Volume Averaged 1 (K)
      2961   2.030762E-04   3.259977E-03   3.350531E-04   2.924204E-03   3.718188E-01   2.223980E-03   2.900688E-03           338.000000             335.466156
      2962   1.818066E-03   2.303868E-03   1.187220E-03   2.075535E-03   7.243032E-02   2.051579E-03   2.884223E-03
      2963   1.697271E-03   1.944743E-03   9.413051E-04   1.525400E-03   2.319225E-02   1.769497E-03   2.869511E-03
      2964   1.355528E-03   1.665246E-03   6.898273E-04   1.233025E-03   1.509573E-02   1.554753E-03   2.843143E-03
Breaking out of time step iteration.
Time solution is in an inconsistent state.
Step once more to complete the time step.
      2965   1.051929E-03   1.444258E-03   5.105713E-04   1.045380E-03   1.108011E-02   1.383038E-03   2.816496E-03
Saving: C:\18.simulation slotted dif\2.sim
```

Figure III.35 Meshed Part by Star CCM

After the mesh quality was obtained boundary conditions were determined. Boundary conditions specify regions on the fluid mesh and have to be placed to describe the real flow situation as closely as possible.

Inlet boundary condition specifies the section for the flow into the storage tank. The flow velocity (m/sec.) has to be specified at the inlet.

Outlet boundary condition specifies the section for the flow out of the storage tank. The flow split in (%) can be defined at the outlet.

The wall boundary condition is applied to all cell surfaces. The flow velocity is forced to zero at those surfaces according to the no slip condition.

The simulation provides the temperature data depending on the time.

The storage tank with slotted diffuser was simulated because of its high thermal stratification which obtained at the experiment. Parameters are:

Flow rate, Q = 520 l/h

Q = 520 l/h = $0.52\ m^3/h = \frac{0.52}{3600} = 1.44 * 10^{-4}\ m^3/s$

Q = A*V

A: Cross sectional area of pipe, m^2

V: Velocity, m/s

$$A = \frac{\pi * D^2}{4} \quad \text{(III.4)}$$

Inner pipe diameter between the tank and diffuser, D = 21.6 mm

$$A = \frac{\pi * 0.0216^2}{4} = 3.664 * 10^{-4} m^2$$

$$V = \frac{Q}{A} \quad \text{(III.5)}$$

$$V = \frac{1.44 * 10^{-4} m^3/s}{3.664 * 10^{-4} m^2} = 0.393\ m/s$$

$$Re = \frac{\rho * V * D}{\mu} \quad \text{(III.6)}$$

Dynamic viscosity of water, $\mu = 0.001\ Ns/m^2$

Density of water, $\rho = 1000\ kg/m^3$

$$Re = \frac{1000\ kg/m^3 * 0.393\ m/s * 0.0216\ m}{0.001\ Ns/m^2} = 8489$$

Re = 8489 > 2300

A turbulent flow model was used due to the Reynolds number.

These parameters are the same like the last test parameters of slotted diffuser in order to have comparability between the test result and simulation result.

Water temperature inside the tank: 65 °C

Cold water temperature: 20.3 °C

Simulation result is shown in figure III.36.

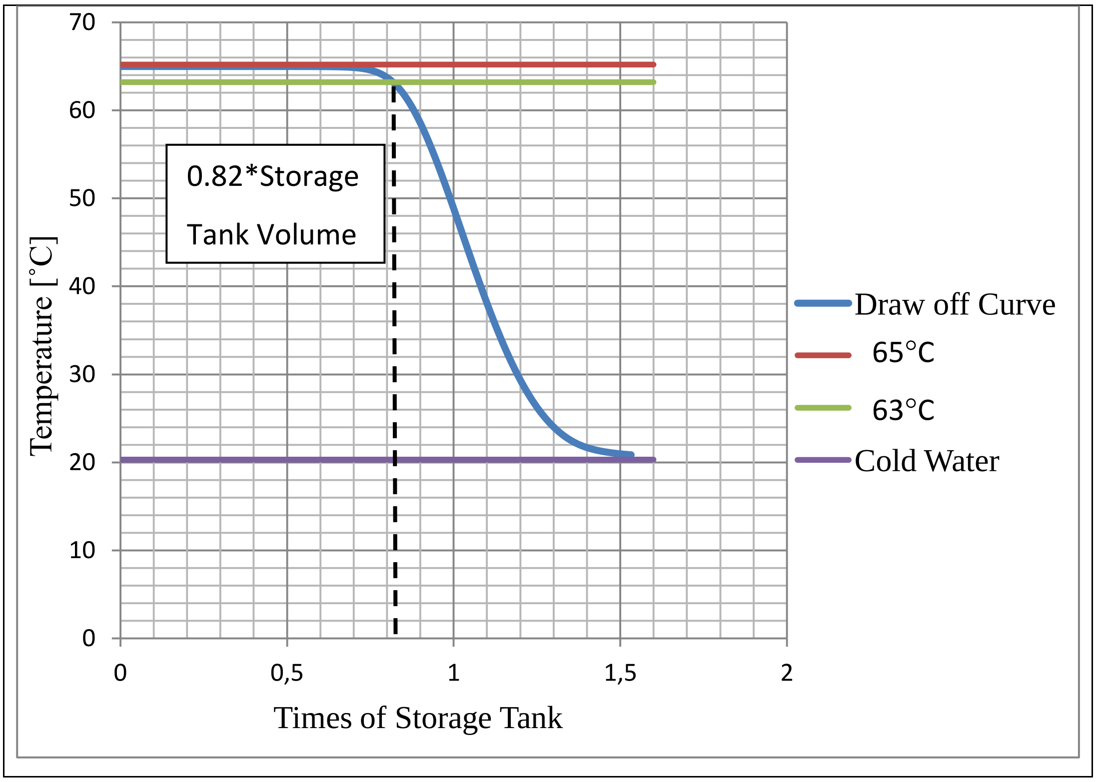


Figure III.36 Simulated Draw off Curve with Slotted Diffuser

The simulation and the test result were presented in the validation of the simulation model and showed good agreement as shown in figure III.37. The deviation between the test result and the simulation result can be explained as the sum of two reasons. The first reason is the fluctuation of flow rate during the test. The flow rate was firstly 520 l/h afterwards it changed. The minimum flow rate was 518.9 l/h, the maximum flow rate was 528.7 l/h and the average flow rate was 524.1 l/h. The second reason is the temperature fluctuations during the test. The temperature was firstly 20.3 ^{o}C afterwards it changed. The minimum temperature was 19.96 ^{o}C, the maximum temperature was 20.49 ^{o}C and the average temperature was 20.25 ^{o}C.

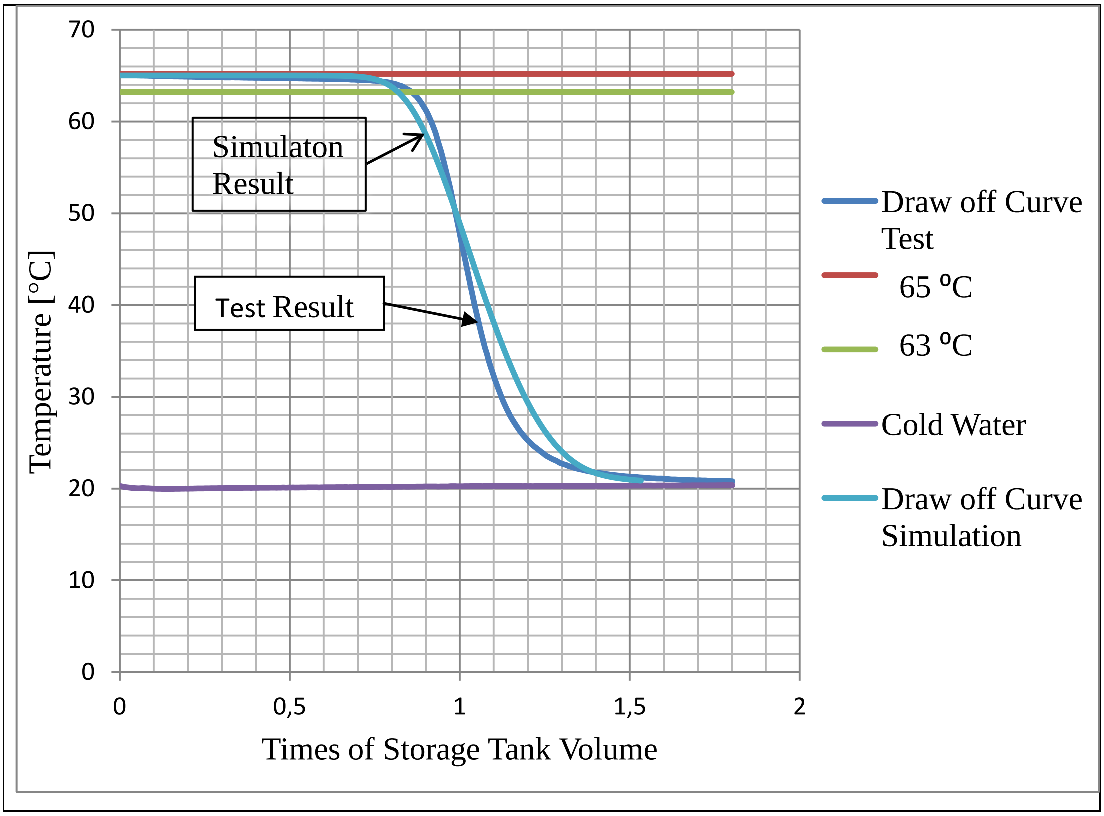


Figure III.37 Draw off Curves of The Simulation and The Test

IV. RESULTS AND DISCUSSION

In this study, thermography tests, thermal performance tests and thermal stratification tests were made.

In the thermography tests, the thermal behaviour of two type absorber was observed by a thermographic camera at different flow rates. One absorber is a volumetric absorber and the other one is sheet pipe absorber. The aim is to observe the flow stream inside the absorber and find a good inlet-outlet configuration for the volumetric absorber. For the sheet pipe absorber the aim is to see the influence of the flow rates.

500 l/h, 350 l/h and 200 l/h flow rates were used at the different configurations and positions for the volumetric absorber test. Table IV.1 shows the tests studied at the different configurations, flow rates and positions.

Table IV.1 Volumetric Absorber Tests

Test	Configuration			Flow Rate, l/h			Position
	1	2	3	500	350	200	90˚
1	X			X			X
2		X		X			X
3			X	X			X
4	X				X		X
5	X					X	X

Volumetric absorber was firstly tested at 90˚ position with flow rates of 500 l/h, 350 l/h and 200 l/h. The aim is to see the effect of the flow rates. 350 l/h flow rate give a better flow distribution than other flow rates at the first configuration.

Sheet pipe absorber tests were carried out at the flow rates of 20 l/h, 40 l/h, 60 l/h, 120 l/h and 240 l/h. 20 l/h, 40 l/h and 60 l/h flow rates gives a non-uniform flow distribution inside the risers. The flow stream is just inside first three risers. 120 l/h and 240 l/h flow rates gives better flow distribution inside the risers.

In the thermal performance tests, thermal efficiency of collectors was determined by using a solar simulator at different flow rates. The aim is to see the effect of the flow rate on the efficiency. 60 l/h, 170 l/h and 280 l/h flow rates were used. In the absorber tests flow distribution inside the absorber was observed and homogeneous flow distribution was obtained at flow rate of 240 l/h. But thermal performance tests show that flow rates do not have a major influence on the collector efficiency.

In the thermal stratification tests, different diffuser types were tested and simulated to see the effect of shape on the thermal stratification efficiency. The tests were carried out in two stages. In the first stage, the tests were made experimentally and efficient diffuser was determined. In the second stage, simulation was made for the efficient diffuser to validate the test result. In table IV.2 test and simulation results are shown.

Table IV.2 Thermal Stratification Test Results

Test	Flow Rate	Without Diffuser	Diffuser Shape			Simulation
			Original	Slotted	Conical	
1	550-650 l/h	0.74				
2			0.91			
3				0.96		
4					0.96	
Without Hot Water inside the Mantle	520 l/h			0.84		0.82

The storage tank has better stratification with diffuser than without diffuser. Slotted and conical diffusers show even a better stratification than the original diffuser. But slotted diffuser is easier to manufacture.

Simulation was carried out just for slotted diffuser due to its efficient thermal stratification. Storage tank was modelled without mantle because of the simple modelling of the storage tank without mantle. Test result and simulation result shows good agreement. The small difference between the test and the simulation is due to fluctuations of flow rate and temperature during the test.

V. CONCLUDING REMARKS AND RECOMMENDATIONS

The research covers the optimisation of thermosyphon solar hot water system experimentally with simulation validation. Thermal behaviour of two absorber types were tested. Effect of the flow rates at different absorber configurations was observed and efficient configuration was determined. Homogeneous flow distribution was determined at the flow rate of 240 l/h. The thermal performance of collectors was simulated at different flow rates. It was observed that the flow rate does not have a major influence on the collector efficiency. Thermal stratification of a horizontal mantle storage tank was tested and simulated for different type of diffusers. The test and simulation results showed good agreement and an efficient diffuser shape was determined.

REFERENCES

Duffie, J.A.; Beckman, W.A.: “Solar Engineering of Thermal Processes”, 3 rd Edition, John Wiley & Sons., **(2006)**

Brandmayr, S.; Zörner, W.: “Thermosyphon Systems: Market, State-of-the-Art and Trends”, **(2007)**

Consul, R.; Rodriguez, I.; Perez-Segarra, C.D.; Soria, M.: “Virtual Prototyping of Storage Tanks by Means of Three-Dimensional CFD and Heat Transfer Numerical Simulations”, **(2004)**

Gupta, C.L.; Garg H.P.: “System Design in Solar Water Heaters with Natural Circulation”, **(1968)**

Gülbahar, L.: GENSED, Güneş Enerjisi Sanayicileri ve Endüstrisi Derneği, RENEX 2010, Presentation of 5.Turkish-German Energy Symposium, **(2010)**

Kalogirou, S.A.: “Solar Thermal Collectors and Applications”, **(2004)**

Kalogirou, S.: “Thermal Performance, Economic and Environmental Life Cycle Analysis of Thermosyphon Solar Water Heatres”, **(2008)**

Morrison, G.L.; Braun J.E.: “System Modelling and Operetion Characteristics of Thermosyphon Solar Water Heaters”, **(1984)**

Morrison, G.L.: “Reverse Circulation in Thermosyphon Solar Water Heaters”, **(1986)**

Morrison, G.L.; Rosengarten, G.; Behnia, M.: “Mantle Heat Exchangers for Horizontal Tank Thermosyphon Solar Water Heaters”, **(1999)**

Norton, B.; Probert, S.D.: “Recent Advances in Natural – Circulation, Solar – Energy Water Heater Designs”, **(1983)**

Vaxman, M.; Sokolov, M.: “Effects of Connecting Pipes in Thermosyphoning Solar Systems”, **(1986)**

Grunwald, M.: Sun&Wind Energy, Magazine for Renewable Energies, 2010

DIN EN 12975-2.: “Thermal Solar Systems and Components – Solar Collectors – Part 2: Test Methods”, Berlin, Germany, **(2006)**

ISO 9452-2.: “Solar Heating – Domestic Water Heating Systems – Part 2: Outdoor Test Methods for System Performance Characterization and Yearly Performance Prediction of Solar – Only Systems”, ISO, Switzerland, **(1995)**

Brandmayr, S.D.: “Optimised Thermosyphon Solar Hot Water Heater – Simulation, Design and Experimental Analysis”, *Transfer Report,* **(2009)**

CD Adapco, STAR CCM+ 5.06.007. New York (United States): CD - adapco

Dassault Systems, CATIA V5R19. United States

ESTIF : European Solar Thermal Industry Federation, http://www.estif.org/pictures/gallery_copy_1/detail/?tx_dammediashop_pi2[uid]=1313, **(2010)**

CURRICULUM VITAE

I was born in Gaziantep. I completed my primary and secondary education in İstanbul. I studied mechanical engineering in Çukorova University in Adana and graduated in 2006. After graduated I worked in an automotive supply industry as an engineer. I made my military service as a lowest ranking army soldier. After military service I started to a master program in mechanical engineering department in Marmara University in 2009. During master education I had a scholarship and I went to the Germany. I studied my master thesis in the Ingolstadt University of Applied Sciences in Germany. During the education in the University in Germany I worked as an assistance student. I am still working on an engineering project in the Ingolstadt University of Applied Sciences.