

EXPERIMENTAL EVALUATION AND CFD STUDY OF THERMAL
COMFORT, IAQ INDICES, AND THERMAL ENERGY STORAGE FOR THE
IMPROVEMENT OF THE ENERGY PERFORMANCE OF OVERCROWDED
AREA

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
ATILIM UNIVERSITY

FADHIL ASAAD. MOHAMMED KADHIM AL-MALAKI

DOCTOR OF PHILOSOPHY THESIS
IN
THE DEPARTMENT OF MODELING AND DESIGN OF ENGINEERING
SYSTEMS (MAIN FIELD OF STUDY: MECHANICAL ENGINEERING)

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Approval of the Graduate School of Natural and Applied Sciences, Atilim University.

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ABSTRACT

EXPERIMENTAL EVALUATION AND CFD STUDY OF THERMAL COMFORT, IAQ INDICES, AND THERMAL ENERGY STORAGE FOR THE IMPROVEMENT OF THE ENERGY PERFORMANCE OF OVERCROWDED AREA

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In recent years, buildings, including prison halls, have contributed significantly to the world's rising energy use, with 34 % of the energy used by these buildings being attributed to cooling and heating. This study examines the use new combination of phase change materials (PCM_s) for energy conservation in buildings through thermal storage, including the use of double layers of PCM_s paraffin waxes with different properties. The study evaluates the indoor air quality characteristics of two protocols for cooling and heating in four different scenarios that are classified according to the seasons in a location, with a high daily temperature range, similar to that of Iraq. An experimental facility for the study was designed, constructed, and tested at Technology University in Baghdad. The experimental measurements were taken in a small-scale model 1:4 of a prison quarry, with dimensions of 1.2 by 0.6 by 0.8 meters and a side inlet grill. This prototype model was used to investigate the impact of integrating double layers of panels on the roof of the space and their ability to minimize fluctuations, energy usage, and shift peak load. The computational work involved solving the partial differential equation for the conservation of mass, momentum, and energy and its rate of dissipation using the finite volume technique. Modifications to the algorithm were made to simulate the space with and without PCM_s in the roof for

all scenarios. The majority of the computed data were presented as temperature contours and other thermal contours, and when compared to the experimental results, a reasonable level of agreement was observed. The use of PCM_s as latent heat thermal energy storage (LHTES) in the room envelope for passive cooling has gained significant attention due to their ability to store large amounts of energy. The results of this study show that the use of TES can reduce the energy required for the space by 47.2 % in the summer and in varying proportions during other seasons, also when PCM_s are used in hot weather, in door temperature drops by 7 °C at average, compared to when they are not used.

Keywords: Crowded prison quarry, Indoor air quality, Phase change materials, Thermal performance, peak shifting.

ÖZ

AŞIRI KALABALIK ALANLARIN ENERJİ PERFORMANSININ İYİLEŞTİRİLMESİ İÇİN TERMAL KONFOR, IAQ ENDEKSLERİ VE TERMAL ENERJİ DEPOLAMASININ DENEYSEL DEĞERLENDİRMESİ VE ÇALIŞMASI

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Ay Yıl, 182 sayfa

Son yıllarda, cezaevi binaları da dahil olmak üzere tüm binalar, dünyanın artan enerji kullanımına önemli ölçüde katkıda bulunmuştur ve bu binalar tarafından kullanılan enerjinin %34'ü soğutma ve ısıtmaya atfedilmektedir. Bu çalışma, çift katmanlı PCM kullanımı ve farklı özellikler de dahil olmak üzere, termal depolama yoluyla binalarda enerji tasarrufu için faz değişim malzemelerinin (PCM'ler) kullanımını incelemektedir. Çalışma, Irak'a benzer şekilde yüksek günlük sıcaklık aralığına sahip bir yerde mevsimlere göre sınıflandırılmış dört farklı senaryoda soğutma ve ısıtma için iki protokol kullanarak iç hava kalitesinin özelliklerini değerlendirmektedir. Çalışma için Bağdat Teknoloji Üniversitesi'nde bir deneysel tesis tasarlanmış, inşa edilmiş ve test edilmiştir. Deneysel ölçümler, 1.2 x 0.6 x 0.8 metre boyutlarında ve bir yan giriş ızgarasına sahip küçük ölçekli bir taş ocağı modelinde 1:4 alınmıştır. Bu prototip model, alanın çatısına çift katmanlı panellerin entegre edilmesinin etkisini ve bunların dalgalanmaları, enerji kullanımını en aza indirme ve pik yükü kaydırma yeteneklerini araştırmak için kullanılmıştır. Hesaplamalı çalışmalar, kütle, momentum, enerjinin korunumu ve enerji dağılım hızlarını bulmak için kısmi diferansiyel denklemlerinin sonlu hacim tekniği kullanılarak çözülmesini

içeriyordur. Tüm senaryolar için çatıda PCM'li ve PCM'siz alan simülasyonu yapmak üzere algoritmada değişiklikler yapılmıştır. Hesaplanan verilerin çoğu sıcaklık konturları ve diğer termal konturlar olarak sunulmuş ve deneysel sonuçlarla karşılaştırıldığında makul düzeyde bir uyum gözlemlenmiştir. Pasif soğutma için oda zarfında gizli ısı termal enerji deposu (LHTES) olarak PCM'lerin kullanımı, büyük miktarlarda enerji depolama yetenekleri nedeniyle önemli ölçüde dikkat çekmiştir. Bu çalışmanın sonuçları, TES kullanımının mekan için gereken enerjiyi yaz aylarında %47.2 oranında ve diğer mevsimlerde değişen oranlarda azaltabileceğini göstermektedir. PCM'ler sıcak havalarda kullanıldığında, kapı sıcaklığı kullanılmadıkları zamana kıyasla 7 °C düşmektedir.

Anahtar Kelimeler: Kalabalık cezaevi ocağı, İç mekan hava kalitesi, Faz değişim malzemeleri, Termal performans, tepe kayması.

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LIST OF ABBREVIATIONS

ACH	Air change per hour
ADPI	Air Diffusion Performance Index
ANSYS	Analysis System
ASHRA	American Society of Heating, Refrigerating Air Conditioning Engineer
ASTM	American Society for Testing the Materials
CFM	Cubic Feet per Minute
COVID19	Coronavirus Disease 2019
CFD	Computational Fluid Dynamics
CVRMSE	Coefficient of Variation of the Root Mean Square Error.
DSC	Differential Scanning Calorimeter
DNA	Deoxyribonucleic Acid Test
EC	Energy Consumption
GPCC	Granular Phase Change Composites
HCW	Healthcare Works Physics around the World
HDPE	High Density Polyethylene
HTF	Hot Heat Transfer Fluent
HVAC	Heating, Ventilating and Air Conditioning System
IAQ	Indoor air quality
ICSP	In-circuit serial programming
IEQ	Indoor Environmental Quality
ISO	International Standardization Organization
LHTES	Latent Heat Thermal Energy Storage
LHTS	Latent Heat Thermal Storage
LPG	Liquefied petroleum gas
MODES	Modelling Design Engineering Systems
NMBE	Normalized Mean Bias Error
NTUA	Nonlinear

OTP	Operational Test Procedure
PCE _s	Phase Change Energy Solutions
PCMs	Phase Change Materials
PMV	Prolonged Mechanical Ventilation
PPD	Primary Power Distribution
PPE	Personal Protective Equipment
RA	Rayleigh Number
RCC	Radiant C hilled Ceiling
RE	Reynolds Number
REC	Reduction Energy Consumption
SAT	Sodium Acetate hydrate
SBS	Sick Buildings Syndrome
SEM	Scanning Electron Microscope
SHS	Sensible Heat Storage
TES	Thermal Energy Storage
VIPs	Vacuum Insulation Panels
FLUNET	Fluid and Heat Transfer Code
3-D	Three Dimensional

LIST OF SYMBOLS

C_p	Specific capacity of heat (kJ/kg K)
C_{pl}	Specific heat of liquid PCM (kJ/kg K)
C_{ps}	Specific heat of solid PCM (kJ/kg K)
T	Temperature (°C)
U	Heat transfer coefficient
h	Enthalpy (kJ/kg)
R	Thermal resistance (°C)
k	Thermal conductivity (W/m. K)
T_m	Melting temperature
k_s	Thermal conductivity of PCM at solid state (W/m. K)
k_L	Thermal conductivity of PCM at liquid state (W/m. K)
ρ_s	Density of PCM at solid state (kg/m ³)
ρ_L	Density of PCM at liquid state (kg/m ³)
α_s	Thermal diffusivity of PCM at solid state
α_L	Thermal diffusivity of PCM at liquid state
h_0	Room outside heat transfer coefficient
h_i	Room inside heat transfer coefficient
q_s	Heat flux in w/m ²
$S_{u,v,w}$	Buoyancy source
T_{Roof}	Roof temperature °C
T_{amb}	Ambient temperature °C
u, v, w	Velocity components
ε	Dissipation Rate of Turbulence Energy m ² /s ³
$\sigma\varepsilon, \sigma k$	Turbulent prandtl Number K and ε
Γ	Diffusion Coefficient
μ	Viscosity N.s/m ²
β	Thermal Expansion Coefficient 1/K
τ_n	Time Constant . Second

CHAPTER 1

INTRODUCTION

1.1 Background

In indoor spaces like buildings and cars, heating, ventilating, and air conditioning (HVAC) systems are used to provide comfortable ambient conditions (temperature and humidity) and fresh air. Both naturally occurring carbon dioxide and man-made carbon dioxide are produced when things like gasoline, coal, oil, and wood are burned. People emit CO₂, which increases the amount of CO₂ in the atmosphere. In locations with high traffic or industrial activity, the outdoor carbon dioxide concentration is 400 parts per million (ppm) or greater. The amount of CO₂ indoors is influenced by several factors, including the number of people present, the length of time an area has been occupied, the amount of outdoor fresh air entering the area, the size of the room or area, the presence of combustion byproducts (such as idling cars near air intakes, leaky furnaces, and tobacco smoke), and the concentration of CO₂ outside. In regions with a high concentration of occupants and inadequate outdoor air ventilation, indoor carbon dioxide concentrations can range from several hundred ppm to over 1000 ppm. Water evaporates in the lungs and on the skin by absorbing body heat, and latent heat is produced when the moisture condenses on cold surfaces. Latent heat is the heat of vaporization of water. The increase in air temperature that results from inhalation is proportional to the sensible heat transfer that occurs in the lungs. Average sensible heat loss for humans are arising from roughly 30 % convection and 70 % radiation [1]. Since humans must be evacuated immediately, the latent and sensible convective heat losses indicate the "instant" cooling burden for people. The air that is breathed during respiration is at room temperature, while the air that is expelled is nearly saturated and close to deep body temperature. As a result, the body loses latent heat through lung evaporation as well as sensible heat through convection.

Based on the objective and functions of the building/vehicle, HVAC systems can be arranged in several ways. Ventilation systems clean the air by exchanging and purifying interior and outdoor air. Air conditioning systems, which provide cooling/heating and dehumidification, may be part of integrated HVAC systems or

stand-alone. Stand-alone systems typically recycle air without mixing it with fresh air from the outside. Inadequate ventilation in enclosed spaces can lead to respiratory diseases spreading more quickly [2]. There have been numerous COVID-19 transmission events associated with closed spaces [3, 4]. The proper insulation of buildings, including their walls, roofs, and floors, is crucial for reducing the rate of heat transfer into buildings during the summer and winter due to the high energy requirements of these systems. Choosing an appropriate insulation material by considering its thermal qualities in each weather scenario can benefit the economics of the buildings. Latent and sensible forms of energy storage are also possible. Energy can only be stored in sensible heat storage (SHS) by altering the temperature of the solid or liquid. SHS systems use the material's heat capacity and temperature variation while charging and discharging. The specific heat of the medium, temperature variations, and the volume of storage material all affect the mass of heat stored [5]. Latent energy storage involves harnessing latent heat and altering the phase of the substance to store energy. Phase Change Material (PCM_s) uses a latent form to store the energy. Additionally, bricks often have a higher heat conductivity than phase change materials (PCM_s). As a result, PCM_s can serve as both thermal energy storage and insulation in building construction. In recent years, the use of PCM_s as a building material has gained consideration due to their energy conservation capabilities and other beneficial properties.

1.2 Problem Statement

This study focused on congested areas with high levels of human crowding, such as jail hallways, hospitals, shelters, and elevators, while considering factors such as dread and terror. As a result of the increased consumption of electricity and the need for periodic maintenance due to the use of air conditioning and ventilation systems, the cost of bills at these locations tends to be higher. In addition, there is a risk of the transmission of viruses and toxins through the jail lobby, prison hallway, or any crowded institution due to the opening and closing of doors. Researchers are conducting research to address these challenges and develop ventilation and mobility strategies for caregivers and employees, with the aim of providing a comfortable

environment, fresh air, and a reasonable cost. Knowing how to do the induction and avoid choking to death in a crowded place is very important. It is also important to study the optimal design methodology for the (MODES) department in a realistic model, with a focus on research competence as logistically sustainable energy and its application in controlled comfortable areas for a global standard IAQ in winter and summer modes, by finding the optimal PCM_s as a barrier or insulator. The construction of high-performance buildings requires high performance building materials. In recent years, there have been numerous experimental tests on PCM_s. Iraq has an abundance of crude oil and related products and is therefore able to provide paraffin as a surplus at a low cost. While local paraffins exist, they have not yet been explored for use as PCM_s in building applications. Using locally extracted paraffin in the construction of buildings in hot and dry climates has the potential to achieve significant energy savings. In such climates, the high cost of maintaining air conditioning and heating systems due to the high consumption of electricity is a concern. In addition, in hot and dry climates like those of most Gulf countries, summers are harsh with high temperatures of up to 55°C for three months of the year. In such circumstances, power outages and substantial shutdowns caused by harsh weather conditions pose a risk to the costly and sensitive electronics and technology in buildings. Designing large air conditioning systems are essential for keeping buildings cool and comfortable during hot and humid summer days. To find alternative, more cost-effective solutions, such as collecting petroleum byproducts as paraffins, must be devised. Maintaining such an air conditioning system using conventional energy generation is very costly in terms of electricity expenditure and the overall economy.

According to this perspective, there is a pressing need to utilize locally sourced, affordable paraffins such as PCM_s in building construction. To date, little research has been conducted to assess the effectiveness of PCM_s as a slightly elevated construction material for thermal control, and their effectiveness in this regard is uncertain. It is necessary to extract paraffins and use them in a prototype sample to construct test rooms and study their thermal performance. If the prototype is successful, these PCM_s can be used to build full-scale chambers and the resulting rooms' thermal performance will be carefully evaluated in terms of temperatures under ambient conditions, heat

storage capacity, latent heat formation, and thermal expansion, etc. It is important to select the optimal PCM_s within the composition for thermal comfort. However, local paraffins as PCM_s have not yet been used in structures in hot temperature ranges, so their thermal effectiveness during the peak of summer has not yet been evaluated. Many studies suggest that these PCM_s could be promising options for building construction materials due to their economic and environmental benefits. This study represents the first time that local paraffins are being used as thermal storage materials in very hot weather conditions with crowded internal areas such as Iraq prison halls. It is essential to conduct a full-scale assessment to demonstrate their commercial viability. So that when the system is implemented on a large scale, it can achieve its objectives. This study is not limited to Iraq, but also applies to other countries with similar hot climatic conditions and especially in crowded facilities. In addition, the adoption of this development could significantly impact electricity consumption and environmental pollution caused by burning fossil fuels on the national economy.

According to a comprehensive literature review, the majority of previous studies – approximately 60% - focused on using organic PCM (paraffin) for passive cooling, while few used inorganic PCM_s. Paraffin is gaining popularity due to its high melting point, compatibility with most building environments, and good performance characteristics such as molecular stability. Hydrocarbons such as local paraffin wax with a specific chemical makeup of C_nH_{2n+2} may be particularly suitable for use in crowded areas. The melting temperature of these standard paraffins can vary depending on the crude oil and its sources, as well as its composition, and ranges from 15 to 60 °C. It is claimed that this wide range of melting temperatures is ideal for areas with high seasonal temperature fluctuations. Previous studies have only used paraffin in roofs or walls with a maximum temperature of 30 °C. However, in hot and arid regions, annual temperature changes are significant, and summer highs can reach 55°C. To assess the suitability of locally extracted materials at this temperature, it will be necessary to construct a prototype with locally extracted paraffin. Earlier studies used a prototype building construction with commercially available conventional paraffin applied to the walls or roof. Therefore, to maintain thermal comfort and reduce energy consumption systematically, it is necessary to use roof and wall structures

containing local paraffin. Figure 1.1 shows the abstract layout for this study.

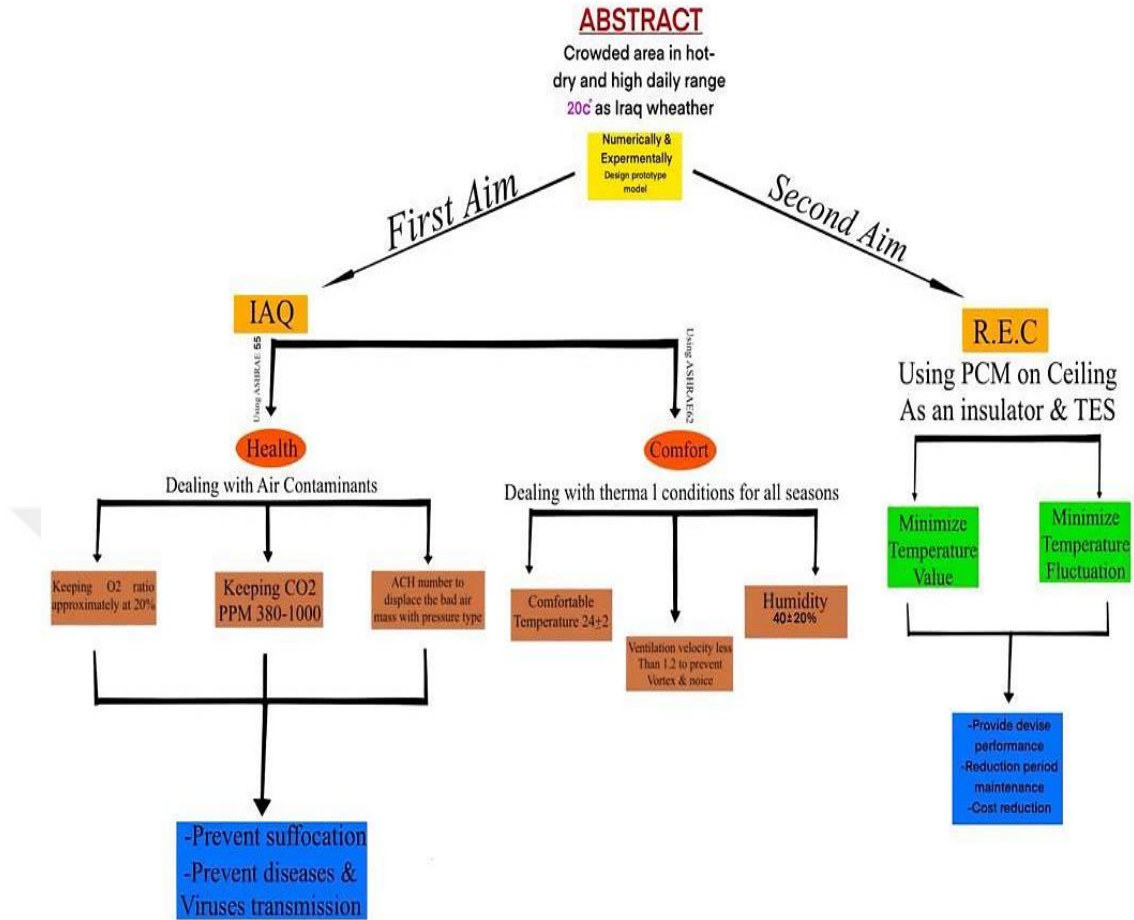


Figure 1.1: layout of the abstract concept.

1.3 Comfort and Air Quality

Thermal energy storage (TES) is a key advanced renewable technology and there has been increasing interest in its use for heating and cooling applications in buildings in recent years [6]. A significant portion of a building's energy requirements are for comfort. An energy-efficient design of building envelopes can lead to energy savings for a structure. Building envelopes consist of a configuration of building materials with thermophysical properties that determine the envelope's response to the climate. To reduce the energy consumption of a building, it is important to understand how the thermal performance of the building envelope affects the indoor environment [7].

Indoor environmental quality (IEQ) can impact the success or failure of a building construction project. As a result, many sustainable building designs today address the issue of indoor environmental quality, including comfort. ASHRAE states that a person is most comfortable when the air temperature is 24 ± 2 °C, the relative humidity is $40 \pm 20\%$, the air speed is less than 0.2 m/s, and there is a mild exchange of radiation. Indoor environmental quality refers to the relationship between a building's environment and the health and well-being of its occupants [8]. IAQ is important because indoor air quality can be more polluted than outdoor air quality and people spend 90% of their time indoors. Complex indoor environments expose building occupants to a variety of pollutants (in the form of gases and particles). Understanding the sources of indoor environmental contaminants and managing them can often help prevent or treat building-related illnesses. Multiple factors can influence the indoor environmental quality of a building. Some of these factors include:

1.3.1 Indoor Air Quality (IAQ)

Indoor air quality (IAQ) is a combination of airflow, management of organic volatile compounds, air temperature, relative humidity, water, and light. There are specific standards that address IAQ requirements by setting minimum ventilation rates for new construction and providing guidance for improving IAQ in existing buildings. These standards also provide lists of maximum pollutant levels for specific areas to maintain acceptable IAQ and reduce the likelihood that building occupants will experience adverse health effects [9].

1.3.2 Thermal Comfort

Thermal Comfort according to ISO 7730 and ASHRAE standards 55-62, thermal comfort is defined as "the mental state that indicates contentment with the thermal environment." Environmental and personal factors, as well as the building's architectural specifications, can affect thermal comfort. Air temperature is the most used indicator of thermal comfort because it is the easiest parameter to measure and the simplest indicator to utilize. However, it is not the only criterion that can be used

to accurately quantify thermal comfort, despite its importance. According to [10], air temperature must always be considered in conjunction with other environmental and design considerations. Temperature and relative humidity are two local climatic factors that affect indoor comfort, while building envelopes, orientation, shading, glazing type and size, vegetation, and thermal mass are design-dependent parameters that contribute to the thermal comfort condition in residential buildings such as hostels. Although these characteristics are independent of one another, they have a significant cumulative effect.

1.3.3 Acoustics Quality

The design community is already focusing on this additional approach to enhancing occupant comfort by creating superior acoustic environments in open-plan office buildings, healthcare facilities, multipurpose halls, and schools in order to improve speech perception and security.

1.3.4 Visual Comfort

This approach aims to create environments that are both utilitarian and aesthetically pleasing by using techniques such as artificial lighting, natural lighting, and creating visually appealing environments [11].

1.4 Affect Factors on the Thermal comfort

Environmental and individual factors influence thermal comfort, as seen in figure 1.1.

1.4.1 Environmental Factors

Ambient temperature is the most commonly used indicator of thermal comfort because it is the easiest to measure and the simplest to use. However, it is not the only criterion that can be used to accurately quantify thermal comfort, despite its importance. It is necessary to consider air temperature in conjunction with other environmental and personal factors. The following are the six environmental and personal factors that contribute to the thermal comfort of a particular location. While

these factors are separate, they have a significant cumulative effect and are illustrated in Figure 1.2.

1.4.1.1 Air Temperature:

The dry bulb temperature, which is the temperature of the air surrounding us, is one of the most important factors to consider. When designing structures for buildings and other habitations, it is important to remember that the human body's main function is to maintain a comfortable temperature [12].

1.4.1.2 Mean Radiant Temperature

The mean radiant temperature, or thermal radiation, is another important factor in determining thermal comfort. Because it stimulates the same sensory organs, falling radiation has the same effect on the human body as warm air. When these radiations strike intervening surfaces, such as clothing, the radiant heat is absorbed and subsequently transferred to the skin through the intermediate material. The mean radiant temperature and air temperature (Dry Bulb Temperature) will result in a thermal sensation of 21.11°C. The mean radiant temperature is the average of heat radiation measurements from all materials in our immediate environment, including walls, floors, other human bodies, etc. The difference between the mean radiant temperature and the air temperature may be significant [12].

1.4.1.3 Air Velocity

Air movement, or the movement of air across the occupants or subjects of a given environment, is also a significant factor in thermal comfort because people are sensitive to air velocity. It can produce the following thermal effects at various air temperatures: When the temperature of the moving air is lower than the temperature of the skin, convective heat loss increases. The airflow increases evaporation through the process of physiological cooling, and its effect is stronger when the relative humidity is below 30 % and absorption is unrestricted even when the air is motionless. Air movement cannot increase evaporation at a humidity level of 85 % because the air is already highly saturated. At a mid-range humidity level (40-50 %),

air movement increases skin evaporation to a greater extent. Activity increases airflow, so air velocity corrections should take into account the individual's level of physical activity [13].

1.4.1.4 Relative Humidity

When water is heated, its water vapor is released into the surrounding atmosphere, and the resulting volume of water in the air provides humidity. "Relative humidity is the ratio between the actual amount of water vapor in the air and the maximum amount the air at that temperature can hold." Unless it is extremely low or high, humidity has a minimal effect on heat experience [14]. Between 40 and 70% relative humidity, there is no significant impact on thermal comfort. The evaporation rate is determined by the relative humidity. In a dry environment, skin moisture evaporates faster than in a humid one. At high temperatures, heat is dissipated mostly through evaporation from the skin surface, but at 100 % saturation (moisture), there will be no cooling by evaporative means. Table 1.1 provides the recommended ranges for indoor temperature and air moisture in relation to the outdoor temperature. In fact, the factors that influence human comfort are numerous and complex, but the inhabited space can be made quite comfortable by controlling certain essential characteristics.

These factors include thermal comfort (space temperature, humidity, thermal radiation, and local air velocity); indoor air quality (air exchange rate and supply of fresh air to the breathing zone); and aural quality (noise criteria or room criteria) [15, 16].

Table 1.1: Values for inside temperature and air humidity in correlation with the outside temperature [16].

Season	Outside temperature (°C)	Inside temperature (°C)	Minimum relative humidity (%)	Maximum relative humidity (%)
Winter	$\leq \pm 20$	22	35	70
Summer	+20	22	not available	70

	+25	23	not available	65
	+30	25	not available	60
	+32	26	not available	55

1.4.2 Thermal Comfort Personal Factors

1.4.2.1 Human Activity

Humans require energy to engage in activity and generate heat to maintain an internal body temperature of approximately 36.5 °C. The higher the activity level, the more heat is produced. When too much heat is produced, the body sweats, which causes discomfort. If insufficient heat is produced, blood is diverted away from the hands and feet, the skin temperature decreases, and the individual feels cold and uncomfortable [17]. Activity level has a significant impact on thermal sensation, comfort, and preferred indoor temperature [18]. The assessment of the heat flux rate for basic activities is listed in Table 1.2.

Table 1.2: Estimate of Heat Flux rate for basic activity [19].

Basic activity	Estimate of Heat Flux Rate
Lying down	48 W/m ²
Sitting quietly	63 W/m ²
Seated office work	75 W/m ²
Light work	93 W/m ²
Medium work	117 W/m ²
Heavy work	175 W/m ²

1.4.2.2 Clothing Insulation

Clothing serves to protect the human body from inhospitable climate conditions and to maintain thermal equilibrium between the body and the surrounding atmosphere. Thermal comfort is determined by the fabric's ability to maintain skin temperature and allow the evaporation of perspiration [20]. The unit for measuring

the insulation characteristics of garments is the clo [21]. Table 1.3 provides an estimate for various clothing insulation materials. Figure 1.2 illustrates the most important environmental factors that affect thermal comfort.

Table 1.3: Clothing Levels and Insulation [19].

Description	Thermal insulation range (Clo)
Winter outdoor clothing	2-3
Normal indoor clothing	1.2-1.5
Summer indoor clothing	0.8-1.2
Indoor “Lightweight” clothing	0.3-0.5

Insulation in clothing can affect heat loss from the body and impact the body's heat balance, either keeping the body warm or causing overheating. The skin temperature of different parts of the body can vary. By adding or removing layers of clothing, people can try to adjust to their surroundings [16]. In general, air speed (increased air speed reduces garment insulation), body movement (pumping action disrupts the air layer), and water vapor transfer are the main factors that decrease clothing insulation (clothing offers resistance to the passage of water vapor and reduces heat loss through evaporation from the skin). Figure 1.3 shows the factors that influence the perception of thermal comfort.

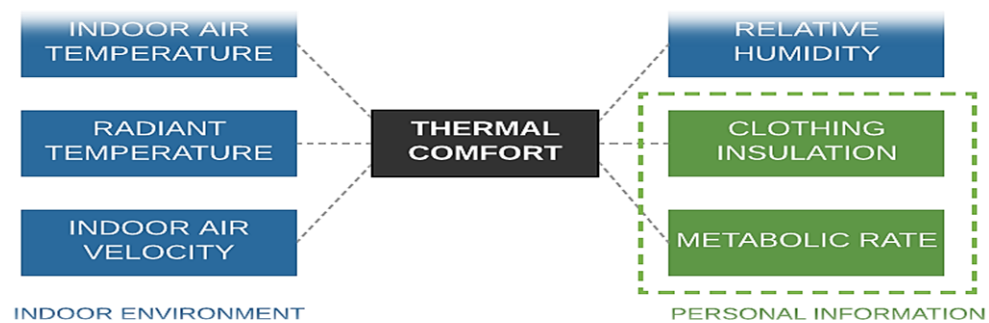


Figure 1.2: The most important environmental factors affecting thermal comfort [22].

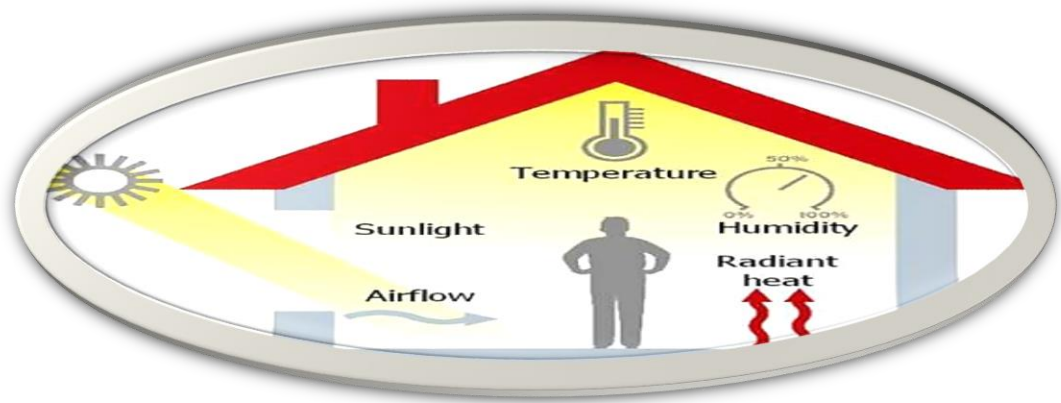


Figure 1.3: Aspects affecting the assumption of thermal comfort [22].

1.5 Ventilation Guidelines and Standards

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) is the most widely recognized standard for ventilation rates in buildings. Different codes and standards regulate ventilation rates for schools and office spaces. Some state and local codes have adopted the ventilation guidelines of ASHRAE Standard 62. According to ASHRAE specifications, the ventilation rate in classrooms should be 7.5 l/s per person to maintain indoor air quality. These values may vary depending on the occupied space and CO₂ concentrations in outdoor air. Therefore, ASHRAE recommends that the average CO₂ concentration inside the building not exceed outdoor CO₂ levels of approximately 380 ppm. Table 1.4 illustrates the relationship between CO₂ levels and the rate of ventilation of outdoor air [23]. The sick building syndrome (SBS) is not caused by obvious physiological factors, but in the long run, sick buildings can have an impact on occupants, so they should be addressed by increasing ventilation to reduce the diseases caused by them and to reduce the sources of pollution. Also it should be noted that the CO₂ readings in this table are estimates based on continuous ventilation and good mixing with a constant rate of carbon dioxide concentration outdoors of 380 ppm [23].

Table 1.4: Ventilation and resultant CO₂ concentration [23].

Carbon dioxide	Outside air (cfm per person)	CO ₂ differential (inside/outside)
800 ppm suggests about	20 cfm(or less)	500 ppm
1000 ppm suggests about	15 cfm(or less)	650 ppm
1400 ppm suggests about	10 cfm(or less)	1050 ppm
2400 ppm suggests about	5 cfm(or less)	2050 ppm

1.6 PCM Principles

Phase Change Materials (PCM_s) are passive solar techniques that utilize natural environmental forces to heat and cool. Figure 1.4 illustrates the various types of phase change heat storage materials that can be used.

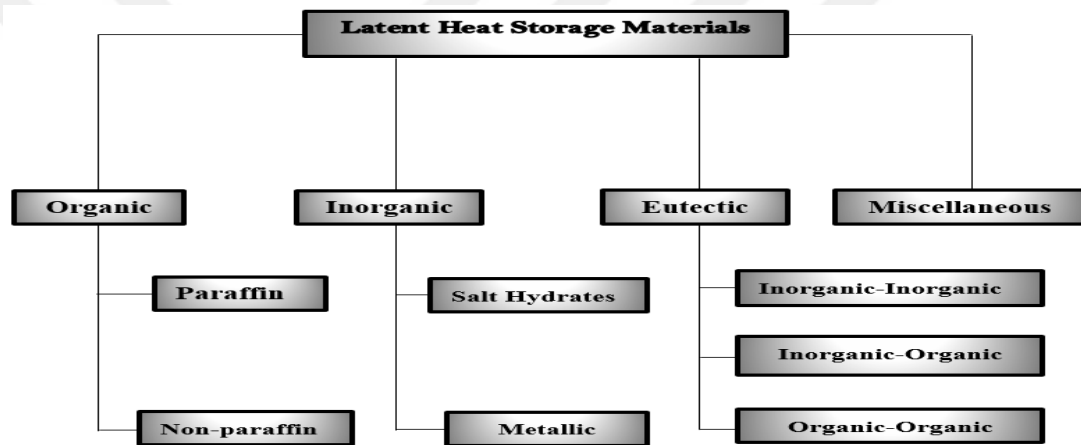


Figure 1.4: Families of phase change heat storage material [24].

In heating mode, as depicted in Figure 1.5 [24], solar radiation is absorbed by sealed PCM_s bags and retracted movable insulation panels during daylight hours. Convective heat transfer distributes thermal energy evenly throughout the roof pond, which is used to transfer heated air to the underfloor area. If solar energy is not available, or in the evening, the heat is radiated to provide illumination for the occupied space below. Radiant heat transfer from the roof pond to the interior occupied space continues to be effective until temperature equilibrium is achieved between the roof pond and the interior occupied space. In cooling mode, as shown in Figure 1.6 [25], movable insulation panels are placed over the water bags to limit heat gain from incident solar radiation and hot external air. The occupied space below consistently gains heat throughout the day, but the roof pond functions as a heat sink, mitigating this heat gain.

The retractable insulation panels are withdrawn at night, when the environment can absorb excess heat from the roof pond. At this time, the roof pond releases the accumulated daytime heat it has collected into the sky.



Figure 1.5: Roof pond heating mode [24].

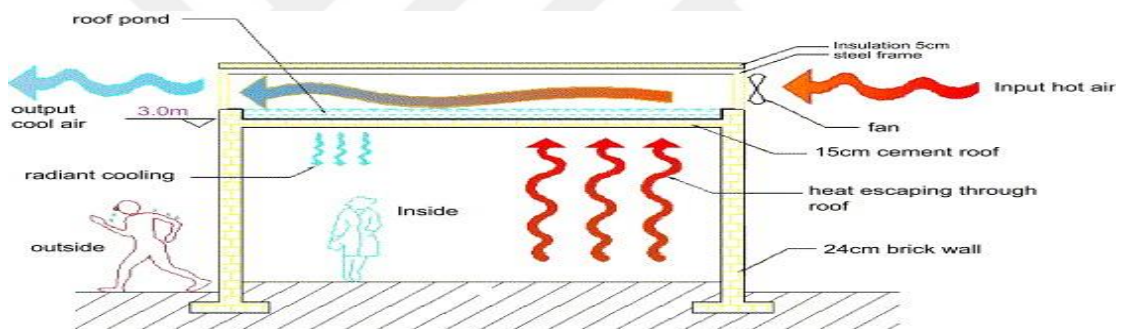


Figure 1.6: Roof pond cooling mode [25].

Phase Change Materials (PCM_s) have two properties that are determined by their molecular-level chemical bonding: melting temperatures and melting enthalpies. Figure 1.7 shows that PCM_s of common compositions have a range of melting enthalpies and temperatures [26].

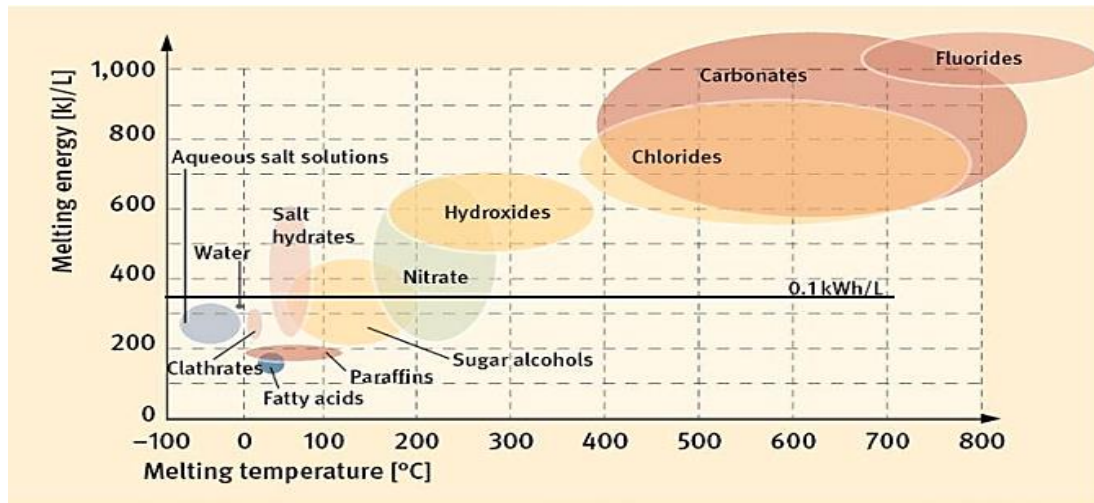


Figure 1.7: Typical range of melting temperature of PCM_s [26].

According to Hiebler et al. (2009) [27], the use of PCM_s as a storage and release method can help prevent power grid failures in emergencies. To maintain the necessary temperature for an extended period, PCM_s products require thermal mass. The graph in Figure 1.8 shows the typical heat cycle of PCM_s.

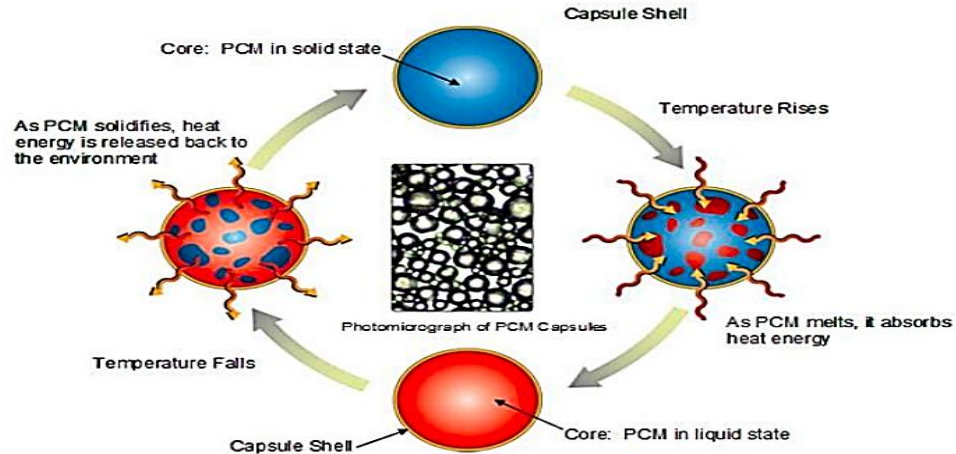


Figure 1.8: PCM_s cycles [27].

1.6.1 Phase change materials for Thermal energy Storage

Phase change materials (PCM_s) are substances that store energy in the form of latent heat during a phase changeover. The main reason for the use of PCM_s is based on the fact that the latent heat of a phase transition can serve as an effective energy storage

medium as can be understood from their name. Water, salt hydrates, and paraffin are some of the most commonly used PCM_s. Compared to traditional thermal energy storage (TES) systems, which store sensible heat, the use of latent heat storage offers a significant advantage. For example, the sensible heat of water is 4.18 J/g, while the latent heat of melting is 335 J/g. This means that the same amount of heat can be stored in a much smaller volume and mass using PCM_s. In order to be suitable for a particular application, a PCM_s should have a melting or freezing point within a specific temperature range, be non-toxic and corrosion-resistant, and have a latent heat capacity per volume that is between 5 and 15 times that of standard sensible heat storage materials (such as water, masonry, and rock). Additionally, the material should have a latent heat of phase transformations greater than 150 joules per gram ideally, and the temperature range over which melting or freezing occurs should ideally be less than 5 degrees. For various applications, it is also important for the PCM_s to have a minimum amount of supercooling (usually around 3 °C) and the ability to withstand repeated freeze-thaw cycles is crucial [28]. Thermal studies and thermal cycle test of Microencapsulated paraffin has been shown that it possess a good energy storage capacity and withstand thermal cycling up to 1000 cycles, as demonstrated by SEM images in figure 1.9 [29].

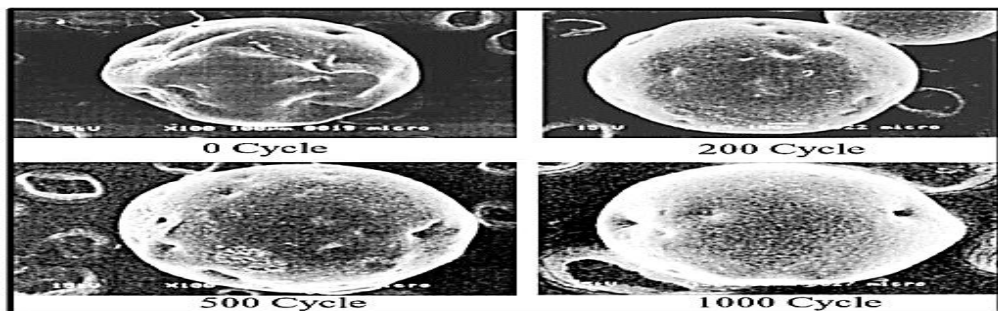


Figure 1.9: SEM images of microencapsulated paraffin at different thermal cycles [29].

1.6.2 Advantages and disadvantages of PCM_s

Phase change materials (PCM_s) can be classified into three categories: organic, inorganic, and eutectic. Organic PCM_s tend to be the preferred choice due to their

advantageous properties and acceptable drawbacks [5]. Table 1.5 compares the benefits and drawbacks of the three types of PCM_s [31, 32].

Table 1.5: Advantages and disadvantages of PCM_s [31, 32].

Classification	Advantage	Disadvantage
Organic PCM _s	(1) Availability in a large temperature range. (2) High heat of fusion. (3) No super cooling. (4) Chemically stable and recyclable. (5) Good compatibility with other materials.	(1) Low thermal conductivity. (2) Relative large volume change. (3) Flammability.
Inorganic PCM _s	(1) High heat of fusion. (2) High thermal conductivity. (3) Low volume change (4) Availability in low cost.	(1) Supercooling. (2) Corrosion.
Eutectics	(1) Sharp melting temperature. (2) High volumetric thermal storage density.	Lack of currently available test data of thermo physical properties.

1.6.3 Criteria of PCM_s selection

PCM_s have a far higher capacity for storing sensible heat and can discharge it at a nearly constant temperature. A list of appropriate PCM_s for latent heat storage over a wide temperature range has been compiled by [33]. However, not all PCM_s are suitable for thermal storage. The following characteristics are desirable for PCM_s used in thermal storage [34]:

- A high latent heat of fusion per unit mass, indicating that a small amount of material can store a large amount of energy during the phase change from solid to liquid.
- A high specific heat, allowing for increased sensible heat storage. Low or no freezing supercooling (supercooling is the cooling of a liquid below its freezing point without it becoming a solid).

- High thermal conductivity to reduce the required temperature gradient for charging the storage material.
- A melting point within the operational temperature range.
- Non-toxic, non-flammable, non-explosive, and not prone to chemical degradation.
- Thermal properties that are stable over time.
- Corrosion-resistant when exposed to the outdoors.

In terms of property stability over time, PCM_s should be able to withstand a large number of cycles without degrading. For example, if a PCM-containing construction material has a lifespan of 30 years, it should be able to withstand 11,000 daily melt and solidify cycles without losing its thermal characteristics. If the PCM_s are encapsulated or contained, the container should have physical and thermal stability that is comparable to that of the PCM_s. According to [35], paraffins have exceptional thermal stability as they do not exhibit any change in their thermal behavior due to repeated recycling. No single material has all these desirable features.

1.6.4 Phase Change Materials Applications

Phase-change energy storage is not only used in heating and cooling with solar energy, but can also be used in several applications, including [36]:

- Spacecraft thermal system.
- Thermal energy storage.
- Thermal production of electronic devices.
- Air - Conditioning system in buildings, such as storage ice.
- Electrical engines, cooling of heat.
- Cooling: food and milk products.
- Medical application: blood transportation, operating tables, and warm/cold therapy
- Off-peak power utilization: heating and cooling hot water.
- Pumps that provide heat.
- Passive energy storage in bioclimatic buildings (HDPE, paraffin).
- Plumping pyrolysis temperature peaks observed in organic molecules.
- Plants that utilize solar energy.

- A comfortable ride in a vehicle.
- Protecting the quality of food when transportation, hotel trade, or ice cream is involved.
- Computer cooling.

1.7 Encapsulation of PCM_s in the building structure

There are significant differences in the use of power during the day and night, as well as during different seasons, due to recreational, commercial, and industrial activities. These variations have resulted in different energy prices during off-peak and peak periods. An efficient thermal energy control system can help reduce energy consumption during off-peak times and can be used to meet demand during peak periods. Encapsulated phase transition materials can increase the efficiency of thermal energy conservation in a building's ceiling, walls, and floor by collecting solar energy and maintaining the inside temperature of the structure for a prolonged period of time. However, it is not possible to heat large buildings with various encapsulated commercial products due to their size (surface area). The ceilings and walls of a building provide a large passively thermal transfer surface area [37]. There are three methods for implementing PCM_s in buildings [38], as illustrated in Figure 1.10: cold and heat management units, floors and ceilings, and building walls. The first method is dynamic because it releases heat in response to demand, while the other two are passive systems because they involve the temperature-dependent storage or release of heat [39].



Figure 1.10: PCM_s encapsulated building structure [38].

1.8 Four- Way cassette air-conditioner

Ceiling air conditioners are a popular choice for adapting classrooms because they have 4-way supply outlets with a variable drainage angle that can be used in different sized spaces. This allows for high mixing efficiency and ideal air distribution within the space, making it easier to maintain a comfortable environment in accordance with ASHRAE Standards 55 [40]. Figure 1.11 shows an indoor unit air conditioning unit mounted to the ceiling.

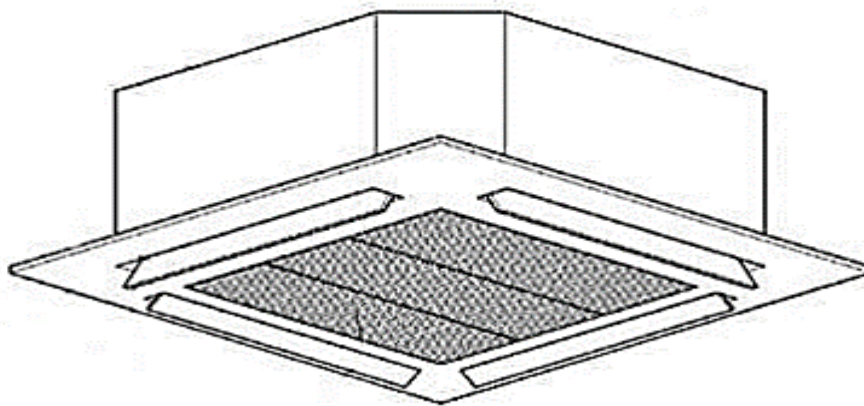


Figure 1-11: Indoor unit of a ceiling type air conditioner according to an embodiment [41].

1.9 Work Aims

Intermittent temperature changes on the surface of an exterior building element, such as thermal stress or excessive heat gains, are generally undesirable. During the heat gain season, it is important to evaluate the use of PCM_s for thermal comfort, minimizing temperature swings, reducing heat flow and power consumption at peak load, and improving the removal of contaminants and the effective air change rate. The indoor pollution level can be used to evaluate ventilation performance. This work will focus on two goals for crowded areas: first, designing and installing suitable tests to study and analyze the performance of using PCM_s on the roof and determining their effect on the comfort level in the zone; and second, developing an optimal design methodology for comfortable areas in overcrowded places using numerical simulation. The software ANSYS Fluent was used to calculate heat flux in the zone, taking into account variables such as the airflow rate of the air conditioner and the ventilation temperature. The study aims to determine the effect of using PCM_s on thermal comfort and to find the optimal cooling of the zone when it is occupied during overcrowding. It also seeks to identify the most suitable PCM_s material with a wide temperature range, low cost, and ample output.

1.10 Objectives

The objectives of this study are:

- 1) To understand the distribution of mechanical parameters and maintain the stability of the oxygen (O₂) ratio in order to prevent asphyxia, while meeting ASHRAE 55 and 62 requirements, particularly in overcrowded areas with a high daily range of temperature (Achieving a thermally comfortable area).
- 2) To analyze the thermal performance of a densely populated area in summer, winter, and transitional seasons using different PCM_s with varying melting points for the double-layer construction of the jail quarry ceiling.
- 3) To reduce temperature swings and lower energy consumption in the zone (Achieving the concept of sustainable energy).

CHAPTER 2

LITERATURES REVIEW

2.1 General

The desire to find a new, advanced, suitable, and economical method for reducing the energy consumption of air conditioning and reducing fluctuations in indoor room temperature to achieve Indoor Air Quality (IAQ) has led researchers to explore the use of Phase Change Materials (PCMs) in building construction. At the same time, airborne and infectious diseases are primarily transmitted through poor ventilation, and the recent coronavirus outbreak has significantly increased infection rates. Healthcare workers, such as physicians and nurses, put their health at risk when treating COVID-19 patients, particularly in the absence of personal protective equipment (PPE) [42]. As shown in Figure 2.1, respiratory viruses can spread and infect healthcare workers through airborne contact, indirect contact with contaminated surfaces, and direct contact when entering a space previously occupied by infected patients who sneezed. Isolation rooms with negative pressure are designed to treat patients with highly contagious disorders. Depending on the types and locations of the supply air diffuser and exhaust air diffuser in the isolation rooms, designs can be proposed to prevent the spread of pollution through the air and reduce exposure to airborne contaminants in open spaces while also enhancing the ventilation benefits of redistributing cooled air throughout the room. IAQ and the distribution of comfortable air directly impact human health. This issue remains a critical concern globally due to its significant impact on human health and worker care in hospital rooms, prison halls, and other crowded areas. Researchers who have contributed to this literature review have discussed and investigated many of the issues they have encountered, which can be divided into three parts.

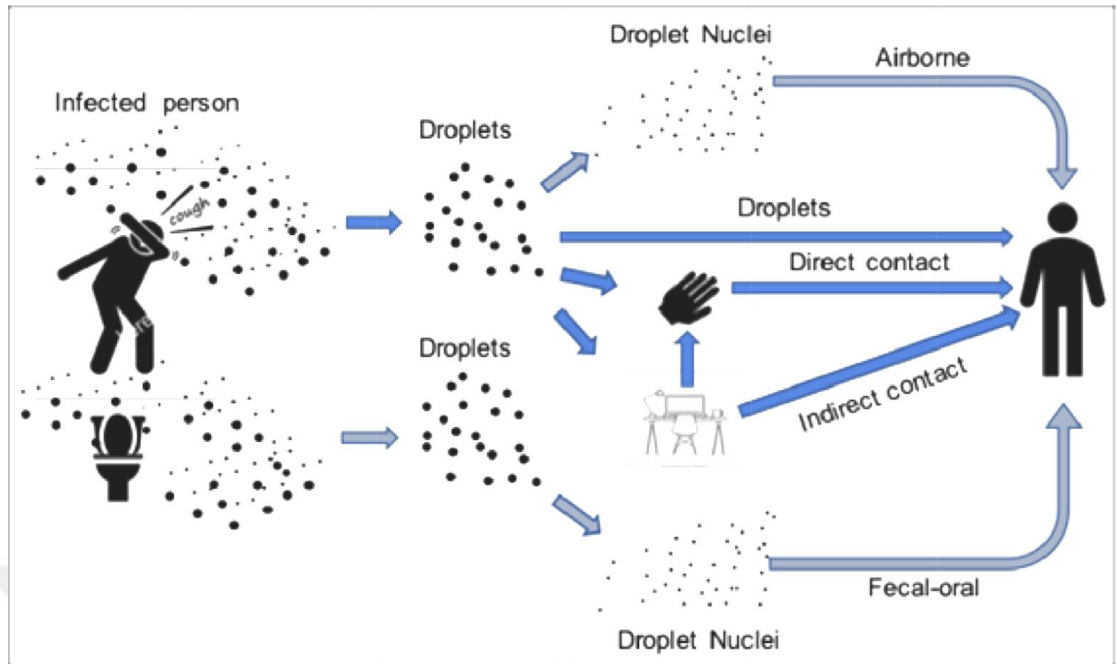


Figure 2.1: Illustrating the pattern of virus transmission [44].

2.2 Phase Change Material (PCM_s)

There has been a significant amount of research published in recent years on integrating Phase Change Materials (PCM_s) in buildings, indicating a growing interest in the potential of this technology. Since its earliest application in the 1940s, the use of PCM_s as thermal storage systems for buildings has garnered significant attention. Several promising developments exist as PCM_s are applied to building heating and cooling. This review will focus on studies that have explored the effects of integrating PCM_s in buildings and will provide conclusions to evaluate what is relevant to study in this thesis.

2.3 Literature Investigation

2.3.1 Numerical Investigation

J.xaman et al., (2008) [45] conducted a two-dimensional numerical analysis of combined heat transfer in a square chamber with a glass wall. The study included laminar and turbulent convection, surface thermal radiation, and conduction and used

the control volume method to generate numerical findings about the cavity. The chamber had a vertical glass wall, an isothermal wall, and two adiabatic walls. The conditions included a uniform temperature of 21°C within the isothermal wall, an ambient temperature of 35°C outside, and constant normal direct sun irradiation of 750 W/m² over the glass wall. The range of Rayleigh numbers used was $10^3 \leq Ra \leq 10^{12}$. The glass wall in the study was non-isothermal and combined with radiated exchange inside the cavity, leading to asymmetric flow patterns. A Nusselt number correlation was found for both laminar and turbulent flows. Kim Wittche et al., (2008) [46] also examined the effects of mechanical parameters on a construction component containing phase change materials (PCM_s), comparing testing measurements to simulation model findings. The study concluded with some simple calculations and a case study. Jørgen Rose et al., (2009) [47] analyzed the effects of latent storage on heating and cooling requirements, developing a method for assessing the effectiveness of latent storage in building components containing PCM_s. The study included the development of a software package to simulate hydrothermal conditions across an entire building. Samira and Hadi, (2009) [48] used a two-dimensional model to demonstrate the simulation and analysis of PCM_s for minimizing energy consumption in buildings. The computational method was applied to actual meteorological data from the Iranian city of Tehran. The study compared two types of brick integrated PCM_s and found that, depending on the number used, the maximum amount of heat entering a building could be reduced by 32.8%. Temperature contour plots were produced to analyze the results, showing how heat flows into bricks with PCM_s over time. The study also found that PCM_s should be placed close to the exterior of a building for optimal performance. Jegadheeswaran and Pohekar, (2009) [49] discussed strategies for improving the performance of latent heat thermal storage (LHTS) devices. These strategies included extended surfaces, multiple PCM_s, thermal conductivity augmentation, and microencapsulation of PCM_s. The study examined the impact of these strategies on the thermal responsiveness of LHTS units. It provided information on the characteristics and limits of each technique to aid in future research. Future mathematical modeling-based research on LHTS units could focus on parameter estimation for units using performance enhancement strategies.

Tabares-Velasco et al., (2012) [50] evaluated and verified a model of energy plus phase change materials (PCM_s) through three distinct applications: PCM_s dispersed in drywall, PCM_s distributed in fibrous insulation, and thin, concentrated PCM layers. The model was tested using one-dimensional tests with finite-difference solutions and validated using an analytical solution, a numerical solution from a model validated with heating at 7.3°C, and experimental data from a hot box device. A simulation of a typical home was also conducted, resulting in a slight decrease in energy usage and a 4.3% drop in peak electrical cooling load. The authors identified and addressed two errors in the PCM_s model and suggested that modeling PCM_s with significant hysteresis could reduce inaccuracy. They also recommended using time stages of less than three minutes for precise hourly efficiency and analysis.

O. Bamodu et al., (2015) [51] conducted a numerical analysis of thermal comfort in an office using a four-way cassette air conditioner. Buildings are responsible for approximately 40 % of global energy usage, much of which is used to power HVAC systems that provide thermal comfort or a high-quality interior environment, given that humans spend around 90 % of their time in buildings. The study found that the ability to adjust specific parameters of four-way cassette air conditioners commonly used in offices in Eastern China for sustainability, as depicted in figure 2.3, offers promising advantages for optimizing the control of similar HVAC systems, resulting in increased building energy efficiency, occupant comfort, and indoor air quality.

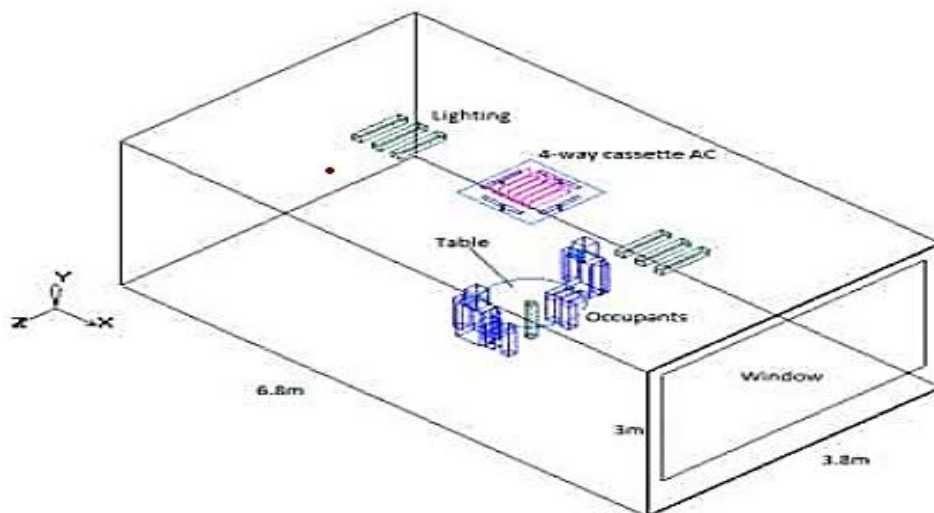


Figure 2.2 CFD model of office room with 4-way cassette air-AC [51].

Yang et al., (2016) [52] conducted a simulation of a new phase change materials (PCM_s) application called New Mass in Energy Plus using Design Builder. The study considered four different cases: no PCM_s, PCM_s with passive discharge, PCM_s with the active release, and PCM_s combined with free cooling. The model was validated using results from a real, fully-functioning building. Two indices were used to evaluate simulation accuracy: coefficient of variation of root mean square error (CVRMSE) and normalized mean bias error (NMBE). The results from the simulation and the actual structure were comparable, and energy savings were found to be between 21% and 36%.

E. Procedia et al. (2017) [53] analyzed a cooling-mode office space ventilated by four-way cassette air conditioners, which are becoming increasingly popular in Eastern China. Based on the difference between the air and velocity values measured by ADPI in the four-way cassette and a normal wall-mounted mixing ventilation system, the study concluded that the four-way cassette is more effective. In this research, computational fluid dynamics (CFD) was used to numerically simulate an office space with a four-way cassette air conditioner in cooling mode. The study compared two rooms of similar size, heated, and cooled, by variations of the layout configuration of a typical mixing ventilation air-conditioner.

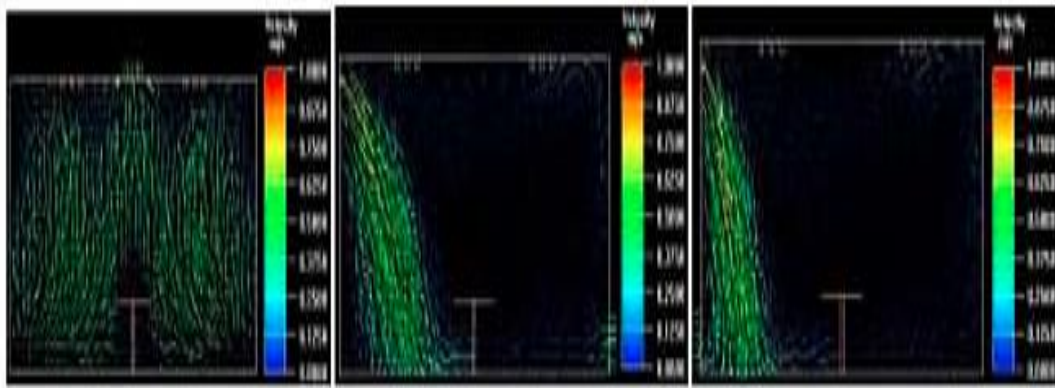


Figure 2.3: Comparing performance of the 4way and wall mounted AC [53].

Elfiky et al., (2018) [54] investigated the thermal performance of single-stage and three-stage PCM_s and units contained in spherical capsules filled with high-temperature PCM_s of melting points of 382.1°C, 439.8 °C, and 505 °C. The study numerically evaluated and compared the characteristics of the single PCM_s unit to

those of the three-stage. The results showed that the three-stage PCM_s unit has a greater heat transfer rate than the single PCM_s unit during the charging and discharging cycles and that the overall efficiency of the three-stage PCM_s device is greater than that of the single-stage PCM_s device. Bayomy et al., (2019) [55] computationally executed a three-dimensional model of a water thermal storage tank to meet domestic hot water demand. The thermal medium in the tank was n-eicosanoid, with a melting point of 36.4°C, and it was coupled to a photovoltaic thermal collector. The model assessed the efficiency of using PCM_s in a 30-gallon building water tank, projecting the exit water temperature and the efficiency of the storage facility. The study also estimated the system performance for varying water flow rates and family sizes. The results showed that the storage efficiency increased from 35% to 39% during charging periods when the hot water supply increased, and that the system's efficiency increased from 35% to 82% when the number of users increased from one to four at a particular flow rate. Additionally, the data showed that the nighttime heat absorption increased from 7869 kJ to 18,288 kJ when most families rose from one to four.

Mao et al., (2019) [56] compiled a calculation of dynamic heat storage characteristics based on MATLAB, examining the phase-change heat storage process using three HTF speeds and three phase change materials (PCM_s) starting temperatures. The PCM_s in the study were a mixture of molten salts with a 220°C melting temperature, consisting of 54% KNO₃ and 46% NaNO₃. The results showed that as the initial temperature of the PCM_s increased from 185°C to 210°C, the latent heat storage increased by 21.8 % while the total heat storage decreased. The study also found that an increase in HTF velocity from 1.8 m/s to 2.2 m/s decreased the melting time from 414 minutes to 390 minutes and expanded the sensible and total heat storage capacities. Suvanjan et al., (2020) [57] investigated the efficacy of mixing conditioned air emitted by air conditioning machines with an aerosol disinfectant to reach every point in an isolation room to kill the COVID-19 virus, as depicted in Figure 2.5. The study used a four-equation SST k-model to model the laminar transition fluxes numerically and conducted a computational fluid dynamics (CFD) analysis to analyze the temperature, turbulent energy, and flow dynamics of the aerosol sterilizer delivery system. Based

on the results, the very rough fields formed inside the isolation room might be a good way to spread disinfectant throughout the room to reduce the COVID-19 virus.

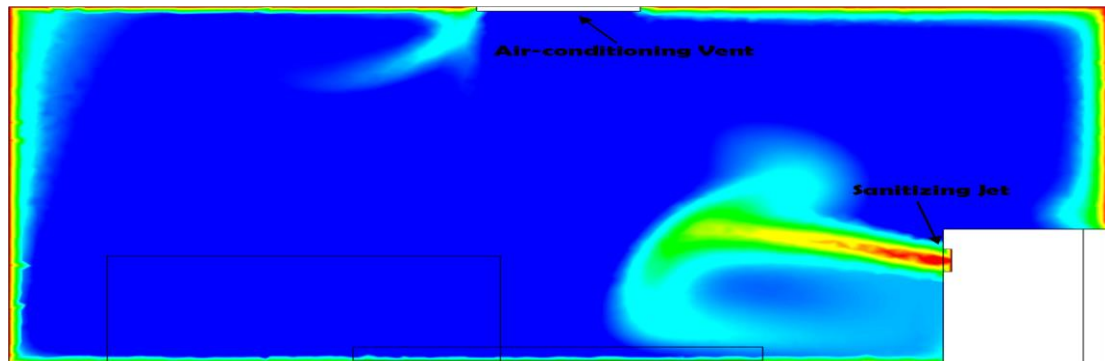


Figure 2.4: Illustrates the isolation room temperature contour (both sanitizing machine (30 °C) and working air-conditioning vent (24 °C) [57].

Lu, Yalin et al., (2020) [58] conducted a CFD study to investigate the diffusion of contaminants in a two-patient, two-bed medical unit and a healthcare worker using different ventilation methods, including layer ventilation, mixed ventilation, downstream ventilation, and compensated ventilation, as shown in figure 2.6. The study used trace gas (CO₂) to simulate pollutants such as exhalation and coughing by patients and considered different positions for the patients (lying down or sitting in bed). The results showed that the contamination layer is substantially thinner when ventilation is present, and the pollutants are effectively removed. A digital software (CFD) application for a purpose is investigated to know the distribution of pollutants in the hospital ward with two beds. A healthcare worker uses layer aeration, mixing aeration, and downward and offset ventilation. CO₂ is used to simulate contamination from exhalation and coughing, using different patient positions, including lying down or sitting in bed, to simulate exhalation and coughing. Also, after studying different pollutant concentrations, it was found that when the layer is aerated, there is relatively less pollution. It was also found that the pollution concentrations differ depending on the patient's cough, and the focus spot is significantly reduced using high ventilation.

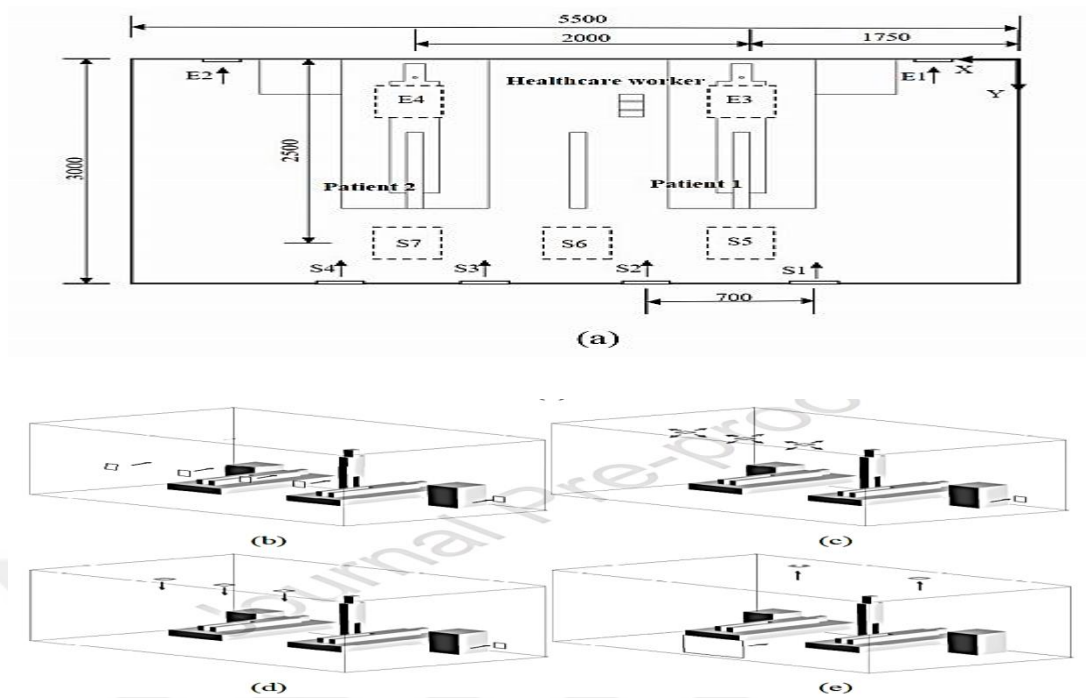


Figure 2.5: layout of the ward (a) Stratum ventilation, (b) Mixing ventilation, (c) Downward ventilation, and (d) Displacement ventilation [58].

Juan Bohórquez-Ordenes et al., (2020) [59] applied passive thermal conditioning alternatives, such as PCM_s in Chile, to improve thermal comfort in building structures. The study aimed to develop an optimized implementation strategy for PCM_s using a house from the national housing monitoring network in Santiago, Chile. The findings demonstrated that the use of PCM_s can achieve thermal comfort indices and reduce the thermal loads of the structure, resulting in reduced energy usage.

Maurizio Detommaso et al., (2020) [60] conducted dynamic thermal simulations to study the effect of new insulation materials, such as Vacuum Insulation Panels (VIPs) and PCM_s, on the amount of energy needed for heating and cooling. The simulations were conducted in climate-controlled rooms in three different cities: Catania, Rome, and Vienna. The results of simulations showed that wall layouts with VIPs could reduce the energy needed for heating but may increase the energy required for cooling. Where it is evident that PCM_s installed on the inside faces of walls have high thermal efficiency.

2.3.2 Experimental Investigation

Alawadhi E. M., (2012) [61] suggests an external shading instrument called shutters can be installed outside the window to reduce the temperature rise within a room. Throughout the day, they are thrown open to allow for the absorption of solar radiation and melting PCM_s. At night, they are closed to limit thermal loss via the window and provide the heating accumulated in the room to preserve its temperature. Using P116 paraffin, n-eicosane, and n-octadecane, a quantitative investigation was conducted on the shutter effectiveness of PCM_s employed as window shutters in Kuwaiti residential properties, as seen in figure 2.8. It was determined that heating gains might be lowered by about 16 % when P116 is used. Moreover, heat gain was decreased by around 23 % when the PCM_s shutter was maintained at 3 cm during the millimetric particle melting process. Then, this relationship seems relevant for optimizing the heat transfer condition of a particle in a heat exchanger.

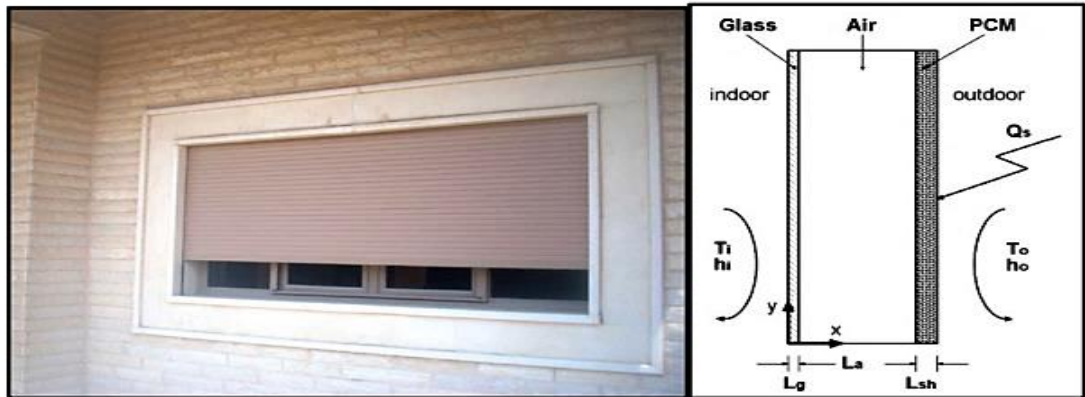


Figure 2.6: Typical windows shutter utilized in Kuwaiti residential building [61].

Hosseini and Nemati, (2017) [62] developed a shell and double tube heat exchanger model analytically for the solar thermal heat storage system. On the inside of the heat exchanger's casing were PCM_s with melting temperatures of 710 °C, 550 °C, and 400 °C. In order to charge the system during the charging cycle, the hot heat transfer fluid (HTF) raced through the tube banks. During the charging procedure, the PCM_s absorbed the thermal energy while the temperature of the HTF decreased. Observations have shown that the provided model can effectively anticipate system behavior and may be used to cascade storage systems for energy analysis.

An experimental energy analysis was conducted by Nagappan et al., (2018) [63] a hyperbolic trough heat exchanger collector is coupled to a converter's thermal energy storage system, providing latent heat storage. A melting point of 55 °C was used for paraffin wax, 96 °C for D-Sorbitol, and 163 °C for the D-Mannitol. The research was focused on controlling the losses and increasing the usefulness of multi-PCMs during the charging process; the collector made a 5.9 % power performance modification, and the experiment was done by altering the mass flow rate of the water in the storage solution for both insulated and uninsulated installations. The results showed that for flow rates of 5 and 10 liters per minute, the energy stored was 26.610 Kw and 40.48 Kw, respectively. With 5 and 10 l/min, the first law of thermodynamics yielded 47.4 % energy efficiency; on the other side, an energy efficiency of 60.4 % was obtained by applying the second law with the same flow rates. Abu- Hamdeh et al., (2019) [64] studied a small aluminum capsule utilized in the solar stove as PCM_s storage container. The capsules were put inside the parabolic reflector's receiver in order to absorb the reflected sunlight and stored it as latent heat. Acetamide was used as the PCMs for the storage system. A solar stove test was conducted using air as a heat source in the PCM_s. Three levels of fan speed were used to analyze the thermal performance. The capsule temperature dropped rapidly in the first few minutes while the pan temperature increased at the same rate. The effectiveness increased with the airflow rate. These results guide the designing process of a solar stove that offers a good thermal performance. Zhibin Wu et al., (2019) [65] In this research, the scientists conducted a thorough investigation in Changsha, China, because of the pleasant location. Between July and September 2016, eleven split-ac office buildings were reviewed. The findings suggested that occupiers desired a temperature of 26.0 °C, which is 0.60 °C lower than the equilibrium temperature of 26.70 °C. The occupants have acclimated to the thermal environment and tolerated greater temperatures than predicted by the PPD. The environmental conditions were functional for 95 % of the inhabitants. The responsive approach proved more relevant to buildings with split air conditioning systems than the PMV model. 8.6 % of summertime cooling energy use was saved. Ahmet Yüksel et al.,(2020) [66] This study focuses on the heating, cooling, and ventilation parameters of Hacı Hasan Mosque in turkey because it has a large volume, limited utilization, and

a significant number of congregants attend this church. The strategies used are going to open windows, turning on air conditioning units, and utilizing fans, as well as their mixtures, while considering the occupant's impact. Even during Ramadan month, when the research is conducted, it is advised to consider pre-cooling the mosque and turning off the air conditioning units during prayers; in this particular instance, all thermal characteristics are enhanced. Qudama Al-Yasiri et al., (2022) [67] In this experiment, two similar rooms are constructed, one with PCM_s and the other without; experiments are done under the severe hot environment of Al -Amarah, Iraq, analyzing the optimal position and thickness of the PCM_s layer in the roof and the best thermal performance of PCM_s capsules that are embedded within concrete bricks. The testing findings indicated that the combination might increase the thermal performance of building casings exposed to high outside temperatures in a manner that is not usually seen. The PCM room's temperature response seems steadier than the first room's due to a decrease in temperature variations across all of its characteristics. This is a result of the PCM_s ability to reflect the heat, which makes the perimeter element better thermally stable against varying weather conditions than local construction materials without PCM_s. The elements of the PCM_s room exhibited unfavorable thermal behavior after sunset (from 18:00 until the next day), with a rise in the interior surface temperatures of all components. This results from PCM_s insertion in a room with an unconditioned casing, during which the stored heat begins to transfer towards the low exterior ambient temperature.

2.3.3 Numerical and experimental investigations

Munksgaard, (2003) [68] studied the behavior of settling particles in most air conditioning and ventilation systems. However, displacement ventilation systems may not always follow this approach, and they typically assume that a buoyant airstream will carry pollutants upward and they will be expelled by the upper zone. Researchers have found high concentrations of decaying particles in the breathing zone, which can cause health complications for people living in the building. The numerical simulations for this study were conducted using computational fluid dynamics (CFD) programs, as shown in Figure 2.9. The study presents particle concentrations, thermal conditions,

and recommendations for modifying ventilation systems.

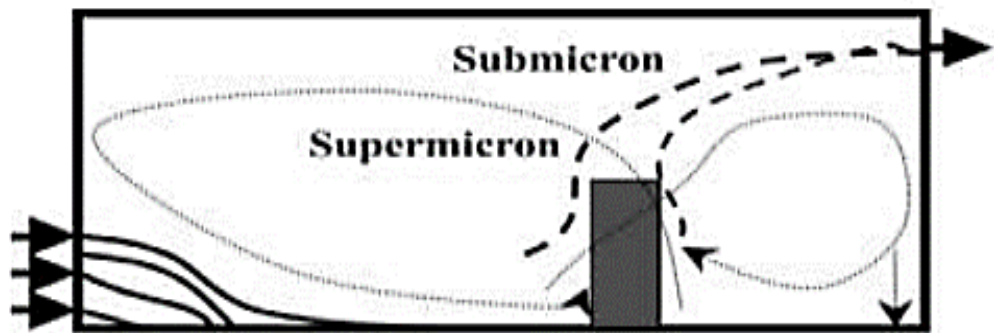


Figure 2.7: Analytical test chamber to simulate displacement ventilation [68].

T. Karimipناه, (2005) [69] conducted a study of confluent jet ventilation in the classroom using an experimental setup. Figure 2.11 shows how air velocity, air temperature, and amounts of tracer gases were affected by thermal climate. In addition to observations made by the team inside the classroom, numerical CFD simulations were performed to analyze the conditions inside, including ventilation performance and air exchange efficiency, and these were compared to measurements. The results showed that the confluent jet system was slightly more efficient than the displacement control method, and the value of the investment air exchange index indicated satisfactory air distribution in all locations.



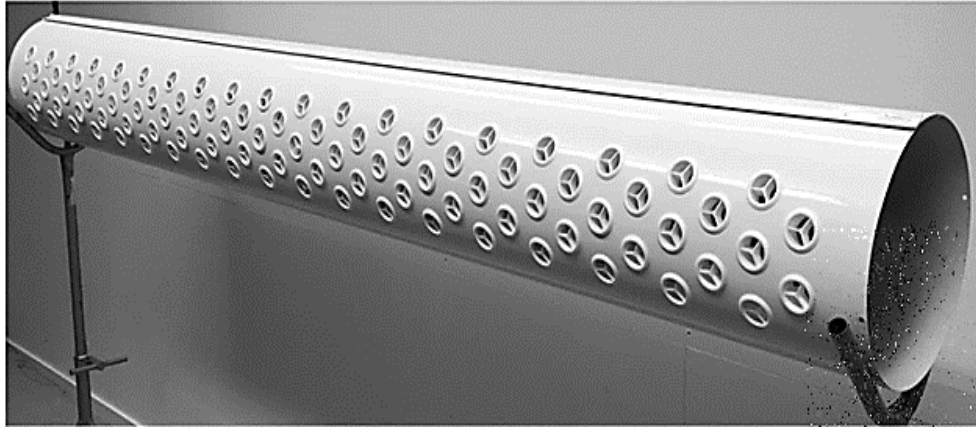


Figure 2.8: Simulators with confluent jet system in lecture hall [69].

Markopoulos, (2008) [70] conducted a study that found that three different types of PCMs have different thermal energy storage capabilities that can be exploited and optimized to minimize the cooling demand of commercial areas and reduce extreme temperatures inside the structure. At the start of the study, modest temperature reductions of around 1°C on average were achieved using each of the chosen PCMs under passive cooling conditions. However, internal temperatures exceeded the human comfort zone by more than 7 °C. The study also found that the latent heat capacity of PCMs was adversely affected by the scheduled operation of air conditioning during melting and freezing, highlighting the need for further research into the thermal characteristics of PCMs in aggressively cooled settings to optimize their performance.

Durmus and Daloğlu, (2008) [71] analyzed the non-steady-state flow behavior in an open, rectangular chamber. Experiments were conducted using a portable freezer to simulate an "open-door" scenario in which airflow was driven by free convection under two-dimensional laminar and transitional flow regimes. A commercial CFD software was used to evaluate the flow behavior in the rectangular prismatic cavity, which was assumed to have a vertical aperture, a chilled top wall, and insulating sides. The speed of the air was measured using a hot-wire anemometer. The experimentally determined average Nusselt numbers were found to be close to the numerically calculated values, and the average Nusselt number of the cooling surface increased as the door was opened and reached a steady state. The Rayleigh number was determined to be 3.2×10^8 when the temperature difference was at its greatest.

Lamberg et al., (2008) [72] used physiological verification to compare experimental results and numerical findings from FEMLAB. A collection of experimental PCM storages with and without heat transfer improvement structures was developed and built. The numerical investigation used both the enthalpy approach and the effective heat capacity method to estimate the temperature distribution of the storages during melting and freezing. Both numerical approaches provided accurate estimates, but the effective heat capacity approach, which used a tighter temperature range ($\Delta T=2\text{ }^{\circ}\text{C}$), was found to be the most accurate mathematical technique when compared to experimental data.

Rady, (2009) [73] investigated the use of granulated phase change composite (GPCC) with varying phase change temperature ranges in packed bed thermal storage. The small particle diameter of GPCC allows for the easy mixing of two or three GPCC ranges in a packed bed to improve storage unit performance. Experiments were conducted to characterize the phase-changing properties of two GPCCs selected for this purpose, and experiments on packed bed columns were conducted to gain a fundamental understanding of the heat transfer mechanism in the composite bed composed of a mixture of GPCCs with varying mixing ratios. A parametric investigation of the overall bed effectiveness at various mixing ratios and Reynolds numbers was conducted using a mathematical formula, and the optimal value of the mixing ratio was determined based on the total charging and discharging timeframes and energy efficiency. The use of units composed of a mixture of GPCCs with an optimal mixing ratio was found to significantly increase unit performance without restrictions on the charging and discharging directions during practical applications, compared to using multiple layers of GPCCs. Agyenim, (2010) [74] studied various PCM_s, the heat transfer and enhancement techniques used in PCM_s to efficiently store and release latent thermal energy, and the formulation of the phase change issue. This study also investigated the shape and geometry of PCM_s containers, and a set of analytical and experimental experiments were conducted to evaluate the impact of factors such as the input temperature and mass flow rate of the heat transfer fluid (HTF) on PCM performance, at temperatures between 0 °C and 60 °C, which are acceptable for household heating applications. Mandilaras et al., (2013) [75] tested a

Mediterranean house with walls impregnated with micronized PCM_s (BASF-micron PCM_s with a melting range of 23 °C) to assess their thermal qualities. An energy system was installed in the house and monitored for 12 months, even though it was not occupied. As shown in Figure 2.12, the demonstration house walls consisted of 50 millimeters of insulating material made from expanded polystyrene 80, one 12.5 mm panel of cement board, a layer of 80 mm rock wool insulation, one 12.5 mm gypsum plasterboard, a 300 mm gap, two 15 mm PCM_s plasterboards joined with a layer of 80 mm rock wool insulation. Internally, the walls were made of two 15 mm PCM_s plasterboards, an 80 mm rock wool insulation layer, and two 12.5 mm gypsum plasterboards. Two 12.5 mm cement boards were used to enclose the boiler room and the kitchen, followed by 80 mm rock wool insulation and two 12.5 mm cement boards. The thermal load of the structure was measured in autumn, early summer, and late spring, and it was observed that the "decrement factor" varied by about 30 % to 40 % with an increase in the time lag of 100 minutes.

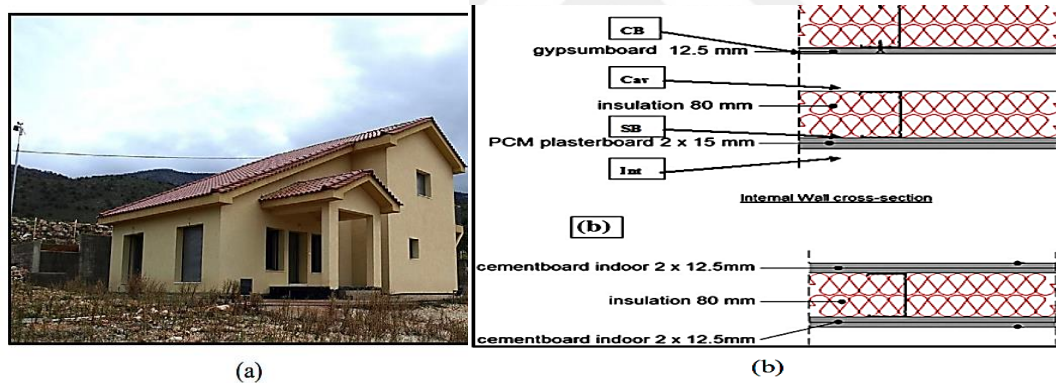


Figure 2.9 External cross-section view of the house: (a) the external wall, correspond to temperature sensors position in the east wall (b) the partition wall with cement boards [75].

Mushtaq T. H. et al., (2013) [76] provided a comprehensive review of the thermal behavior of PCM_s for energy conservation in construction through thermal storage. An experimental procedure involving two similar test areas was developed to investigate the impact of placing a PCM_s panel on the top of a building. For comparison, a room was also created without PCM_s. The PCM_s used had a melting point range of 36.7-37°C. Multiple simulations were performed for the mean ambient conditions and several additional factors of interest. The results showed that the heat transmission was

decreased by 46.71% due to the poor thermal conductivity of the PCM_s, compared to a roof without PCM_s. Stalin et al., (2013) [77] studied a customized ceiling fan designed to provide efficient cooling solutions, as depicted in Figure 2.13. The fan was made of small metal tubing with spherical PCM disks and had an intake from the building's water tank and an exit leading to the outside. The goal of the research was to compare the numerical solutions of the PCM_s cold storage simulation model in buildings. When the fan was set to 30 centimeters, the method was able to recover (17 % - 36 %) of the heat on the first gains.

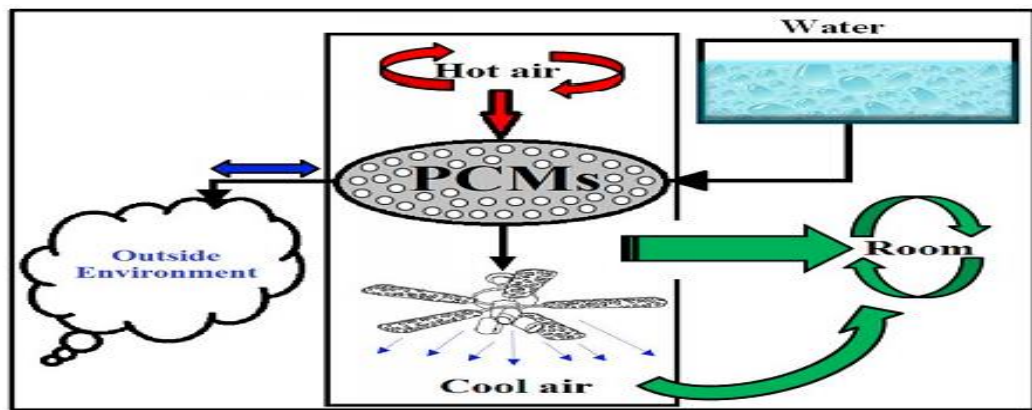


Figure 2.10: PCM design for ceiling fans [77].

Li et al., (2018) [78] suggested the use of erythritol, a phase transition material, in a novel solar collector and storage system. Three percent of expanded graphite was also added to the PCM_s. An experiment was conducted to examine the performance of the system during the charging process, and an enthalpy-porosity model was developed and experimentally validated using numerical simulation. The trial findings showed that the daily average storage efficiency of the system was 39.98 %. The simulation results also indicated that the PCM_s temperature field was uniform throughout the charging process due to the excellent thermal conductivity of the composite PCM_s, and the storage efficiency reached 34.3 %. The study also found that a decrease in incoming water temperature or an increase in water flow velocity could reduce the discharge time.

Salih et al., (2019) [79] analyzed and evaluated the thermal efficiency of a double-pass solar air heater using paraffin wax contained within multiple rectangular capsules. The researchers used a finite-volume mathematical model to address turbulent and

forced convection flow in the solar heater and conducted experiments at various airflow speeds (0.6, 0.9, 1.2, 1.5, and 1.8) and sun radiation intensities (625, 725, and 825 W/m²). The results showed that the decrease in paraffin's melting temperature due to an increase in airflow rate extended the melting duration. In addition, with the same airflow rate of 0.6 kg/min, the best discharge time and air temperature reduction were 3 hours. 2 hours at 17.95 °C for solar intensities of 825, 725, and 625 W/m², 1.25 hours at (14.3) °C and 1.25 hours at (11) °C were used respectively.

Gohar Gholamibozanjani et al., (2020) [80] used PCM_s as a passive cooling material to improve thermal comfort by stabilizing the interior temperature in this study. The thermal efficiency of an active PCM_s system was compared to that of a passive system. The test was conducted at the University of Auckland, where both cabins were cooled with an air conditioner or heated with both solar and electric heaters. Despite having 50 % less energy storage capacity than the active system, the cabin with active PCM_s required 8 % more power for space cooling to maintain comfort. Over the course of ten days in the winter, the energy consumption of a cabin equipped with an active energy storage system was 22 % less than that of a cabin equipped with a passive energy storage system. Utilizing an active storage system also reduced the cost of shifting peak load by about 32 %.

Seyedmostafa Mousavi et al., (2021) [81] conducted an evaluation to determine the performance PCM_s embedded radiant chilled ceilings (PCM-RCCs) for space cooling based on the existing literature. It was found that PCM-RCCs may be more energy-efficient than traditional air-only systems due to their ability to provide thermal comfort through direct radiant cooling, which absorbs cooling loads during the day and rejects heat at night. In Table 2.1, a full review of the available literature that has been researched is provided, along with a breakdown of each study.

Table 2.1: A comprehensive overview of the existing literatures.

N0	Author & year	Geometry/ Country	Method- ology	Findings
1	J.xaman et al., 2008	With a square hollow and a glass wall. / Mexico	Numerical	The range of values for the Rayleigh number was $10^3 \leq Ra \leq 10^{12}$. Due to the combined impact of a non-isothermal glass wall and radiative exchange in the inside hollow, the flow pattern is not symmetrical. A correlation was obtained for the total Nusselt number for both laminar and turbulent flows when correlated heat flux was included.
2	A. Durmus, et al , 2008	Top refrigerator / French	Numerical& Experimental	The system reviewed was unsteady-state natural convection in an open rectangular prism cavity. Experiments were conducted utilizing a tabletop refrigerator as an "open door." A numerical analysis of experimentally acquired average Nusselt numbers was found to be pretty similar to computationally estimated values. The average Nusselt number for the cooling surface rises as the door is opened and achieves a steady state as time passes. When the temperature difference was at its highest magnitude
3	Piia Lamberg et al., 2008	Improvement buildings were planned and built. Finland	Numerical& Experimental	Obtain physical validation of the FEMLAB-generated numerical findings. This validation was achieved by comparing experimental data and numerical findings. Both numerical techniques provided accurate estimates for the temperature distribution of the storages throughout the melting and freezing processes.

N0	Author & year	Geometry/ Country	Method- ology	Findings
4	Rady, 2009	Multi granular phase change compounds (GPCC)/ Egypt	Numerical& Experimental	Tests on packed bed columns were conducted to get a fundamental knowledge of the heat transmission mechanism in a composite bed comprised of a combination of GPCCs with varying mixing ratios. The charging and discharging operation dynamics have been analyzed using a mathematical model. Finally compared to the use of multiple sequential layers of GPCCs was done.
5	Jørgen Rose et al., 2009	Specific building/ Denmark.	Numerical	This article outlines a numerical method for computing the latent storage capacity of a structure components including PCM for assessing the Influence on heating and cooling requirements. The developed approach was included into the whole-building simulation software package (Wittchen, 2008)
6	Samira et al, 2009	Contour plots / Iran-Tehran	Numerical	This work proposes a two-dimensional model for modeling and assessing PCM in buildings in order to reduce energy usage. Two types of brick-integrated PCM are studied, and the findings indicate a 32.8% decrease in the maximum heat flux into a structure, depending on the amount of PCM.
7	Alawadhi E. M. 2012	Residential room / Kuwait	Experimental	The thermal efficacy of the proposed PCM shutter system is determined by comparing the indoor space gain to the indoor space gain of the foam shutter during normal working hours. The results reveal that PCM with the highest investigated melting temperature has the best thermal performance, reducing heat absorption by windows by as much as 23.29 %.

N0	Author & year	Geometry/ Country	Method- ology	Findings
8	Mandilaras et al., 2013	Residential apartment	Numerical& Experimental	The insulated configuration outperforms internal insulation by 8%. Meso-scale hygro-thermal simulations are also conducted with the in-house-created HETRAN code. Consequently, internal insulation requires roughly 50 percent less investment than external insulation, resulting in a shorter payback period.
9	Mushtaq T. H, et al, 2013	Building room / Iraq Baghdad	Numerical& Experimental	PCM has a melting point in the region of (36.7-37) ⁰ C. Numerous simulation runs were conducted for the average ambient conditions and for a variety of other parameters of interest. As a result of the PCM's low thermal conductivity, it provides barrier to heat flow, reducing heat transmission by 46.71 % compared to a roof without PCM.
10	E. Procedia et al. 2017	Office room / China	Numerical	Computational fluid dynamics (CFD) results suggest that the 4-way cassette air conditioner achieves higher air distribution performance than the wall-mounted system. Using the 4-way cassette AC, the results also reveal that it has an energy-saving potential.
11	Hosseininasab et al, 2017	Shell of heat exchanger /	Experimental	Using 3 PCM with high melting point 400C°-550C°-710C°, located inside heat exchanger, the results indicate that thermal energy has been absorbed while the HFT (Hot Heat Transfer) temperature has decreased.
12	Elfiky et al., 2018	Packed bed / Islamabad, Pakistan	Numerical	In this approach, spherical capsules containing PCMs with variable thermo-physical properties are utilized, and the capsules are put in the bed at various sections depending on the PCMs melting temperature and developed with the Concentric-Dispersion (C-D) equations. According to the results, the three-stage PCMs system with different melting points demonstrated the maximum energy and energy efficiency. The three-stage PCMs unit can significantly increase the heat transfer rate and substantially reduce the heat storage duration.

N0	Author & year	Geometry/ Country	Method- ology	Findings
13	Nagappan et al., 2018	Parabolic special mechanisms / India	Experimental	In both insulated and uninsulated storage systems, the energy analysis is conducted by varying the mass flow rate of the HTF. The observed energy variation for 5 and 10 liters per minute is 24.609 and 40.48 kW, respectively. The vast amount of energy and exergy stored in the system can be linked to the high flow rate of the HTF.
14	Li et al., 2018	Evacuated tube parabolic trough collector /Shanghai ,China	Numerical& Experimental	Erythritol-based solar collector and storage system. The results demonstrate that the solar collector/storage system with composite PCM has excellent thermal storage performance, with an average daily storage efficiency of 39.98%.
15	Bayomy et al., 2019	30-gallon commercial domestic hot water tank utilized in buildings/ Canada.	Numerical	The results revealed that an increase in the solar collector's hot water supply produced a rise in the outlet water temperature during the discharge period for a single family's demand. The storage efficiency was found to be relatively poor. An increase in the proportion of energy recovered during the evening as a result of the family's increased need improved the thermal storage efficiency.
16	Mao et al., 2019	Solar thermal power station with solar energy storage Wuhan, China	Numerical	The latent heat storage increases by 21.8 % when the initial temperature of the PCM _s is raised from 185 °C to 210 °C, whereas the total heat storage decreases. By raising the HTF speed from 1.8 m/s to 2.2 m/s, the melting time was reduced from 414 minutes to 390 minutes, and total heat storage and sensible heat storage were also increased. In addition, the results indicate that altering the initial temperature of the PCM _s and the flow rate of the HTF will impact the thermal storage performance of the system.

N0	Author & year	Geometry/ Country	Method- ology	Findings
17	Zhibin Wu et al 2019	HVAC devise in China	Experimental	Indicated that residents favored a temperature of 26 °C, which was 0.6 °C lower than the neutral temperature of 26.7 °C. Occupants have acclimated to the thermal environment and have accepted temperatures higher than those predicted by PPD. 95% of the occupants were able to function in the temperature environment.
18	Hamdeh et al., 2019	Solar stove / Saudi Arabia	Experimental	The energy efficiency between the PCM tubes and air flow increased as the air flow rate rose. The results provide vital information for the construction of a prototype solar stove with a high thermal performance material for thermal energy storage.
19	Salih et al., 2019	Dual-pass solar air heater Basra, Iraq	Numerical & Experimental	The TSE of a dual-pass solar air heater with PCM was investigated. Effects of sun energy and airflow velocity on paraffin's melting/freezing duration enhanced by encapsulation technology were described. Results demonstrated that an increase in airflow rate causes a delay in the melting period and a drop in the melting temperature of paraffin during the melting period.
20	Suvanjan et al., 2020	Isolation room in hospital / Rajasthan, India	Numerical	Four transport equations are used in the current study to investigate the effectiveness of conditioned air from air-conditioning machines mixing with Aerosol sanitizer to reach every point in the isolation room in order to kill the COVID-19 virus. The analysis reveals that high turbulent fields generated inside the isolation room may be an effective means of distributing sanitizer in the entire volume of the isolation room in order to kill the COVID-19 virus.

N0	Author & year	Geometry/ Country	Method- ology	Findings
21	Lu, Yalin et al. 2020	Hong Kong, China	Numerical	Highlights of this work include the treatment of exposure risks in hospital wards under stable conditions and the comparison of transitory states with MV, DV, and DWV. SV minimizes the exposure risk of healthcare workers in the hospital ward; hence, the study of ward air dispersion is indicated, followed by the recommendation of a working area for healthcare workers. Under strata ventilation with two patients breathing, the pollutant concentration in the breathing zone (1.3–1.7 m above the floor) is significantly lower, and the contaminant removal efficiency is relatively higher. Under strata ventilation, the aspirated pollutant is rapidly diluted, and the high-concentration location is diminished considerably.
22	Bohórquez- Ordenes, et al. 2020	Building in Santiago, Chile	Numerical	Results from the study achieved thermal comfort indexes and thermal loads were reduced, resulting in decreased energy usage.
23	Maurizio Detommaso, et al. 2020	Test room is situated in three distinct locales (Catania, Rome, and Wien).	Numerical	According to simulation data, wall layouts that use VIPs can reduce heating energy requirements but may give raise to energy requirements for cooling. Observable evidence suggests that the PCM installed on the inner wall face is thermally efficient.

N0	Author & year	Geometry/ Country	Method- ology	Findings
24	Gohar Gholamib ozanjani, et al. 2020	Two cabins are built At the University of Auckland/ NEWZALA- ND	Numerical & Experimental	For ten days of testing in the winter, the energy consumption of a cabin equipped with an active storage system was 22% less than that of a cabin equipped with a passive storage system with the same amount of energy storage capacity. Using an active storage system resulted in a 32% decrease in the cost of power for peak load shifting research.
25	Ahmet Yüksel, et al. 2020	Mosque in Yalova Turkey	Experimental	It is advised to consider pre-cooling the mosque and shutting off the air conditioning during prayers, in this scenario, all thermal parameters are enhanced. In consideration of the effect of occupancy, the following tactics are employed: opening windows, turning on air conditioners, employing fans, and various combinations thereof.
26	Seyedmos tafa Mousavi, et al. 2021	Radiant chilled ceilings (RCCs) that incorporate phase change materials (PCMs), Univ ersity of Melbourne, Australia	Numerical & Experimental	It was determined that PCM-incorporated radiant chilled ceiling (PCM-RCC) is more energy-efficient than the conventional all-air system for space cooling. Study showed that, its ability to offer thermal comfort by direct radiant cooling, which covers cooling loads during the day and rejects heat at night is the major advantage of PCM-RCC.

N0	Author & year	Geometry/ Country	Method- ology	Findings
27	Qudama Al-Yasiri, et al, 2022	Two identical rooms Al Amarah city, Iraq	Experimental	The components of the PCM room exhibited unfavorable thermal behavior after sunset (from 18:00 till the next day), as the interior surface temperatures of all elements rose. This is because of the PCM inclusion in the PCM chamber has a non-conditioned casing in which the stored heat begins to move towards the exterior low ambient temperature during the peak time.

2.4 Summary:

The different models investigated in this study have two main aims. The first is to achieve IAQ while preventing the transmission of viruses, such as the Coronavirus, by displacing polluted air masses. The second is to avoid or reduce high energy consumption by improving the performance of HVAC devices by using different kinds of PCM_s on the roof and thermal energy storage (TES) systems. Most of the research in this area has been conducted through numerical simulations, experimental studies, or a combination of both. The distribution of temperature, air velocity, and carbon dioxide concentration are commonly explored using CFD models, which assume that the airflow in the models is two-dimensional or three-dimensional, steady-state, incompressible, and laminar or turbulent. Previous literature reviews have demonstrated that various approaches have been used to increase indoor air quality and regulate the interior temperature and ventilation. The researchers (*Lipinski, T., et al., 2020; Bamodu, O. et al., 2015; E. Procedia et al., 2017; Munksgaard B., 2003; T. Karimipannah, 2005; A. Durmus and A. Daloğlu, 2008; Suvanjan et al., 2020; Lu, Yalin et al., 2020; J. Xaman et al., 2008; Ahmet Yüksel, et al., 2020; Zhibin Wu et al., 2019*) previously used the above processes.

The focus of the other research teams in this literature review has been on organic PCM_s (paraffin), although a few have used inorganic PCM_s as a passive cooling technique in buildings. PCM_s have been shown to be effective in reducing energy consumption and saving energy as a sustainable energy solution through the TES method. Scientists have used CFD techniques and simulation programs to study the performance of different kinds of PCM_s, as well as experimental studies. PCM_s are sometimes embedded in walls or ceilings during construction or on floors. However, previous research has only tested PCM protocols in dry and hot climates that reach up to 40 °C, with the exception of one study. In Iraq, the climate is extremely hot and dry, with summer temperatures reaching 56 °C and a daily range of about 20 °C. Qudama Al-Yasiri, et al., (2022) conducted a study similar to this one to a certain extent, but only tested one PCM_s layer, used only one type of it, conducted experiments in a non-conditioned room, and only studied one season with no occupancy.

Therefore, the goal of the current study is to investigate, both numerically and experimentally, the effects of mechanical parameters such as model geometry, different conditions, different levels of occupancy (crowded areas), different heat loads, and comfort levels to achieve IAQ as defined by ASHRAE standards. Numerical and experimental prototype models will be used with and without PCMs, with two layers of different melting points for summer, winter, and transitional seasons. The study will also aim to:

- Test the performance of PCMs on the roof in crowded areas as a passive cooling scenario and study the energy savings results.
- Determine the comfort level of the space using specially formulated paraffin waxes that are extracted from the ALDORA refinery at a low cost as an accidental product.
- Simulate temperature distribution, airflow, and CO₂ concentrations using ANSYS FLUENT as a CFD dynamic tool, to ensure that the space is not suffocating, especially in prison halls with overcrowded areas.
- Controlling the temperature fluctuation in arid climates, especially in a hot and dry climate such as Iraq with high daily range temperatures.

CHAPTER 3

THEORETICAL ANALYSIS

3.1 Introduction

Numerical modeling is an important tool in understanding and predicting the behavior of flow, heat transfer, turbulence, and other phenomena in various industrial applications. This chapter presents a numerical method for solving the differential equations that govern these physical processes, including the momentum equations, the energy equation, and the continuity equation[82]. Additionally, the governing equations for the PCMs layer are also solved. To do so, a Computational Fluid Dynamics (CFD) processor was utilized in ANSYS versions 2018 and 2019, which is specifically designed to simulate fluids and thermals in a given system. The mathematical approach used in this method involves solving the governing equations in Cartesian coordinate systems (x, y, and z). For creating a visual model of the system, SOLIDWORKS software was used, as shown in Figure 3.1. When it comes to computational fluid dynamics, numerical methods refer to techniques for approximating the governing differential equations of fluid flow by forming a set of algebraic equations that can be solved. This process, typically involves one of three main approaches:

- Finite difference methods
- Finite element methods
- Finite volume methods

The finite volume method is utilized in this research. The process through which all numerical methods work is the same in terms of a number of basic steps:

- Unknown flow variables are approximated using simple functions
- Resulting algebraic equations are solved.

- While a variety of numerical techniques are available for use in Computational Fluid Dynamics (CFD), the finite volume method is particularly effective in handling complex geometries and boundary conditions.

More detailed information on the specific characteristics and capabilities of different numerical methods can be found in [83].

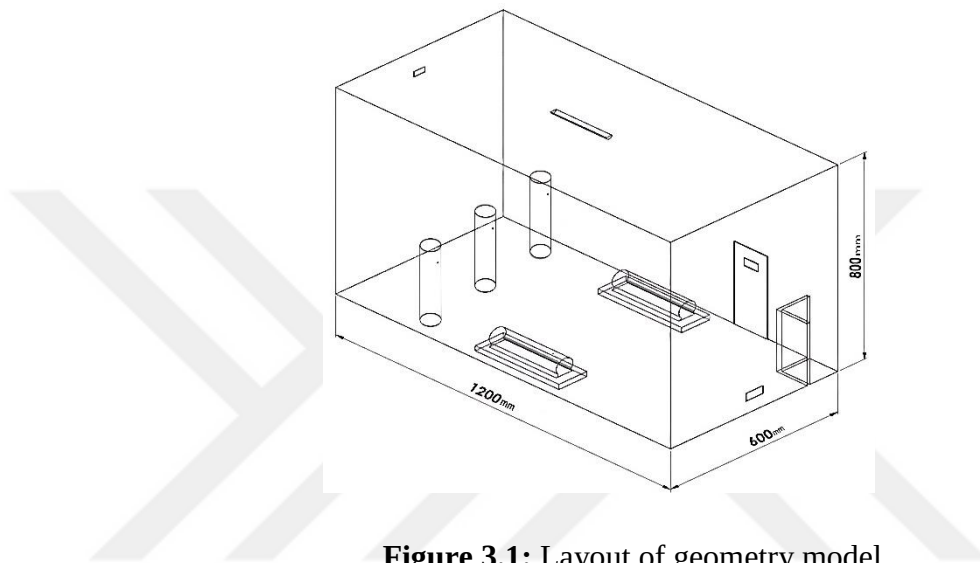


Figure 3.1: Layout of geometry model.

3.1.1 Finite Difference Methods

Finite difference methods involve approximating certain unknowns (ϕ , say) using point samples at the node points of a grid of coordinate lines. Truncated Taylor series expansions are used to generate finite difference approximations of derivatives ϕ , which are then substituted into the governing equations to form a set of algebraic equations. These equations can be solved to find the values of the unknowns at each grid point.

3.1.2 Finite Element Methods

Finite element methods utilize simple piecewise functions (e.g., linear or quadratic) that are valid on elements to approximate the local variations of unknown variables ϕ . The governing equation is satisfied exactly by the exact solution ϕ . However, if the

piecewise approximating functions for the unknown variables are substituted into the equation, they will not hold exactly, and a residual is defined to measure the errors. The residuals (and therefore the errors) are tried to be lessened by using different applications like multiplying them with a weighting functions and taking their integrations [84].

3.1.3 Finite Volume Methods

The finite volume method, which was originally developed as a specialized finite difference formulation, has become a commonly used numerical technique in CFD codes. The code used in this work is based on the finite volume method, making it highly relevant. The numerical algorithm consists of several steps [84]:

- Formal integration of the governing equations of fluid flow over all (finite) control volumes in the solution domain.
- Discretization, including substituting various finite-difference-type approximations for terms in the integrated equation representing processes such as diffusion and sources. Hence a set of algebraic equations are obtained from the integral equations.
- Solution of the algebraic equations by an iterative method.

One key aspect that distinguishes the finite volume technique from other CFD methods is its use of the integral form of the conservation equations as its starting point.

3.2 Assumptions:

In the current work, running fluid in the room is assumed to be air with CO₂ and top panel material is PCM_s. The characteristics of the flow is given below:

- Transient.
- Three dimensional.
- Newtonian.
- Incompressible.
- Turbulent.

3.3 Geometry Room Model:

The geometry of the room for all cases is shown in Figure 3.2. In this study, a prison cell (quarry) containing five people, two of whom are depicted as lying on their backs. The room model is windowless and has dimensions of 120 cm by 80 cm by 60 cm. It contains one fluorescent light with a power consumption of 10 watts and has no open exposure due to security concerns. The room was constructed using the SOLIDWORKS version 2021 program, a description model of the prison cell's components, including dummy inmates, lighting, a toilet, and minor furnishings. The human body was represented as a cylinder with a cap, with dimensions of 0.3 m in diameter and 1.2 m in height. Five individuals with a heat flux of 100 W occupy the model [85]. A carbon dioxide concentration of 0.005 l/s is considered to be emitted from the mouth of the prisoner during inactive activities; stationary-level occupants expel 4–5 % of carbon dioxide from their lungs [86]. ASHRAE Standard 62-1-2013 recommends that the temperature and humidity of exhaled air be 33 °C and 95 %, respectively.

PCM_s with diverse crude petrochemical feedstock compositions and oil-to-wax ratios are used in the prototype roof to provide thermal comfort in a hot climate. The melting temperatures and flashpoints of these paraffin waxes range from 19 to 55 °C and 177 to 256 °C, respectively. A ventilation scenario with an entry grill of dimensions 4 cm in width and 6 cm in length and an exit area of 6 cm by 8 cm is shown in Figure 3.2, as well as the boundary conditions of the room model. The cooling and heating scenarios have an entry hole of dimensions 6 cm in width and 8 cm in length and an exit area of 8 cm by 10 cm. Figure 3.3 shows the design of the PCM_s panels used, and Figure 3.4 shows a sketch of the building roof.

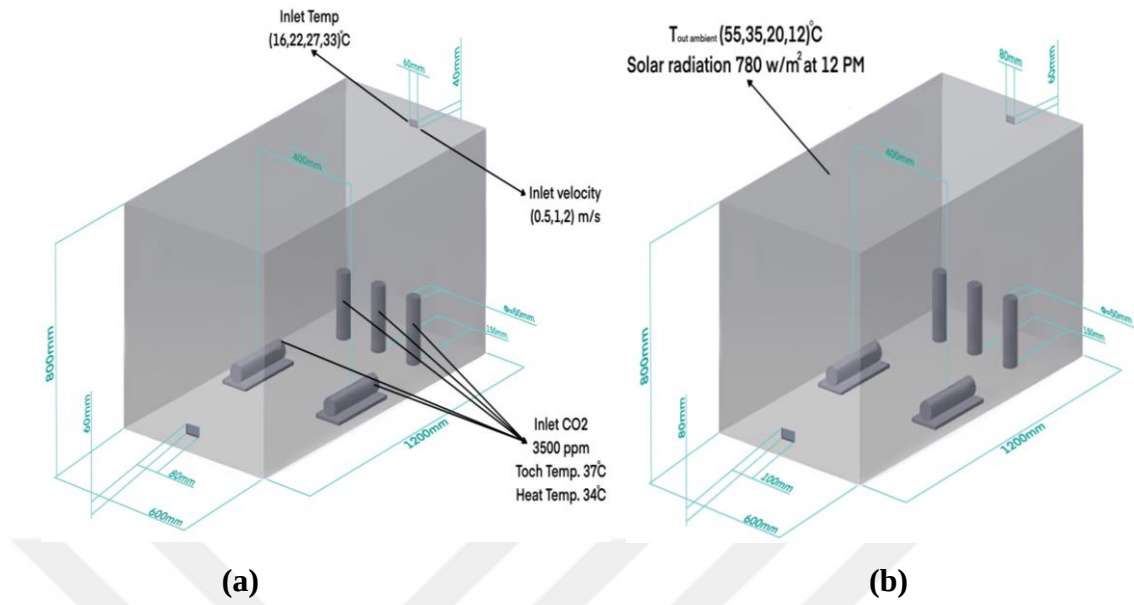


Figure 3.2: Model of room geometry

(a) At ventilation in spring and autumn.

(b) At summer time cooling and winter time heating.

Two PCM_s containers are used together, separated by an aluminum partition. One is useful for the summer mode and the other is useful for winter mode. Each panel is characterized by its width and height, which are the same dimensions as the room roof, with a thickness of 2.5 cm.

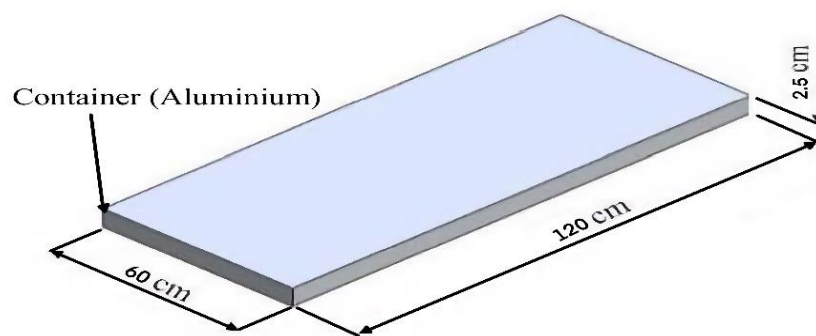


Figure 3.3: PCM_s panel design.

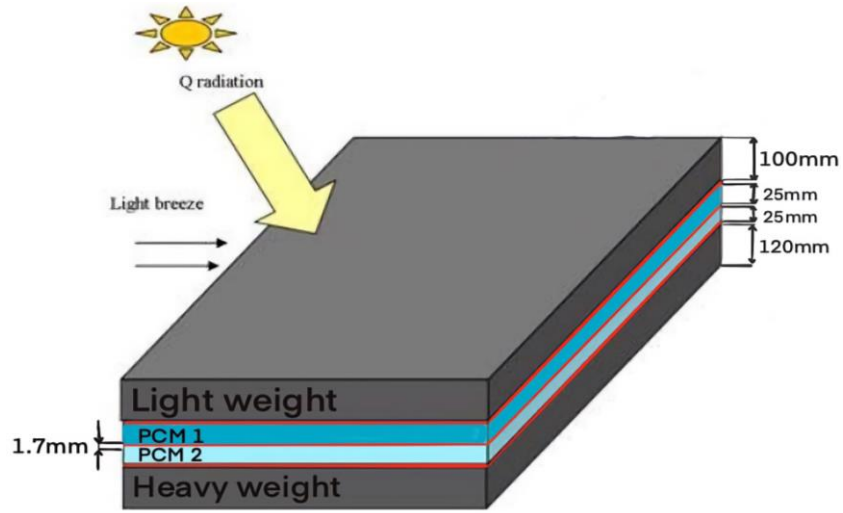


Figure 3.4: Sketch of the building roof.

3.4 Quality and Dependency of Mesh

3.4.1 Quality of mesh

It is important to investigate the quality of the mesh and check the orientation of elements. A key parameter to consider is face alignment, which measures the skewness of cells. Elements with high skewness should be avoided, as they can negatively impact the accuracy of the simulation. The face skewness can be calculated using the following equation:

$$Face\ skewness = 1 - \frac{\text{length of shorter face diagonal}}{\text{length of longer face diagonal}} \quad (3.1)$$

A face skewness value of 0.2 to 0.5 is generally considered acceptable. It is also important to have a sufficient number of cells to ensure good resolution [87].

3.4.2 Convergence Criteria

To conduct an analysis, the solution domain is often divided into multiple sub-domains, known as cells. The combination of these cells in the computational structure is referred to as a mesh. A necessary component of any rigorous CFD investigation is a grid dependency check, as coarse grids can sometimes lead to a solution that does not fulfill the conservativeness property. To ensure that a solution is fully converged,

it is necessary to solve a problem using successively refined grids until the solution remains unchanged. The convergence criteria used in all of the CFD tests described here required the ratio of the first and last residual error values to be at 1×10^{-3} . For the purpose of this investigation, grid independence tests were conducted on external flow simulations. The grid refinement process included:

- Increasing the density of the grid surrounding the test structure.
- Increasing the density of the grid on the test structure. The mesh dividing used in this study is shown in Figure 3.5.

The convergence criteria for the numerical solution applied in the present problem is based on the residual of any variable (ϕ) at node (p), where the residual from Eq. (3.2) is given by [88].

$$R_{\phi} = a_p \phi_p - \sum_{E, -, U} a \phi + b \quad (3.2)$$

(R_{ϕ}) for an exact solution must be zero to satisfy the (FDE), but for inexact or nearly exact solution, the normalized residual for the different variables can be defined as:

$$\sum |R_{\phi}| \leq \lambda \quad (3.3)$$

For all field

Where (λ) is called convergence criteria which its value is adopted for the current work.

3.4.3 Total cell count- Mesh independence

The growth in available mesh elements and mesh connectivity is a direct result of this innovation. In the current study, unstructured tetrahedron frameworks were used. ANSYS supports solid geometry mesh generation in three dimensions. The number of cells used in this study was (2,496,452) tetrahedron elements, with element sizes of 15 mm and a set time step of one second, as shown in Figure 3.5 and Table 3.1.

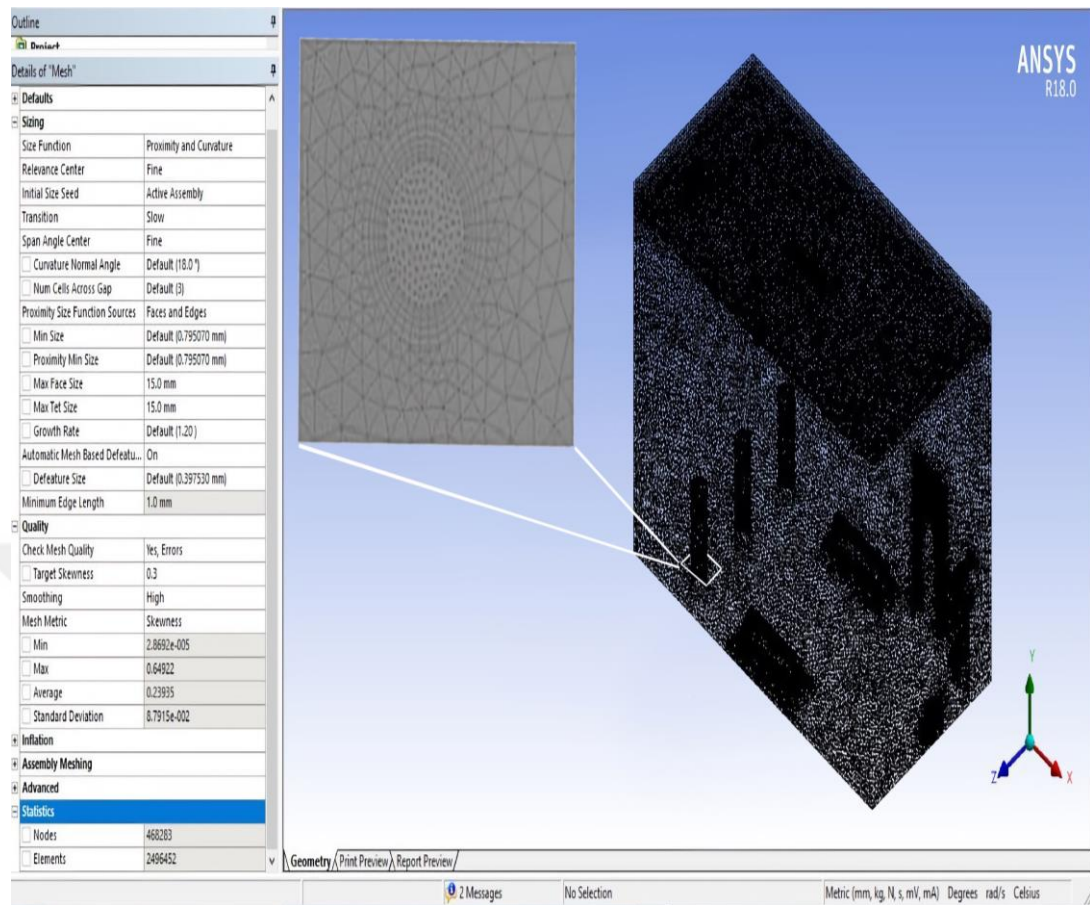


Figure 3.5: Mesh generated.

Table 3-1: The different number of elements with average of air temperature and CO₂.

Type of mesh	Number of elements	Skewness	Air temperature °C	CO ₂ concentration ppm
Coarse	1.547.700	0.208	26.1	751
Fine	2.496.452	0.205	26.6	760
Percentage difference			1.8%	1.1%

3.5 Governing Equations

3.5.1 Navier-Stokes Equations

The other fundamental set of equations that govern the flow of a fluid are derived from Newton's second law, also known as the conservation of momentum. These equations are called the Navier-Stokes equations, and for incompressible fluids, the full instantaneous equations take the form 3.4 to 3.6:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} + \frac{\partial(\rho wu)}{\partial z} = -\frac{\partial p}{\partial x} + \mu \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] \quad (3.4)$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} + \frac{\partial(\rho wv)}{\partial z} = -\frac{\partial p}{\partial y} + \mu \left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right] \quad (3.5)$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho ww)}{\partial z} = -\frac{\partial p}{\partial z} + \mu \left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right] \quad (3.6)$$

Where: u , v and w are the stream wise, lateral and vertical velocity components respectively.

x , y And z are the Cartesian component directions to the velocity components.

μ : is the fluid viscosity.

ρ : is the fluid density.

p : is the pressure.

A more compact and elegant way of writing the equations 3.4 to 3.6 using Cartesian tensor notation is given in Eq 3.7 [89].

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left[\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + S_{bj} \quad (3.7)$$

Where the indexes i, j represent the three coordinate direction. S_{bj} are buoyancy source or sink terms and (t) is time.

3.5.2 The K- ε Turbulence Models

This is the role of the turbulence model, Launder and Spalding [90] proposed a modified version of the K- ε model, which has been widely applied and is commonly referred to as the standard K- ε model. At each grid point, the eddy viscosity is related to values of the turbulence kinetic energy (k) and the dissipation rate of turbulence energy (ε) as given by equation 3.8:

$$\mu_t = \frac{C_D \rho K^2}{\varepsilon} \quad (3.8)$$

Where C_D is a empirically determined constant and turbulent energy is derived from fluctuating velocities as in equation 3.9:

$$K = \frac{1}{2} \overline{(u'^2 + v'^2 + w'^2)}. \quad (3.9)$$

Local distrubution of k and ε can found by solving two additional transport equations which is also derived from Navier-Stokes equation. The k-transport equation is given in equation 3.10:

$$\frac{\partial}{\partial x}(\rho UK) + \frac{\partial}{\partial y}(\rho VK) + \frac{\partial}{\partial z}(\rho WK) = \frac{\partial}{\partial x} \left(\frac{\mu_t}{\sigma_k} \frac{\partial K}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\mu_t}{\sigma_k} \frac{\partial K}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{\mu_t}{\sigma_k} \frac{\partial K}{\partial z} \right) + G_k - \rho \varepsilon \quad (3.10)$$

Also,

$$G_k = \mu_t [2((\frac{\partial U}{\partial x})^2 + (\frac{\partial V}{\partial y})^2 + (\frac{\partial W}{\partial z})^2) + (\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x})^2 + (\frac{\partial U}{\partial z} + \frac{\partial W}{\partial x})^2 + (\frac{\partial V}{\partial z} + \frac{\partial W}{\partial y})^2] \quad (3.11)$$

Transport equation of ε is given by equation 3.12:

$$\frac{\partial}{\partial x}(\rho U \varepsilon) + \frac{\partial}{\partial y}(\rho V \varepsilon) + \rho \frac{\partial}{\partial z}(\rho W \varepsilon) = \frac{\partial}{\partial x}(\frac{\mu_t}{\sigma_k} \frac{\partial \varepsilon}{\partial x}) + \frac{\partial}{\partial y}(\frac{\mu_t}{\sigma_k} \frac{\partial \varepsilon}{\partial y}) + \frac{\partial}{\partial z}(\frac{\mu_t}{\sigma_k} \frac{\partial \varepsilon}{\partial z}) + (C_1 G_k - C_2 \rho \varepsilon) \frac{\varepsilon}{K} \quad (3.12)$$

Model can be called empirical because of the way the model parameters ($C_1, C_2, C_D, \sigma_\varepsilon, \sigma_k$) are introduced. The recommended values of constants by Launder and Spalding [90] is given in table B.1 in APPENDIX (B).

3.5.3 The general partial differential equation to be solved

The general form of the overmentioned differential equations to be solved is given as [83]:

$$\underbrace{\frac{\partial}{\partial x}(\rho v_x \Phi) + \frac{\partial}{\partial y}(\rho v_y \Phi) + \frac{\partial}{\partial z}(\rho v_z \Phi)}_{\text{Convection term}} = \underbrace{\frac{\partial}{\partial x}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial z}\right)}_{\text{Diffusion term}} + \underbrace{S_\Phi}_{\text{Source term}} \quad (3.13)$$

Where (Φ) is defined as general dependent variable, (Γ_Φ) is generalized diffusion coefficient and finally (S_Φ) is called source term. The general differential equation is defined by three terms which are the convection term, the diffusion term and the source term of the scale variable (Φ) .

3.6 Development of Numerical Model for PCM Layer

3.6.1 one-phase solution Method

The immediate persistence of heat flux and temperature at interfaces $x = L1, L2, L3$ and $L4$ are conserved, the governing equations are shown as 3.14 [91]:

$$k_m \frac{\partial^2 T_m}{\partial x^2} = \frac{\rho_m c p_m \partial T_m}{\partial t} \quad (0 < x < L); m = 1, 2, 3, 4 \quad (3.14)$$

Where $m = 1$ for root top slab $m = 2$ for PCM₁ panel $m = 3$ for PCM₂ panel $m = 4$ for bottom slab.

With the boundary condition:

$$T(0, t) = T_o(t)$$

$$T(L, t) = T_l(t)$$

An explicit method of numerical solution for a single material node is given by [92]

$$T_i^{j+1} = T_i^j + \frac{Kn\Delta t}{\rho n C n (\Delta X)^2} (T_{i+1}^j - 2T_i^j + T_{i-1}^j) \quad (3-15)$$

Using an appropriate value for k , ρ , c_p , the same equation holds true for all four material zones. At the exterior boundary ($x=0$), where the floor is exposed to solar radiation, the boundary condition is given by equation 3.16:

$$k_1 \left. \frac{\partial T_1}{\partial x} \right|_{x=0} = q_{rad} + h_0(T_\infty - T_{x=0}) \quad (3.16)$$

The radiation is considered to be effective only for the three peak daylight hours, in this study it was started from 780 W/m². The boundary condition of the base layer of a bottom slab at $X=L$ is given as:

$$+ k_4 \left. \frac{\partial T_4}{\partial x} \right|_{x=L} = h_i(T_{x=L} - T_{room}) \quad (3.17)$$

3.6.2 Two-phase solution

When the PCM_s layer consists of more than one phase, the boundary points between the solid and liquid are held constant at the melting temperature of the material. An explicit numerical solution for a single material two-phase node is given by:

$$T = T_m \quad \text{Is} \quad T_m - \Delta T < T < T_m + \Delta T \quad (3.18)$$

The movement of the solid–liquid boundary x_{SL} is governed by the Stefan condition [93, 94] which is expressed as:

$$K_{PCM} \left[\lim_{x \rightarrow x_{SL}^+} \left(\frac{\partial T}{\partial x} \right) - \lim_{x \rightarrow x_{SL}^-} \left(\frac{\partial T}{\partial x} \right) \right] = \frac{\rho_{PCM} \alpha_{d_{xSL}}}{dt} \quad (3.19)$$

Where x_{SL+} and x_{SL-} denote the limits approaching the solid– liquid interface. An explicit numerical solution for a single material two-phase node is given by

$$T_i^{j+1} = T_i^j = T_m \quad (3-20)$$

3.7 Boundary Conditions:

The boundaries are divided on the basis of their quality as shown in the tables 3.2, and 3.3.

Table 3.2: boundary conditions.

Variable	Boundary Condition					
	Right wall	Left wall	Back wall	Forward wall	Floor	Ceiling
V_x	0	0	0	0	0	0
V_y	0	0	0	0	0	0
$K_{(j)}$	$\frac{dk}{dx} = 0$	$\frac{dk}{dx} = 0$	$\frac{dk}{dy} = 0$	$\frac{dk}{dy} = 0$	$\frac{dk}{dz} = 0$	$\frac{dk}{dz} = 0$
ε	0	0	0	0	0	0
grad(12:00,1:00,2:00,3:00) pm	0	0	0	0	0	(780,1099,866,601)m ²
$T(k)$	The four vertical walls are insulated					$\frac{\partial T}{\partial t}$

Table 3.3: Prisoner human boundary conditions with CO₂ ppm.

Part	Characterized	Boundary Conditions
Human Body	Dummy As a Cylinder	5 prisoners - $(0.3D \times 1.2H) \text{ m}^2$, CO ₂ Concentration=0.31 l/Min, Thermal Heat Flux $\sim 100 \text{ W/m}^2$. One person emits daily 500 l .Annually 182.500 l CO ₂ .
Human Body	Dummy As a Cylinder	Touch Temp= 37.5 °C ,Sensible Temp=34 °C -Relative humidity from exhalation =95% as ASHRAE 62-1-2013.
Human Body	Dummy As a Cylinder	Nostril hole presented 12mm, high 1.2m above the floor when he is staying and 0.37m when he is laying to sleep from the bed.

3.8 Initial Conditions:

The Initial Conditions are listed in a table 3.4.

Table 3.4: Initial conditions.

Parameter	Unit	Initial Value
Gauge Pressure	Pascal	0
x-Velocity	m/s	0
y-Velocity		0
z-Velocity		0
Time	sec	0
CO ₂	ppm	380-400
Starting Time	hr.	12 :00 pm
Temp- of PCM _{1,2}	°C	18 (Sold-fraction)

3.9 Materiel Properties:

The Materiel Properties are listed in a table 3.5, table 3.6 is shown air properties for all the cases, and table 3.7 is shown PCM_s properties which are tested.

Table 3.5: Model construction parts and properties.

Part	Material Type	Density (ρ)	Specific Heat (C_p)	Thermal Conductivity (k)
		(kg/m ³)	(J/kg. K)	(W/m. K)
Ceiling	Aluminum	2719	871	202.5
Floor and Insulators	Glass-Wool	64	670	0.04
Side Walls	Perspex	1180	1450	0.2

Table 3.6: Air properties for all the cases.

Parameter	Unit	Inlet Temp			
		16 °C	22 °C	27 °C	33 °C
Density	Kg/m ³	1.2215	1.965	1.1726	1.1534
Dynamic viscosity	Kg/m.s	1.80×10^{-5}	1.83×10^{-5}	1.85×10^{-5}	1.882×10^{-5}
Specific Heat C_p	J/Kg.k	1.006×10^3	1.0062×10^3	1.0064×10^3	1.0066×10^3
Conductivity K	w/m.k	0.0252	0.0257	0.0261	0.026
Prandtl Number		0.716	0.715	0.714	0.713
Thermal Diffusivity	m ² /s	2.05×10^{-5}	2.138×10^{-5}	2.219×10^{-5}	2.287×10^{-5}
Thermal Expansion Coefficient	1/k	3.45×10^{-3}	3.38×10^{-3}	3.32×10^{-3}	3.26×10^{-3}

Table 3.7: PCM_s properties.

Parameter	Unit	Value	
		Paraffin's Wax	
		PCM1	PCM2
Melting point	°C	40-55	19-37
Density (ρ_s)	(kg/m ³)	1270	785
Density (ρ_l)	(kg/m ³)	1180	749
Specific Heat (C_p) at solid	(KJ/kg. °C)	2.71	1.4
Specific Heat (C_p) at liquid	(KJ/kg. °C)	2.87	2.2
Thermal Conductivity (k_s)	(W/m. K)	0.41	1.09
Thermal Conductivity (k_l)	(W/m. K)	0.22	0.51
Diffusivity α_s	(m ² /s)	PCM ₁ = 2.6×10^{-4} PCM ₂ = 9.9×10^{-5}	
Diffusivity α_L	(m ² /s)	PCM ₁ = 1.0×10^{-4} PCM ₂ = 3.03×10^{-5}	
Layer thickness	cm	2.5	2.5
Enthalpy (h)	(KJ/Kg)	250	146

The flow chart in figure 3.6 is clarified the solutions of numerical methodology.

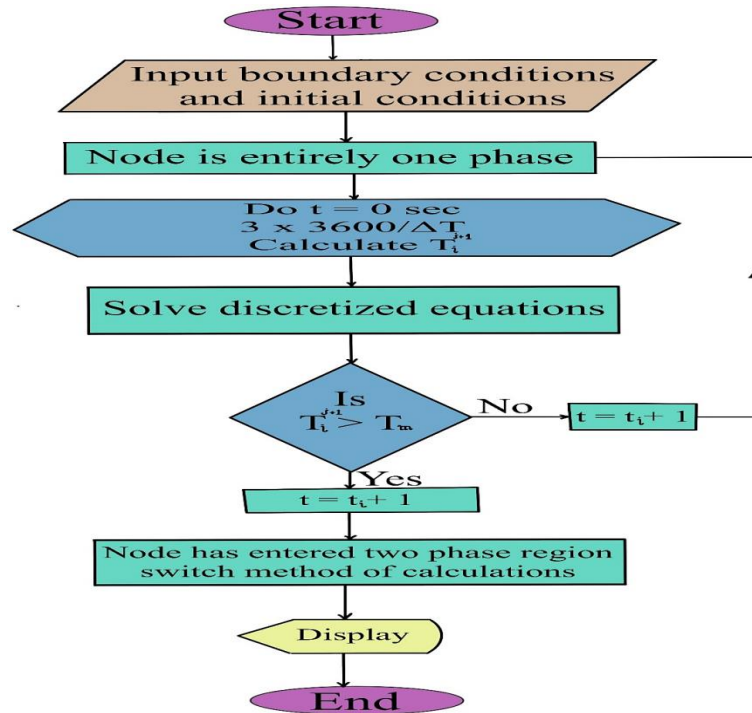


Figure 3.6: Flow Chart for Numerical Solution.

CHAPTER 4

EXPERIMENTAL WORK

4.1 Introduction

In countries with hot and cold climates, air conditioning and domestic space heating are responsible for most of the variations in energy load, respectively. To better manage power generation and distribution, a differential pricing system can be implemented for peak and off-peak periods of energy consumption. It would be beneficial to shift some peak load to off-peak periods if a greater percentage of peak load could be moved there. Building establishments, such as residential homes and commercial buildings that cannot control the fluctuations inside of them can achieve this by storing thermal energy to power heating and cooling systems. This study examines the thermal performance of a thermal storage system based on phase change materials (PCM_s) for energy conservation and achieving ASHRE requirements for indoor air quality (IAQ) in crowded areas. The effects of having two layers of PCM_s in a thermal management system on the roof of a prison quarry building have been studied using an experimental setup consisting of a test rig. The heat transfer properties of organic PCM_s, which melt at various temperatures ranging from 19 °C to 37 °C and 40 °C to 55 °C, were analyzed and discussed.

4.2 Experimental setup description:

To obtain more accurate measurements, several requirements must be met in the new experiment:

- 1- It should be one-dimensional and allow for the transfer of heat between the PCM_s and the heat source.
- 2- Uncontrolled outside influences should result in a low heat flow compared to the applied heat flow.
- 3- Ideally, the temperature changes of the PCM_s should follow real-life rates, as the thermal properties of PCM_s are affected by the specific heat transfer rate.

4.3 Experimental apparatus design

The prototype model used in this study was based on a real prison cell (quarry) with dimensions of 4.8 m in length, 2.4 m in width, and 3.2 m in height. A scaling factor of 4 was applied to calculate the dimensions of the model, resulting in a model with dimensions of 1.2 m in length, 0.6 m in width, and 0.8 m in height. The model was elevated 0.7 m above the floor to facilitate the installation of devices and equipment, and could accommodate five people. The room had no windows and contained two reclining statues. For security reasons, the room had no open exposures. The experimental room was well insulated from its surroundings, and the frame was made of aluminum, as shown in Appendix A. The walls of the experimental model were constructed of insulated Perspex sheets with a thickness of 6 mm, which were attached to the steel structure of the model using studs. The only connection between the room and the outside world was through the supply and return grilles. The inlet grill had dimensions of 0.08 m by 0.06 m for two seasons and 0.04 m by 0.06 m for another season, and was located on the western wall with a distance of 0.06 m between the upper edge of the grill and the panel surface. The dimensions of the return grill were 0.1 m by 0.08 m and 0.08 m by 0.06 m, and it was positioned on the eastern wall with a distance of 0.05 m above the floor surface, as shown in Appendix A. In addition, an air conditioning laboratory unit was used to control the inlet temperature and speed, as shown in Appendix B.

The ceiling of the experimental apparatus was made of an aluminum container filled with PCM_s. Two aluminum containers were used, each containing a different PCM with a melting point and dimensions of 1.2 m by 0.6 m and a thickness of 2.5 cm.

4.4 PCM_s properties testing

The Midland Refineries Company's Daura Refinery in Iraq provided the phase change materials for the experiment. Suitable materials for Baghdad's weather conditions were selected after studying the properties of all available materials. Materials RRM₁ (80 % crystal grade with 20 % soft wax) and RRM₂ (soft wax only),

which are refined oil and waxy compounds (aromatic material), were chosen. A total of 36.3 kg of PCM_s were used, 14.3 kg of RRM₁ and 22.0 kg of RRM₂. Table 3.7 in Chapter 3 shows the properties of these materials.

4.4.1 Methods for determining densities and thermal properties

The local paraffin density in the solid (ρ_s) and liquid (ρ_L) phases is based on Archimedes' principle, and is determined using the ASTM D792 displacement method. A convenient size specimen is used as long as the volume is at least 1 cm³. The specimen must be weighed both in air and when immersed in distilled water or another suitable liquid. To determine the local paraffin content, many different apparatus can be used. Manually operated and standardized instruments are available, and the Transient Plane Source (TPS-500) method is one of the most common techniques for studying thermal transport properties. The thermal conductivity, thermal diffusivity, and specific heat are calculated using computerized gauges, and the TPS device with its accessories is shown in Appendix C.

4.4.1.1 Differential scanning calorimetric analysis:

Differential Scanning Calorimeters (DSC) were used in the test in accordance with ASTM D3418 standards to extract some of the thermal values of PCM materials. Figures in Appendix C show the DSC, which is used to determine the melting point and enthalpy change (h) for PCM_s. Appendix C shows how the sample is weighed and compressed to become a specimen ready for the second phase. All measurements were performed on a specimen of mass 0.1 g, which was positioned in an aluminum cell as a reference and tightly coated.

4.5 Hardware measurement equipment

4.5.1 Design overview of the monitoring system

The indoor monitoring system developed in this study utilizes a system architecture with sensor nodes that measure primary variables such as temperature, humidity, air velocity, and CO₂ concentration. These sensor nodes are managed by two Arduino microcontrollers, with a third one in standby for future use. The recorded information

is sent to a PC for display. The indoor air speed, relative humidity, CO₂ concentration, and indoor air temperature are measured using a digital-output relative humidity sensor (model DHT22) for temperature and humidity, a MG-811 GAS SENSOR and an MQ-2 GAS SENSOR for CO₂ concentration as can be seen from figure 4.1, and a hot wire anemometer (model Lutron YK-2005AH) for air velocity. Appendix C shows all aforementioned sensor along with their data sheet. The outdoor temperature is measured using an infrared thermometer (model GM700). Before use, these devices were calibrated to ensure their reliability and accuracy. The calibrated equipment was used to correct the measurements of environmental physical characteristics. Table 4.1 shows the characteristics of each system device.

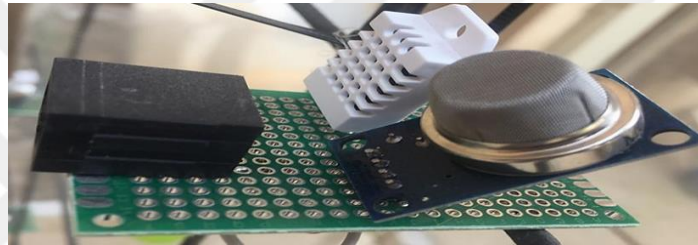


Figure 4.1: Sensor card.

Table 4.1: Characteristics of the measurement system.

Sensor-model	Function	Range	Resolution	Accuracy
MQ-2	CO ₂	350-1000 ppm	10 ppm	±1ppm
DHT22	Temperature	-40~80 Celsius	0.1 Celsius	< ±0.5 Celsius
DHT22	Humidity	0-100 % RH	0.1% RH	±2% RH
YK2005.AH	Air velocity	0.2-20m/s	0.01 m/s	±0.025m/s
GM700	Temperature	-50~700 Celsius	0.1°C	±1.5 Celsius
Mg-811	CO ₂	350-1000 ppm	10 ppm	±1 ppm

4.5.2 Temperature and humidity measurement

The DHT 22 sensor outputs a calibrated digital signal using a proprietary digital signal collection technique and humidity sensor technology, ensuring its reliability and stability. The sensing device is connected to a single-chip, 8-bit computer. Each temperature sensor in this model is calibrated and compensated in a precise calibration chamber, and the calibration coefficient is stored in OTP memory in the form of a program. When the sensor detects a factor, it is cited from RAM. The small size, low power consumption, and 20-meter transmission range make the DHT 22 suitable for a variety of demanding applications. It comes in a single-row package with four pins for easy connection. The data sheet for the DHT 22 is shown in Appendix C, it is used to measure temperature and humidity in experimental work.

4.5.3 Air Velocity measurement

The hot wire anemometer used to measure air velocity in this study is shown in Appendix C. It has a model number of YK-2005AH and offers a high level of precision and accuracy. It is particularly useful for installation and sensor work. Its features and benefits include a large, easy-to-read display, precise air velocity measurement, and a certificate of calibration. It has a velocity range of 0.2 to 20 m/s, accuracy of $\pm 5\%$ of reading or ± 0.025 m/s, resolution of 0.01 m/s, and probe length of 101.6 cm.

4.5.4 CO₂ concentration measurement

- **MQ-2 gas sensor.**

The MQ-2 gas sensor is sensitive to flammable gases such as LPG, propane, and hydrogen, as well as methane and other combustible gases. Its sensitive material is SnO₂, which has a lower conductivity in clean air. When the gas of interest is present, the conductivity of the sensor increases along with the gas concentration. The change in conductivity is converted into an output signal corresponding to the gas concentration using a simple electronic circuit. The MQ-2 gas sensor is cost-effective and suitable for a range of applications. It is shown in Appendix C. It is measured the ppm of CO₂ concentration in experimental work.

- **MG -811 gas sensor.**

The Air Quality Control sensor is able to detect carbon dioxide with high sensitivity when the relative humidity and temperature are low. The sensor's surface temperature rises due to a heater element supplied by an external circuit, and the resulting signal is transferred through two lines. In order to test the sensor, in accordance with Nernst's Equation results, the amplifier impedance should be within the range of 100-1000 G Ω , and the testing current should be controlled. The sensor and its technical specifications are shown in Appendix C, it is used to measure the ppm of CO₂ and calibration the values with previous type.

4.5.5 Arduino mega 2560

The Arduino Mega 2560 is a microcontroller board based on the ATmega 2560 microcontroller (data sheet). It has 54 digital input/output pins, 14 of which can be used as PWM outputs, 16 analog inputs, 4 hardware serial ports (UARTs), a 16 MHz crystal oscillator, a USB connector, a power jack, an ICSP header, and a reset button. It comes with everything that need to operate the microcontroller; simply connect it to computer via USB cable or power it with an AC-to-DC adapter or battery. The Arduino Mega can be powered through USB or an external power supply. It has an automatic power source selection feature which allowing to use an AC-to-DC adapter (wall wart) or battery as the external power source. To use the adapter, simply insert a 2.1 mm center-positive connector into the board's power connector. The board is capable of operating with an external power source ranging from 6 to 20 volts. However, it is recommended to use a voltage between 7 and 12 volts. If the voltage is less than 7V, the board may provide less than five volts and become unstable. If the voltage is more than 12V, the voltage regulator may overheat and cause damage to the board. The Arduino Mega 2560 has 256 KB of memory chips for storing code and is illustrated in Appendix C. it is very important part to read the signal and displays it in computer display screen.

4.5.6 Power supply

The power unit is responsible for supplying power to all sensors. The power supply converts alternating AC voltage (220 volts) to DC voltage (5 volts and 12 amperes) to

be used by the sensors. This is necessary because the Arduino power is not able to provide such a large amount of power to all sensors without a strong power source. The technical specifications for the power supply can be found in Appendix C.

4.5.7 Heater pad

The thermal pad was used to simulate human body temperature for the characters. It was shaped into a cylinder and inserted into the center of the character's cylinder. It was powered by a 5 V voltage, providing 100 W of heat. The thermal pad or heater pad can be seen inside the bogus dummy in Appendix A, on the other hand, it is a heat generation inside dummy to achieve 100 W for heat flux for every character.

4.5.8 Thermocouples of PCM panels

Thermocouples were used to measure the K-Type temperature of the panels. These thermocouples, were evenly distributed across the panels with three thermocouples per panel, as shown in Appendix A. The temperature readings were converted to the Arduino device using the Max 6675 device control.

4.6 Connections and read the results

The two types of sensors will be placed on a piece that has a LAN port, where the grounding, voltage, and signal areas are connected to be transmitted via LAN cable. The connections of the Arduino system can be seen in Appendix A. The main board has numbered entries for the LAN cables, with the first three exits reserved for voltage, ground, and signal, respectively. These outputs are connected to the Arduino device and displayed on the computer screen. The Arduino Mega device is capable of receiving 15 analog sensors, so two devices were used due to the larger number of sensors. The sensors protocol is divided into three layers of circuit unit of signal receptors. The first and second circuits are comprised of 13 temperature, humidity, and carbon dioxide sensor groups. The layout for the first and second circuits can be seen in Figure 4.2. The third layer circuit unit contains two sections, six thermocouples, and a breathing mechanism scenario. The layout for the third unit can be seen in Figure 4.3.

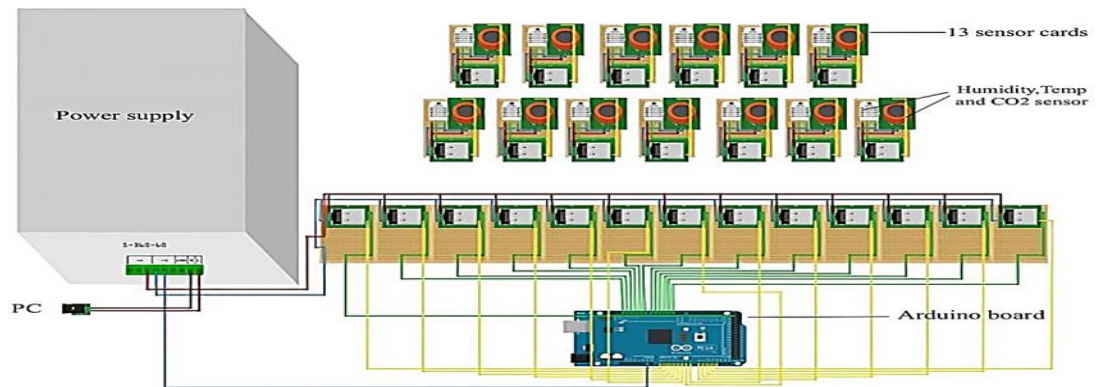


Figure 4.2: First and second circuit layer units.

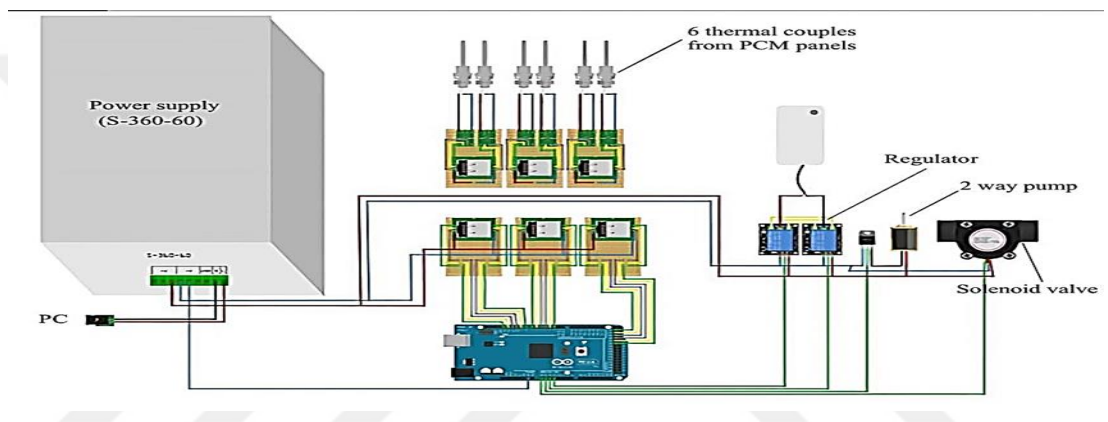


Figure 4.3: Third closed circuit layer unit.

Once all the connecting tools, devices, and fittings were completed, the process of installing the panels and pouring the paraffin wax began. Figure 4.4 shows the completed rig before insulating. The details of the work can be seen in Appendix A.



Figure 4.4: Completing rig for testing.

4.7 Breathing system protocol:

A sober inhalation and exhalation system for the pseudo dummy was created. It consists of solenoid valves, a two-way pump, a CO₂ gas bottle, a fitting segmentation, and a tube orifice grid. The system is controlled through the Arduino. The breathing process of inhalation and exhalation can be seen in Appendix D. The fitting segmentation of the breathing system with the Arduino simulating unit inside the box can be seen in Appendix A.

4.8 Full-Scale Thermal Load Determination Carrier HAP:

The thermal load for the full-scale prison quarry was calculated using the Hourly Analysis Program (HAP), a widely used simulation software introduced by Carrier Corporation (version 4.90-2014). This software was chosen because it is easy to use, reliable, and well-known, and is capable of performing the detailed load calculations required. The total cooling load for the full-scale room was found to be 1 TR, as simulated. The total air flow rate needed to achieve this load is 500 ft³/min, with a cooling load of 3.517 kW and a heating load of one third of this value. For the model, the cooling load will be 0.25 TR, as shown in Appendix B.

4.9 Experimental procedure for the model:

Steps for conducting experiments:

1. 1- After designing and manufacturing the prototype items and connecting the thermocouples, the model is placed in an open space (on the ceiling of the HVAC laboratory at the Technology University) to ensure direct sunlight. The ceiling is then filled with PCM_s materials.
2. 26 sensor cards are used inside the room. These sensors are arranged in a matrix form with two columns and four rows, with 6 thermocouples divided into two groups of three thermocouples per PCM_s panel.
3. Electronic selector readers are used to connect all the sensors to the ceiling and inside the space.
4. The breathing mechanism for inhalation and exhalation is installed.

5. All the connected elements and devices are checked and calibrated.
6. Due to high levels of sunlight in Iraq, the measurements are conducted during the summer in August for three hours continuously, under suffering conditions. The prototype is connected to the air conditioning laboratory unit (A660/15611) via a flexible duct, which controls all inlet air parameters, as shown in Appendix C.
7. The slim 2-layer PCM_s panels are tested during the summer season.
8. The rate of heat exchange between the surrounding environment and the roof, and the heat distribution within the room, are calculated during the summer month.
9. Experimental energy consumptions with and without PCM_s is calculated.

4.10 Experimental uncertainties:

The difference between the measured value and the true value of a quantity is called an error. Uncertainty is a value assigned to represent this error. The uncertainty in a measurement contributes to the uncertainty in an experiment. It is a non-negative parameter that represents the statistical dispersion of the measurement uncertainty. There is always some degree of uncertainty associated with all measurements, and including a statement of that uncertainty is necessary to complete the measurement result.

4.10.1 Uncertainties in temperature measurements

- **Uncertainties in the type (K) thermocouple**

The equation 4.1 is used to determine the Uncertainty in measurement:

$$\delta_{\text{total}} = \sqrt{(\delta \text{ Sensor})^2 + (\delta \text{ Instrument})^2}. \quad (4.1)$$

Sources of error which causes uncertainty in the temperature measurement is coming from type K-thermocouple, its wire properties, selected switch and the digital reader of the thermocouple. Wire of the type K-Thermocouple has an uncertainty $\pm 0.4 \text{ } ^\circ\text{C}$. The estimated error for the connection with the selected switch is

$\pm 1^{\circ}\text{C}$. The digital reader of the thermocouple has the error margin of $\pm 0.5^{\circ}\text{C}$.

Then the error for temperature measurements can be calculated as in equation 4.2:

$$u_T = \sqrt{(\pm 0.4)^2 + (\pm 1)^2 + (\pm 0.5)^2} = \pm 1.2^{\circ}\text{C} \quad (4.2)$$

Table 4.2 explains the rest of the uncertainties for measurements:

Table 4.2: Uncertainty of measurements.

Uncertainty measurements	Measuring Items	Model	Uncertainty Value	Units
Temperature Measurements in PCM _s	Thermocouple	Type (K)	± 1.2	$^{\circ}\text{C}$
Air temperature Measurements in door	Digital-output relative humidity	DHT22	± 0.5	$^{\circ}\text{C}$
Air Relative Humidity Measurements	Digital-output relative humidity	DHT22	$\pm 0.2\%$	RH
Air velocity Measurements	Hot wire Anemometer	No. yk-2005AH	± 0.025	m/s
CO ₂ Concentration Measurements	Gas sensor	MQ-135 GAS	± 1.0	ppm
CO ₂ Concentration Measurements	Gas sensor	Mg-811 GAS	± 1.0	ppm
Surface Temperature Measuring	Infrared thermometer	GM-700	± 1.5	$^{\circ}\text{C}$
Breathing Airflow Measurement	Hot wire Anemometer	No. yk-2005AH	± 0.01	m ³ /s

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

In this chapter, we present the results of numerical and experimental tests conducted using a 3D computational fluid dynamics software package and a model of a room. The experiments, described in detail in this chapter, consist of two protocols: cooling and heating. The cooling protocol is further divided into two scenarios: cooling in summer and cooling ventilation in spring. The heating protocol is also divided into two scenarios: heating in winter and heating ventilation in autumn. Elicitation layout summary of the numerical results is presented in Table 5.1.

Table 5.1: Summary division of numerical results.

Results									
Cooling Protocol					Heating Protocol				
Summer					Winter				
Inlet Velocity	Pattern				Inlet Velocity	Pattern			
0.5m/s	Temperature	CO ₂	Vapour fraction	Stream line	0.5 m/s	Temperature	CO ₂	Vapour fraction	Stream line
1 m/s	Temperature	CO ₂	Vapour fraction	Stream line	1 m/s	Temperature	CO ₂	Vapour fraction	Stream line
2 m/s	Temperature	CO ₂	Vapour fraction	Stream line	2 m/s	Temperature	CO ₂	Vapour fraction	Stream line
Spring					Autumn				
Inlet Velocity	Pattern				Inlet Velocity	Pattern			
0.5m/s	Temperature	CO ₂	Humidity	Velocity	0.5m/s	Temperature	CO ₂	Humidity	velocity
1 m/s	Temperature	CO ₂	Humidity	Velocity	1 m/s	Temperature	CO ₂	Humidity	velocity
2 m/s	Temperature	CO ₂	Humidity	Velocity	2 m/s	Temperature	CO ₂	Humidity	velocity

5.2 Numerical work results

The tests were conducted with air intake temperatures of 16 °C, 22 °C, 27 °C, and 33 °C, corresponding to the weather conditions of sweltering summer, warm, cool, and cold winter, respectively, in Iraq. Inlet velocities ranging from 0.5 to 2.0 m/s were selected for most of the tests. The supply grill dimensions were 4cm × 6cm for the

ventilation scenarios and $6\text{ cm} \times 8\text{ cm}$ for the other scenarios. This study builds upon the previous sections and focuses specifically on the cooling mode in summer, as it aligns with the long-duration weather conditions in Iraq and the problem statement. Figure 3.3 in Chapter 3 shows the model of the room geometry, and Figure 5.1 displays the description of the plot in Section A and the plot in Section B.

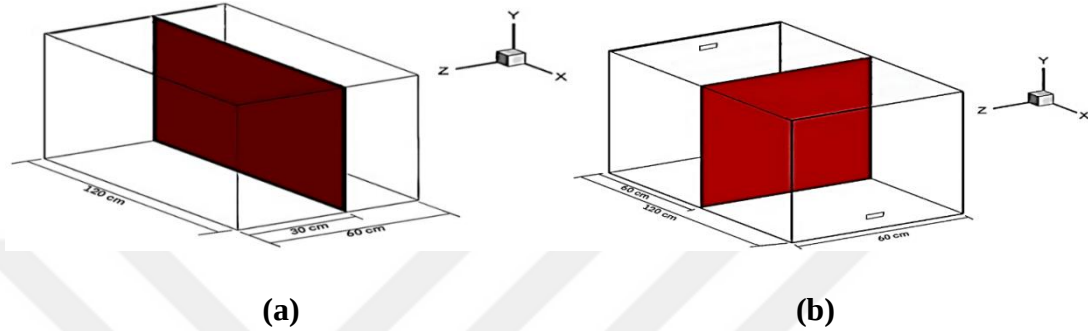


Figure 5.1: Displays the sections in the test room

(a) Plot section (A), at $Z=0.3\text{m}$.

(b) Plot section (B), at $X=0.6\text{m}$.

5.2.1 Cooling protocol

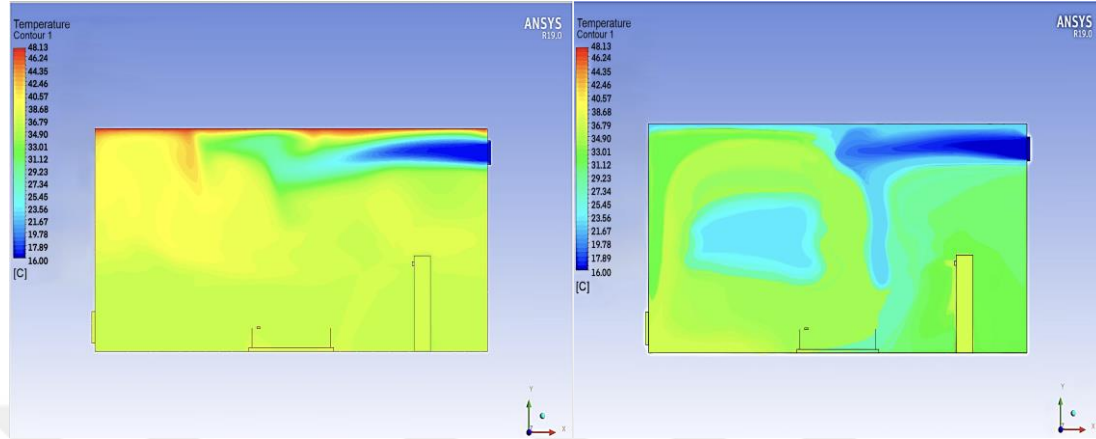
5.2.1.1 Cooling scenario in summer season

A- Case study at inlet velocity mode 0.5 m/s

I. Temperature pattern without and with PCM_s:

Figures 5.2 and 5.3 show the temperature distribution with an inlet velocity of 0.5 m/sec , both with and without PCM_s. The test was conducted in August using meteorological data and a virtual solar radiation of 780 W/m^2 , which varied with time, reaching 1099 W/m^2 at 1:00 pm and 866 W/m^2 at 2:00 pm. The test was conducted from 12:00 pm to 3:00 pm with a peak ambient temperature of $55\text{ }^\circ\text{C}$. In Section (a) of Figure 5.2, it can be seen that the air temperatures are highest at the top of the room model and gradually decrease over most of the area. In Section (b) of Figure 5.3, it is shown that when the PCM_s mechanism is used, there is a more stable temperature distribution in the comfort area of most of the prison quarry model, and a cold flow rate reaches the latter half of the room model in an acceptable fractional style. When PCM_s is used, the temperature at the ceiling is reduced from $48\text{ }^\circ\text{C}$ to $33\text{ }^\circ\text{C}$, and in the

middle of the room, the temperature is reduced from 35 °C to 26 °C at the peak cooling load at 1:22 pm.



(a)

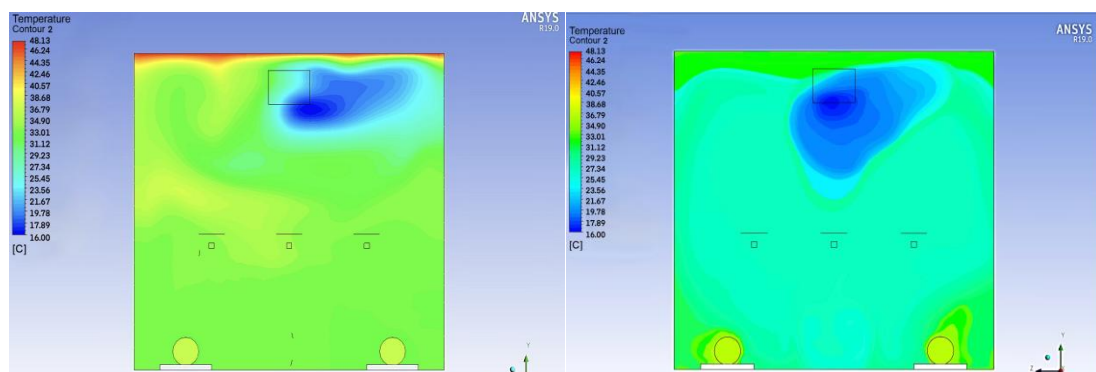
(b)

Figure 5.2: Temperature contour, 0.5m/s in section (A).

(a) Without PCM_s.

(b) With PCM_s.

Figure 5.4 illustrates the behavior of the air streamlines and 3D temperature streamlines in the room model. In Section a, the strong vortex movement with severe temperatures is shown to have high fluctuations. When PCM_s system is used, as shown in Section b, the fluctuating vortex is dramatically reduced and the temperature distribution overlaps with comfortable conditions. It can be concluded that the types of PCM_s used are very effective in severe and hot summer seasons.



(a)

(b)

Figure 5.3: Temperature contour, 0.5m/s in the section (B)

(a) Without PCM_s.

(b) With PCM_s.

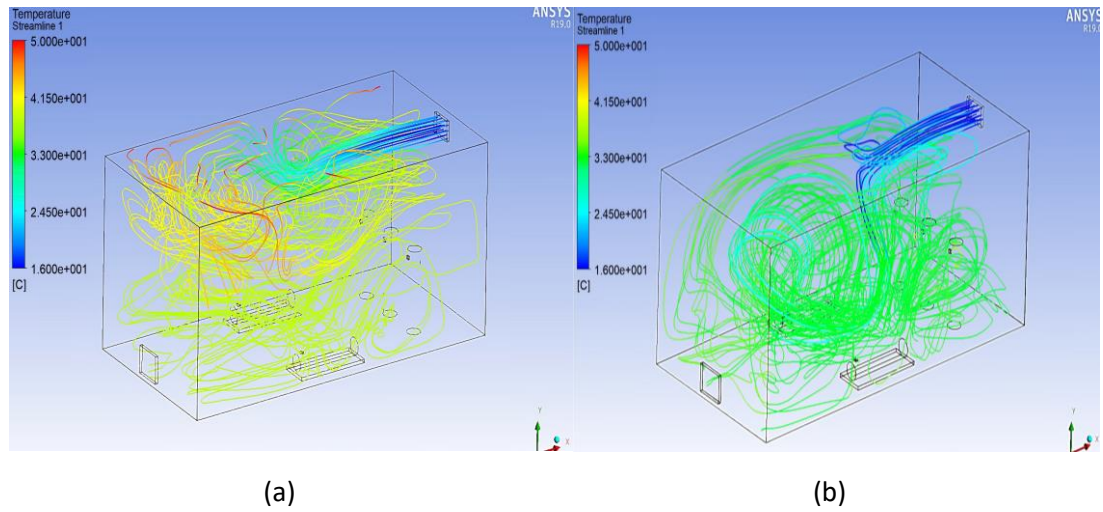


Figure 5.4: 3-D Temperature streamline, 0.5m/s in the room model.

(a) Without PCM_s.

(b) With PCM_s

II. Carbon Dioxide (ppm) pattern without and with PCM_s:

Figures 5.5 and 5.6 show carbon dioxide concentration contours with and without the use of PCM_s. In this case study, the concentration of ppm CO₂ is slightly higher without the use of PCM_s, especially in the corners in contact with lying occupants, reaching 850 ppm due to the breathing of occupants and temperature differences between zones. However, all the values remain within safe limits due to good air circulation within the space. Therefore, it can be seen that the use of PCM_s has little effect on the ppm CO₂ concentration.

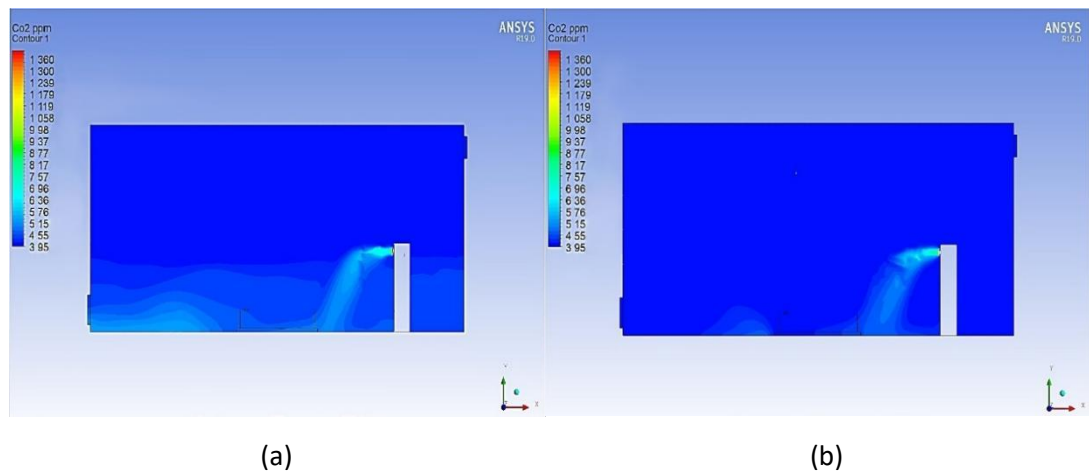
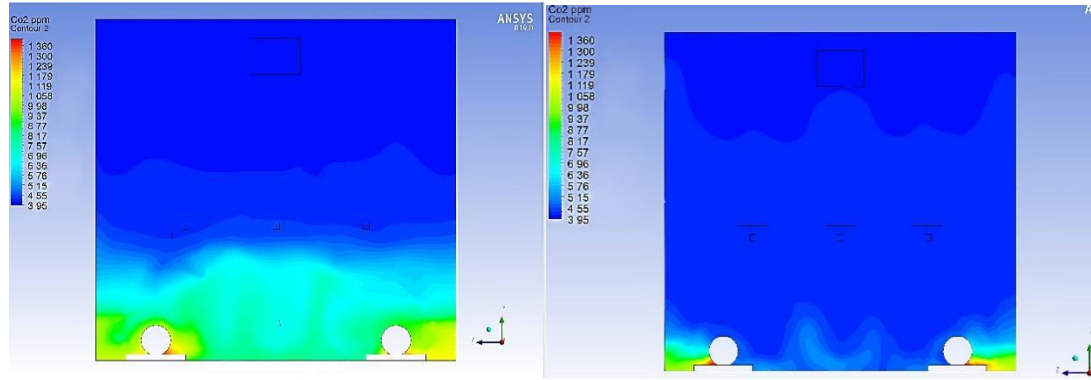


Figure 5.5: CO₂ Concentration contour, 0.5m/s in the section (A).

(a) Without PCM_s.

(b) With PCM_s



(a)

(b)

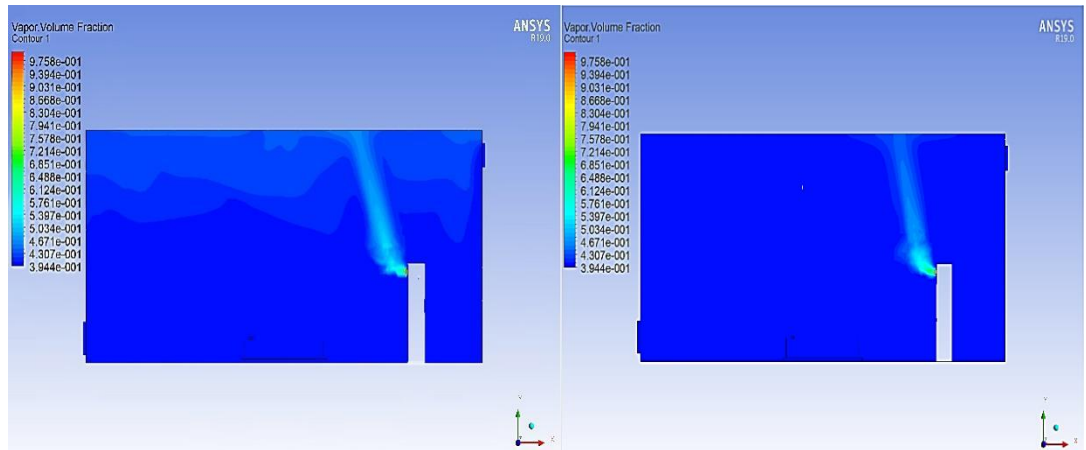
Figure 5.6: CO₂ Concentration contour, 0.5m/s in the section (B).

(a) Without PCM_s.

(b) With PCM_s

III. Vapour volume fraction pattern without and with PCM_s:

Figures 5.7 and 5.8 show the Vapour Volume Fraction, which is defined as the volume of the H₂O vapour constituent divided by the volume of all constituents of the mixture. It is noted that the humidity fraction is slightly better in the case study with PCM_s, due to the smooth vortexes and good air circulation. Additionally, it is known that humidity is higher in the summer season than in the winter season. It can be seen that the use of PCM_s reduces the vapour volume fraction from 4.6×10^{-1} to 3.2×10^{-1} , due to the improvement in temperatures.



(a)

(b)

Figure 5.7: Vapour Volume Fraction, 0.5m/s in the section (A).

(a) Without PCM_s.

(b) With PCM_s

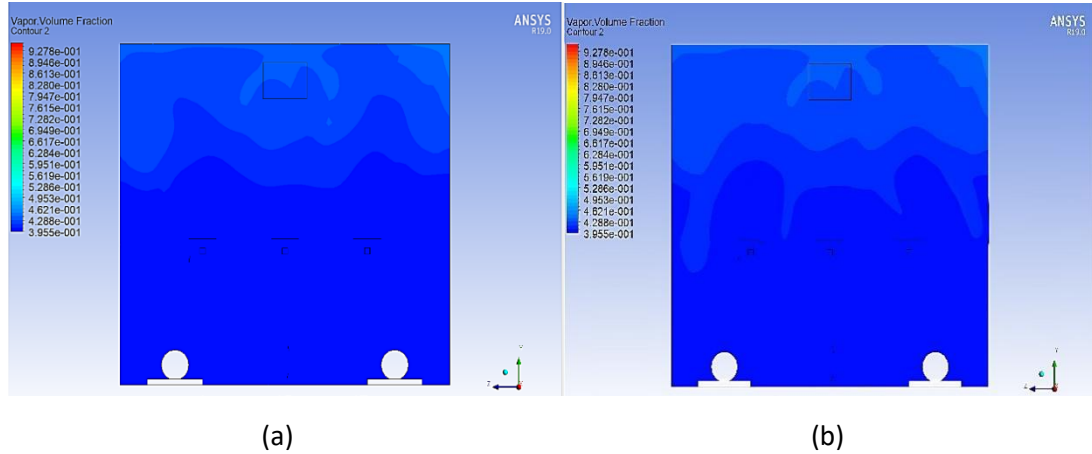


Figure 5.8: Vapour Volume Fraction, 0.5m/s in the section (B).

(a) Without PCM_s.

(b) With PCM_s

B- Case study at inlet velocity mode 1.0 m/s

I. Temperature pattern without and with PCM_s:

Figures 5.9 and 5.10 show the temperature distributions inside the room model when an inlet velocity of 1 m/sec is used. In Section a, it can be seen that the flow rate only reaches the last third of the zone directly before it hits the wall and dissipates. In Section b, it is clear that the use of PCM_s has a significant effect on the temperature, particularly on the ceiling and inside ambient temperature, reducing it by about 5 °C. The ceiling temperature is reduced from 42.6 °C to 37.4 °C.

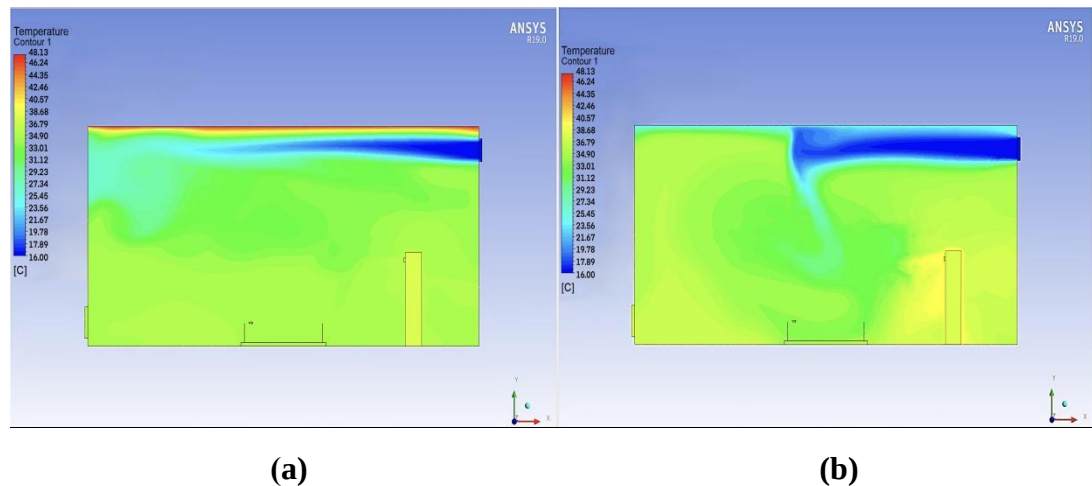


Figure 5.9: Temperature contour 1.0 m/s, in the section (A)

(a) Without PCM_s.

(b) With PCM_s.

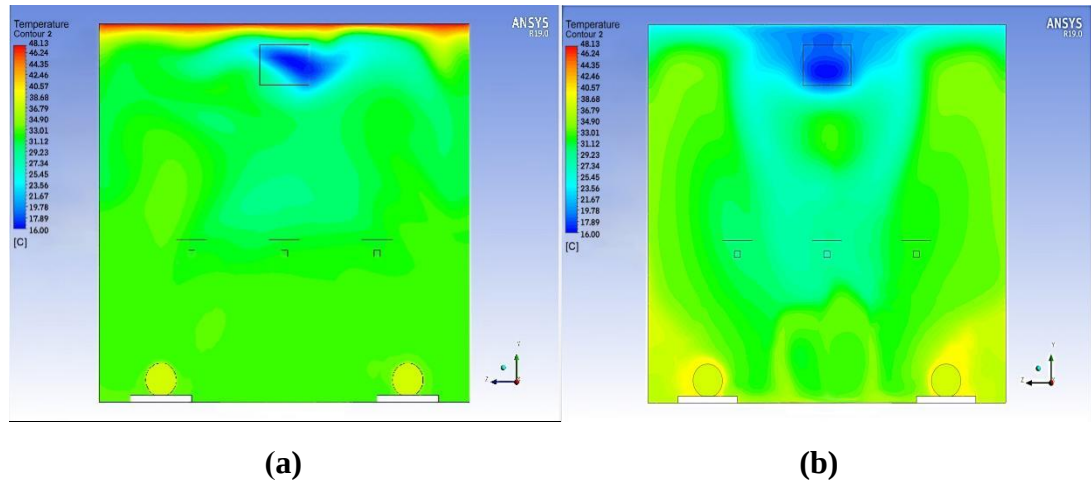


Figure 5.10: Temperature contour, 1.0 m/s in the section (B)

(a) Without PCM_s.

(b) With PCM_s.

Figure 5.11 shows the 3D temperature streamlines in the room model. The scope of the cold streamlines covers the entire space with a high vortex fluctuation for both test portions, affecting the comfort area and energy consumption.

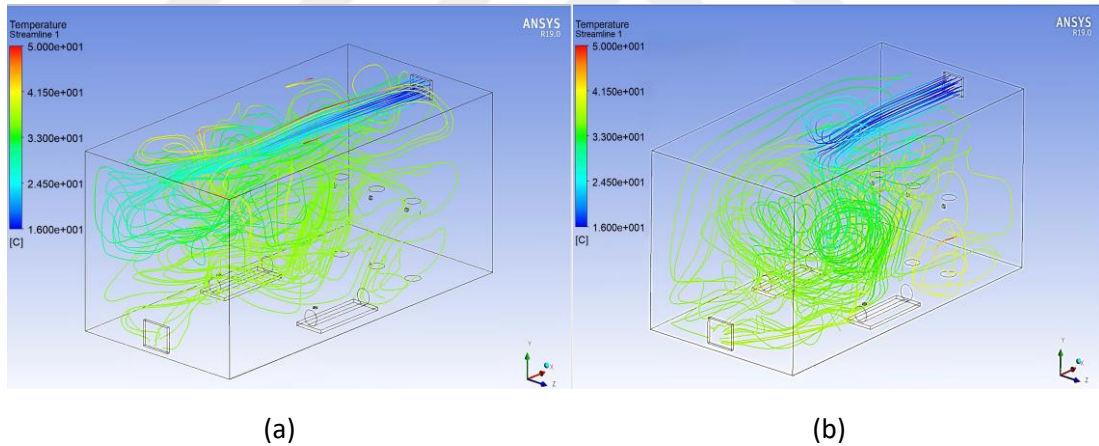


Figure 5.11: 3-D Temperature streamline, 1.0 m/s in the room model.

(a) Without PCM_s.

(b) With PCM_s.

II. Carbon Dioxide (ppm) pattern without and with PCM_s:

Figure 5.12 shows the ppm CO₂ concentration contour. In Section A, it can be seen that the carbon dioxide concentrations converge on the sidewall of the jail quarry's discharge grill. The levels remain normal and non-suffocating in all circumstances, but the danger level for annoyance begins at 1000 ppm. Figure 5.13 represents the plane in Section B, showing the carbon dioxide distribution in the room along 0.6 m

in the x-direction. The ppm of carbon dioxide converges around the outlet grill, indicating good air circulation and a good air changes per hour (ACH). With the use of PCM_s, it can be seen that the minimum dominant value is 410 ppm and the maximum dominant value is 950 ppm in a simple part of the room.

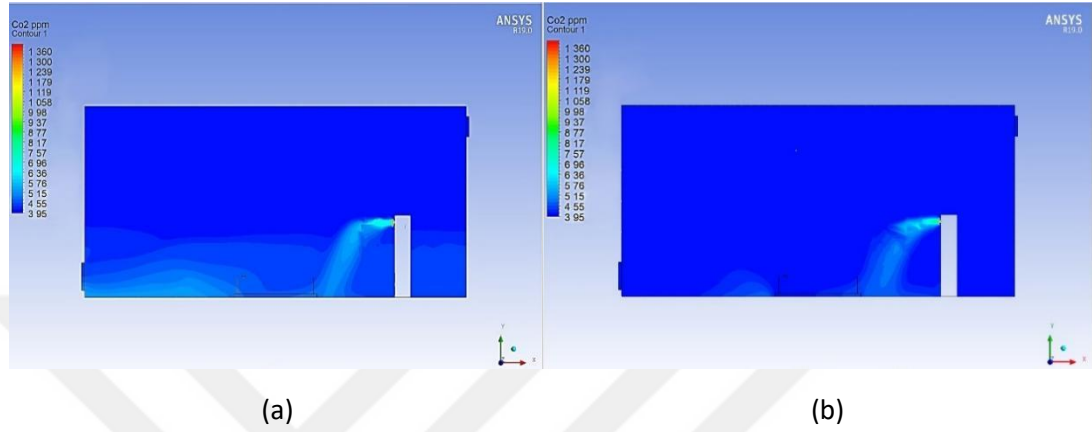


Figure 5.12: CO₂ Concentration contour, 1.0 m/s in the section (A).

(a) Without PCM_s.

(b) With PCM_s.

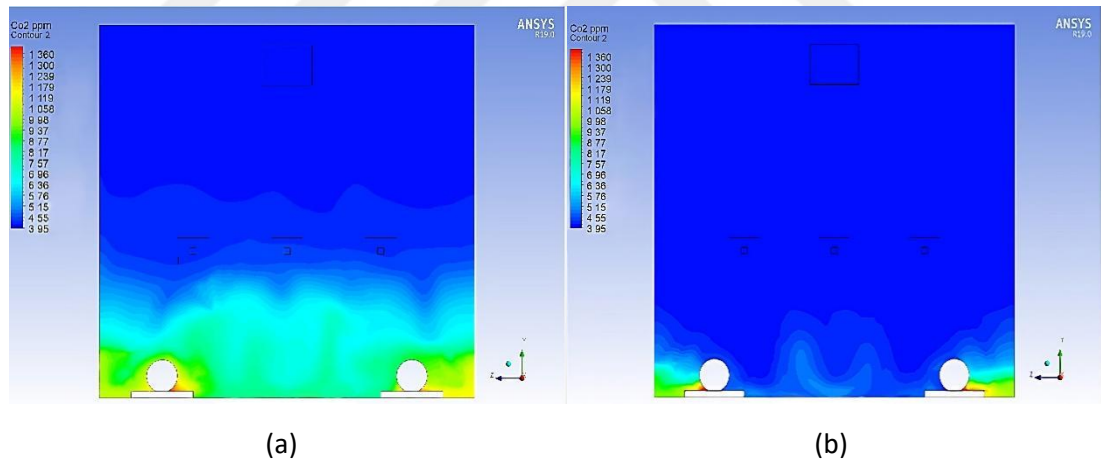


Figure 5.13: CO₂ Concentration contour, 1.0 m/s in the section (B)

(a) Without PCM_s.

(b) With PCM_s.

II. Vapour volume fraction pattern without and with PCM_s:

Figures 5.14 and 5.15 show the Vapour Volume Fraction with an inlet velocity of 1 m/s. As seen in these figures, the humidity is concentrated above the dummy occupants, due to the vortex of the streamlines with the peak value of the parameter.

It can always be seen that the value of water vapour is improved with the use of PCMs, by reducing, even if only slightly. It is noted that the water vapour is lifted off from the middle of the room, which is likely due to the vortex and the improvement of the temperature inside the room, resulting in a slightly better performance.

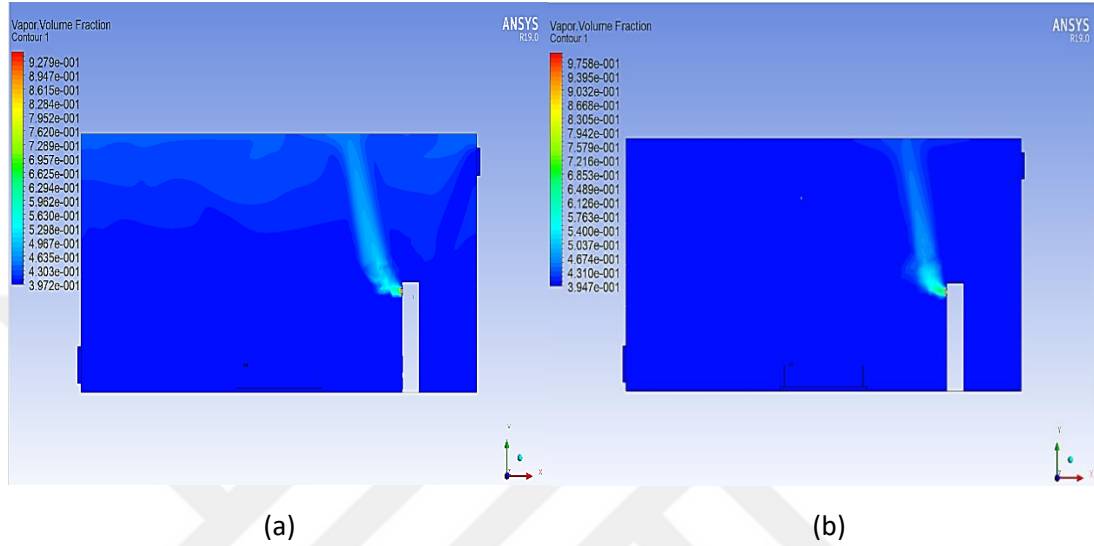


Figure 5.14: Vapour Volume Fraction, 1.0 m/s in the section (A).

(a) Without PCMs.

(b) With PCMs.

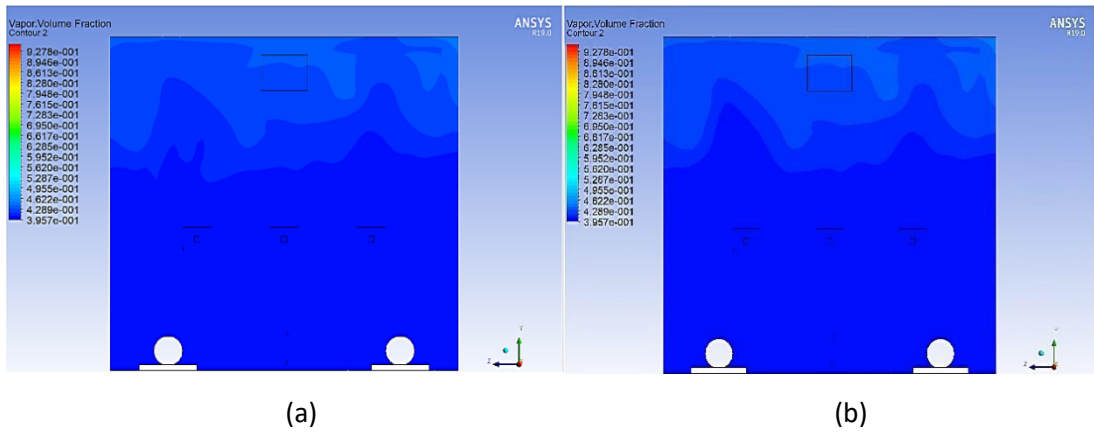


Figure 5.15: Vapour Volume Fraction, 1.0 m/s in the section (B).

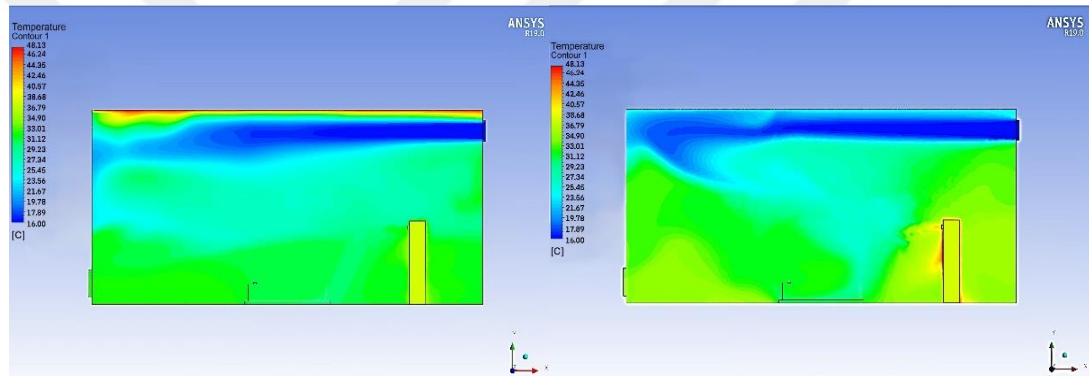
(a) Without PCMs.

(b) With PCMs.

C- Case study at inlet velocity mode 2.0 m/s

I. Temperature pattern without and with PCMs:

Figures 5.16 and 5.17 show the temperature distributions at Section A and Section B, respectively. In Section a, it can be seen that the air temperatures higher at the ceiling of the room model, particularly above the occupied area, due to the high outdoor temperature and strong vortexes. In Section b, it is shown that the cold zone becomes wider, but not regular, near the lying characteristics, causing a significant increase in energy consumption (E.C.). Figure 5.18 shows the disrupted streamlines due to the high velocity collision with the wall. When PCM_s are used, the ceiling temperature is reduced from 41°C to 28 °C due to the high velocity coming into contact with the ceiling, but in the middle of the room, the temperature remains in the range of 27 °C.



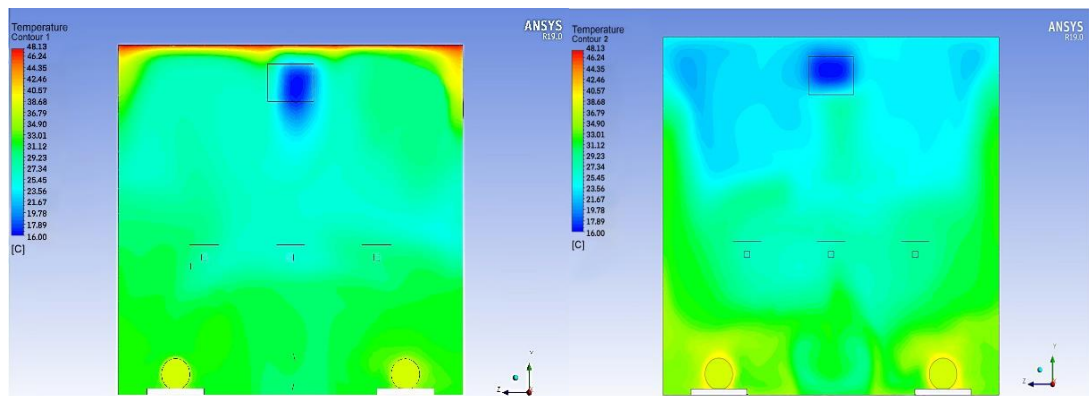
(a)

(b)

Figure 5.16: Temperature contour, 2.0 m/s in the section (A)

(a) Without PCM_s.

(b) With PCM_s.



(a)

(b)

Figure 5.17: Temperature contour, 2.0 m/s in the section (B)

(a) Without PCM_s.

(b) With PCM_s.

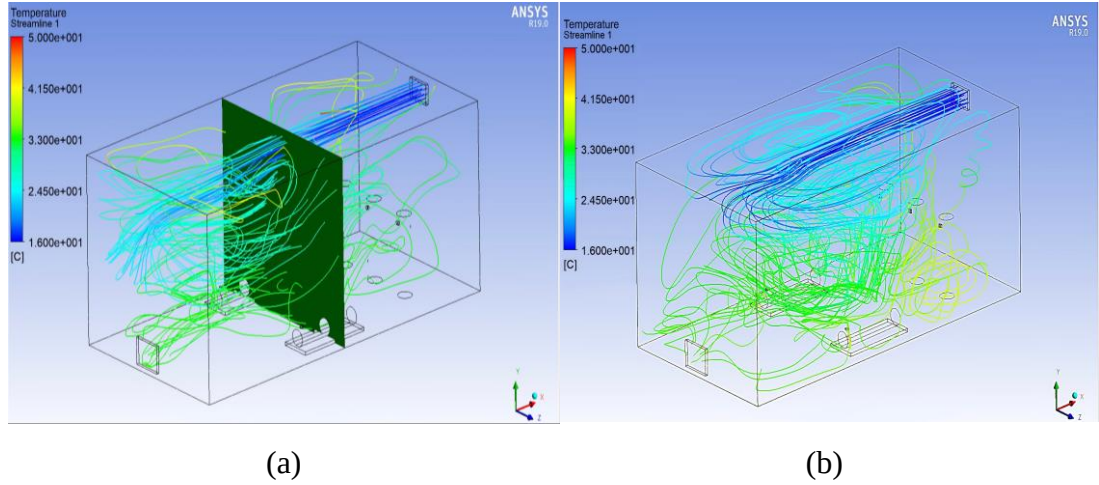


Figure 5.18: 3-D Temperature streamline, 2.0 m/s in the room model.

(a) Without PCM_s.

(b) With PCM_s.

II. Carbon Dioxide (ppm) pattern without and with PCM_s:

Figures 5.19 and 5.20 show the ppm CO₂ concentration contour with and without PCM_s. It can be noted that any decrease in temperature inside the space leads to a small decrease in carbon dioxide concentration. The effect of the value of the inlet velocity and the addition of phase change materials is very clear. The CO₂ ppm around the occupants is reduced from approximately 850 ppm to 500 ppm. We conclude that the invented PCM_s are useful for all the parameters.

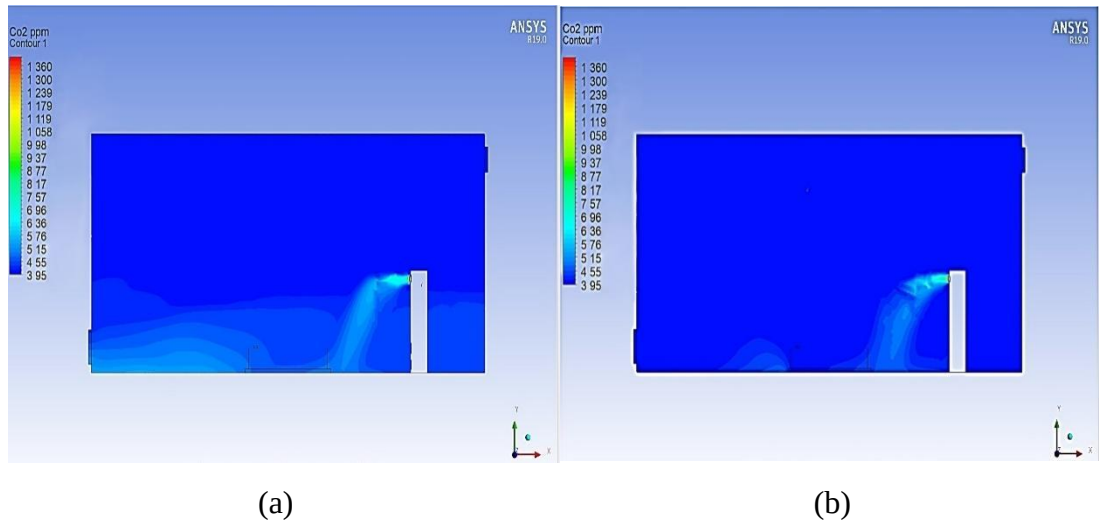


Figure 5.19: CO₂ Concentration contour, 2.0 m/s in the section (A).

(a) Without PCM_s.

(b) With PCM_s.

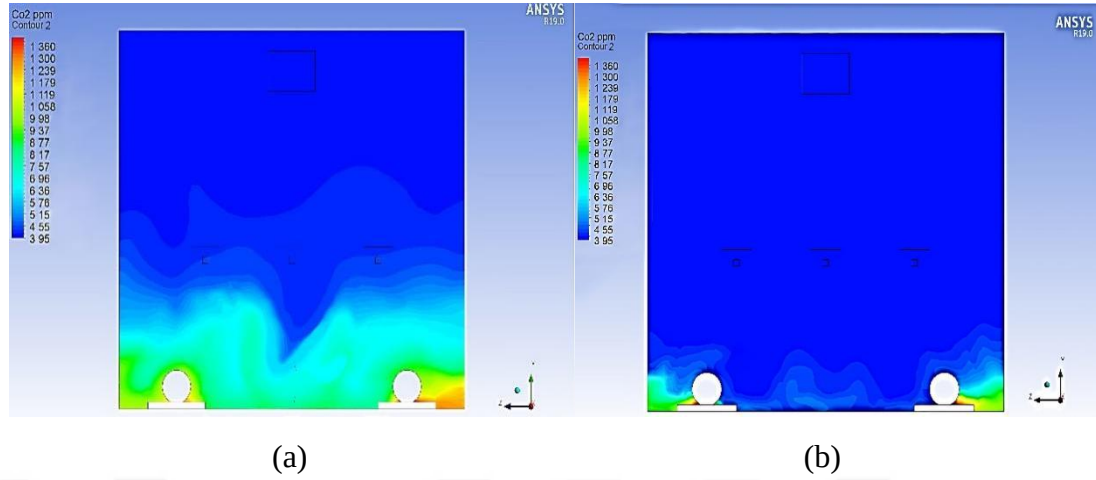


Figure 5.20: CO₂ Concentration contour, 2.0 m/s in the section (B).

(a) Without PCM_s.

(b) With PCM_s.

III. Vapour volume fraction pattern without and with PCM_s:

Figures 5.21 and 5.22 show the Vapour Volume Fraction at an inlet velocity of 2 m/s. To increase accuracy, the Vapour Volume Fraction was selected for calculating the contours. It is observed that in the designated area near the ceiling and the western side where the residents are located, the concentration is nearly constant and equal. It is noted that there is no significant difference between the two cases.

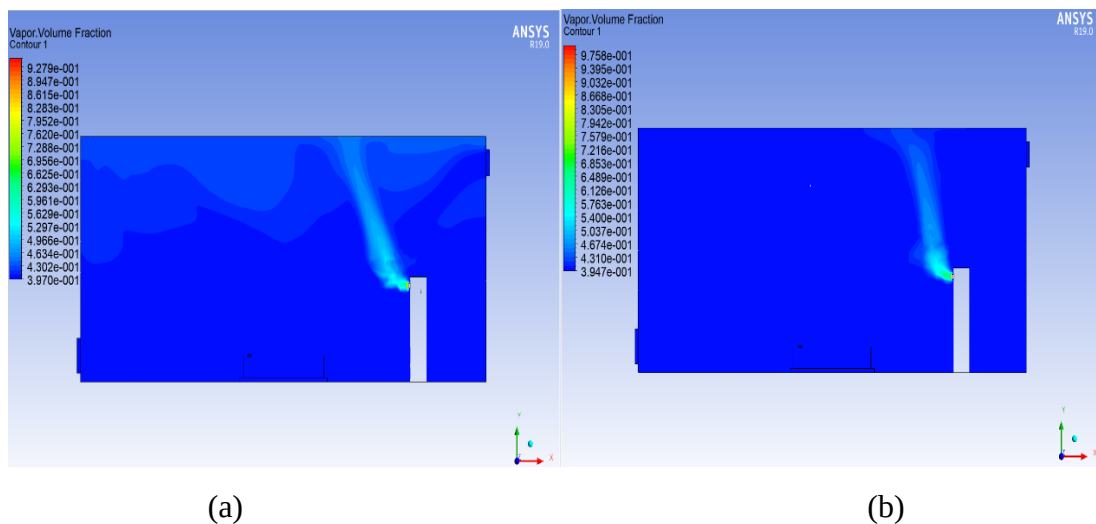


Figure 5.21: Vapour Volume Fraction contour, 2.0 m/s in the section (A).

(a) Without PCM_s.

(b) With PCM_s.

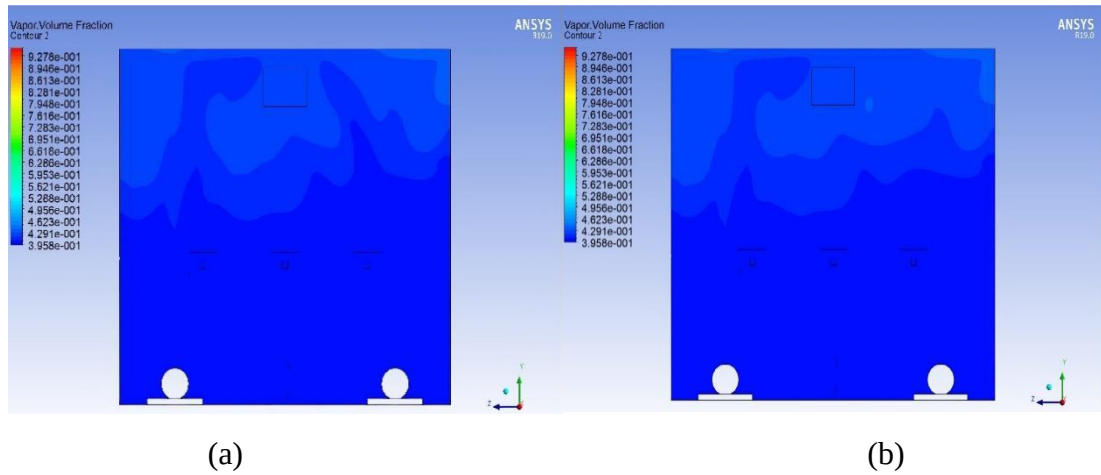


Figure 5.22: Vapour Volume Fraction contour, 2.0 m/s in the section (B).

(a) Without PCM_s.

(b) With PCM_s.

5.2.1.2 Cooling ventilation scenario in spring season

This scenario focuses on the need for moderated temperatures in air conditioning, which is often necessary in Iraq's weather during spring. Many times, outdoor ambient temperatures exceed 36 °C, requiring the use of an HVAC device for cooling. Therefore, the experiments were conducted with an air intake temperature of $T_{in} = 22^\circ\text{C}$ and a charge grill dimension of 4 cm × 6 cm.

A- Case study at inlet velocity mode 0.5 m/s

I. Temperature pattern without and with PCM_s:

Figure 5.23 shows the temperature contour distributions at an inlet velocity of 0.5 m/s. It can be seen that the high heating is concentrated on the ceiling, reaching above 32 °C, and gradually decreasing near the psuedo dummies. When PCM_s are used, the chart is dramatically changed to a better distribution, as seen in Section b. Comfort is clearly apparent in all zones. It is noted that the temperature behavior is reduced by approximately 4 °C along the inside surface of the room due to the effect of the PCM_s layers, which function as thermal energy storage.

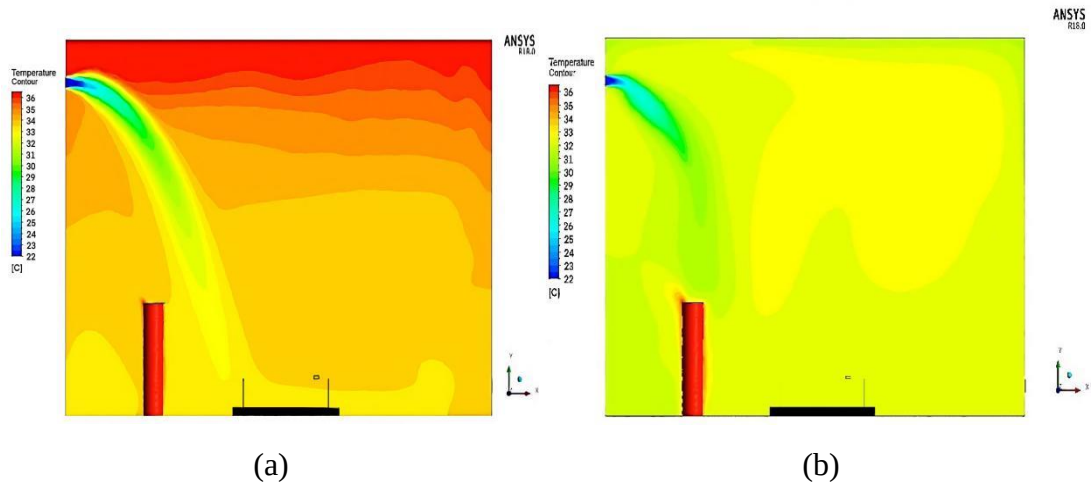


Figure 5.23: Temperature contour, 0.5 m/s in the section (A)

(a) Without PCM_s .

(b) With PCM_s .

II. Carbon Dioxide (ppm) pattern without PCM_s :

Figure 5.24 shows the ppm of CO_2 concentration in Section A without the use of PCM_s . As previously noted, the effect of PCM_s on the carbon dioxide percentage is very small. It can also be seen that the higher percentage of ppm of CO_2 is concentrated in the corners of the room model, without posing any risk to the occupants or the space, remaining limited between 390 to 650 ppm.

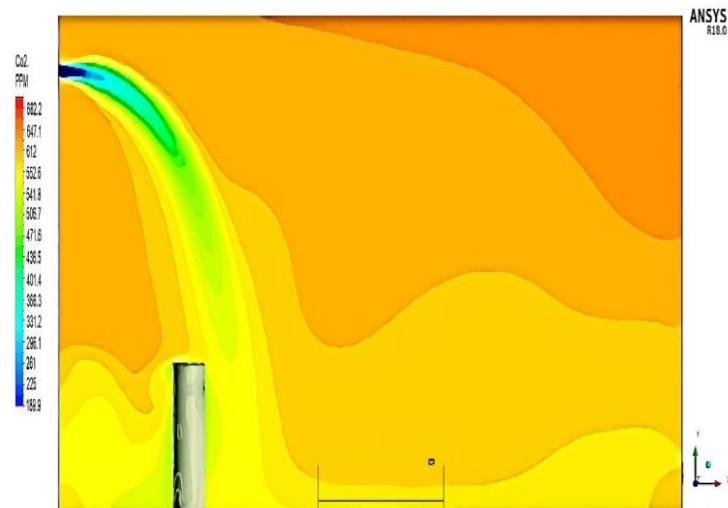


Figure 5.24: CO_2 Concentration contour, 0.5 m/s in the section (A).

III. Relative Humidity pattern without PCM_s:

Figure 5.25 shows the relative humidity pattern of this case, which is a measure of the actual amount of water vapour in the air compared to the total amount of vapour that can exist in the air at its current temperature. It can be seen that the acceptable humid streamlines converge towards the dummy occupants before gradually dissipating upwards, due to the balance of air displacement and the exhaust of air from the grill. The relative humidity is simulated instead of the vapour fraction due to the use of Ansys R18 in this scenario, which is synchronized with Ansys R19 and requires more computers for simulation solving, but has a lighter workload when running.

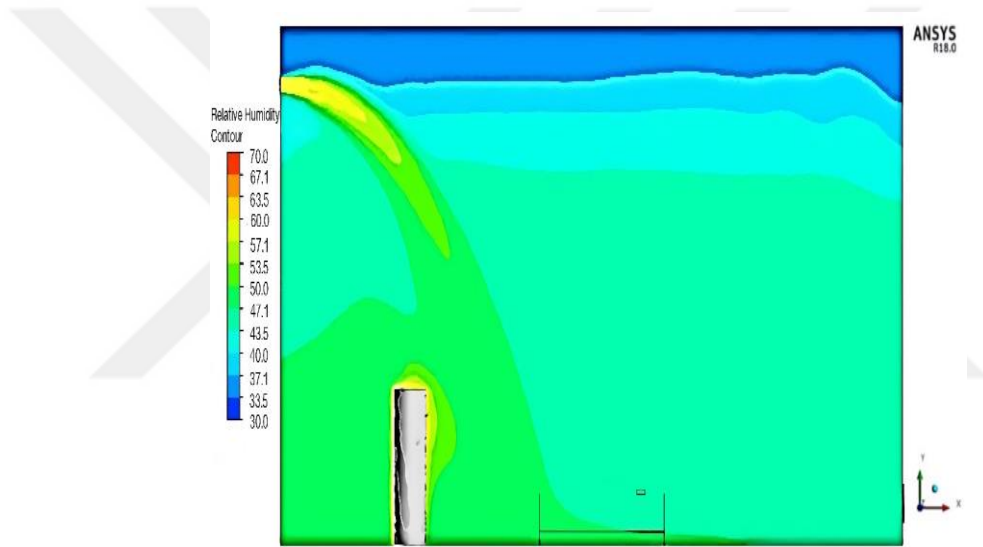


Figure 5.25: Relative Humidity contour, 0.5 m/s in the section (A).

IV. Velocity pattern without PCM_s:

The velocity counter is used in this case to simulate the inlet velocity on the room model. Figure 5.26 shows that the indoor velocity is acceptable near the level of sleeping and standing occupants and is low in the upper half zone, which is located away from the charge grill. The velocity contour is used instead of a streamline figure. It can be seen that the minimum velocity reaches 0.04 m/s at the corners.

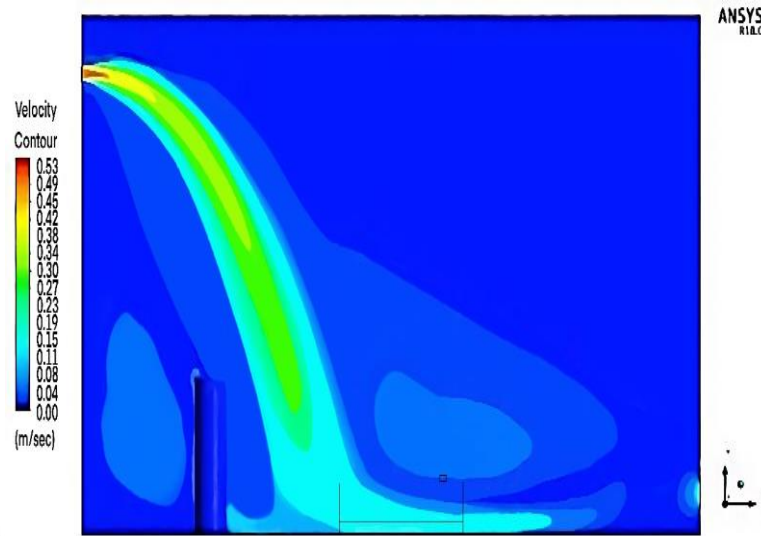


Figure 5.26: Velocity contour, 0.5 m/s in the section (A).

A- Case study at inlet velocity mode 1.0 m/s

I. Temperature pattern without PCM_s:

Figure 5.27 shows the temperature distributions inside the room model when the following boundary conditions are used: an inlet velocity of 1 m/s, $T_{in} = 22\text{ }^{\circ}\text{C}$, T_{out} ambient = $36\text{ }^{\circ}\text{C}$, inlet grill dimensions of $4\text{ cm} \times 6\text{ cm}$, and outlet grill dimensions of $6\text{ cm} \times 8\text{ cm}$. It can be seen that the temperature increases upwards and downwards of the inlet scope. If the comparison is made with the previous case, it can be seen that the previous case has better cold air diffusion with energy consumption.

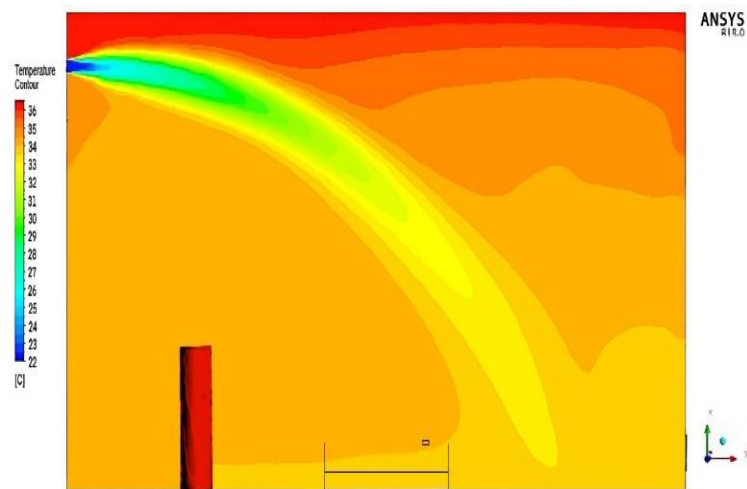


Figure 5.27: Temperature contour, 1.0 m/s in the section (A).

II. Carbon Dioxide (ppm) pattern without PCMs:

Figure 5.28 illustrates the behavior of ppm CO₂ when an inlet velocity of 1 m/s is used. The reduction in the ppm percentage is clear because the ACH is greater than in the previous case. It can be seen that the ppm is limited between 350 to 620 ppm.

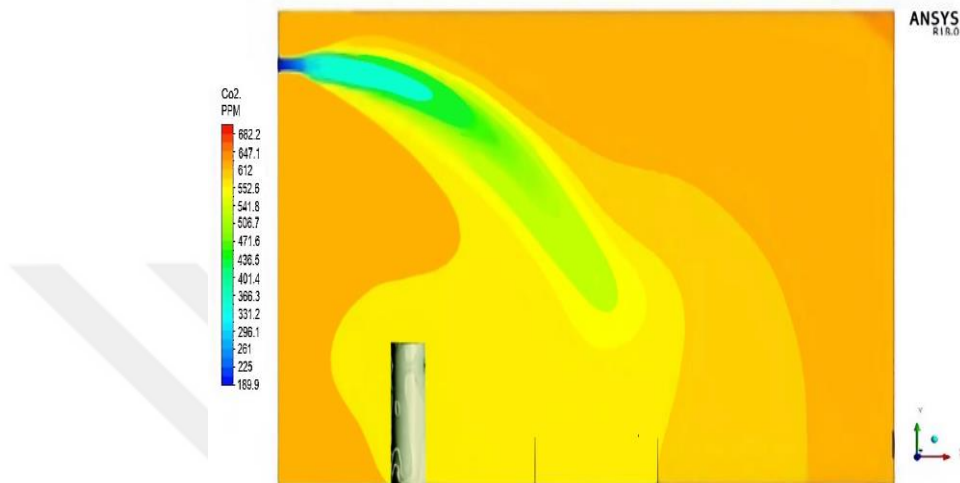


Figure 5.28: CO₂ Concentration contour, 1.0 m/s in the section (A).

III. Relative Humidity pattern without PCMs:

Figure 5.29 illustrates the water vapour inside the model when an inlet velocity of 1 m/s is used. It is noted that in the restricted region close to the occupants, the concentration is almost equal and fixed in many zones. It can be concluded that the relative humidity complies with ASHRE standard.



Figure 5.29: Relative Humidity contour, 1.0 m/s in the section (A)

IV. Velocity pattern without PCM_s:

Figure 5.30 shows that the indoor velocity is acceptable near the level of sleeping and standing occupants and is low in the upper half zone, which is located away from the charge grill. All the cases were conducted under turbulent conditions, with the minimum value being 0.07 m/s at the corner and farthest end of the room. This does not affect the thermal comfort of the occupants.

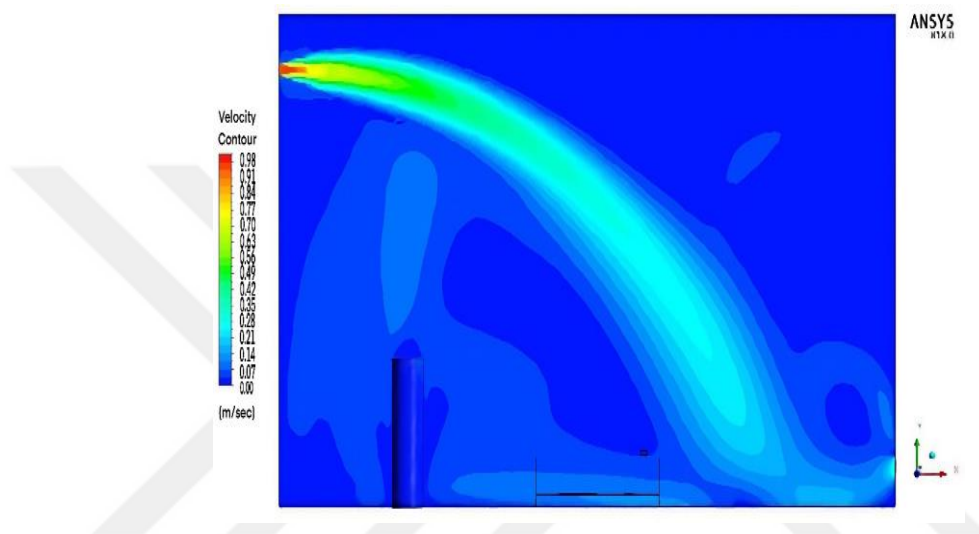


Figure 5.30: Velocity contour, 1.0 m/s in the section (A).

A- Case study at inlet velocity mode 2.0 m/s

I. Temperature pattern without PCM_s:

Figure 5.31 shows the temperature distributions. It can be seen that the inlet air flow rate directly tends to the end of the room and most of the cold treatment stream flux is lost. Therefore, the air conditioning at this velocity is ineffective. In addition, the high speed will cause noise from the inlet grill.

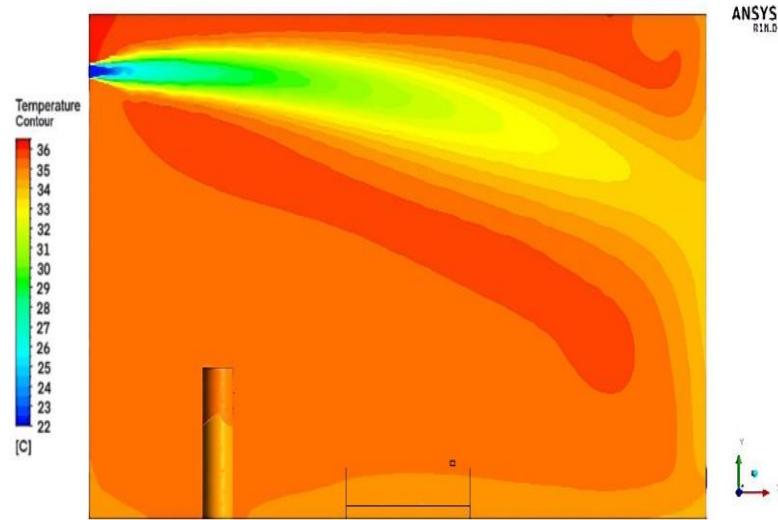


Figure 5.31: Temperature contour , 2.0 m/s in the section (A).

II. Carbon Dioxide (ppm) pattern without PCM_s:

Figure 5.32 illustrates the behavior of ppm carbon dioxide when an inlet velocity of 2 m/s is used. It can be seen that ppm is limited between 400 to 700 ppm.



Figure 5.32: CO₂ Concentration contour, 2.0 m/s in the section (A).

III. Relative humidity pattern without PCM_s:

Figure 5.33 shows that the water vapour is irregular in the entire conditioned area, with 55 % being the dominant concentration. Regardless of humidity concentrations, this is observed in the entire conditioned area.

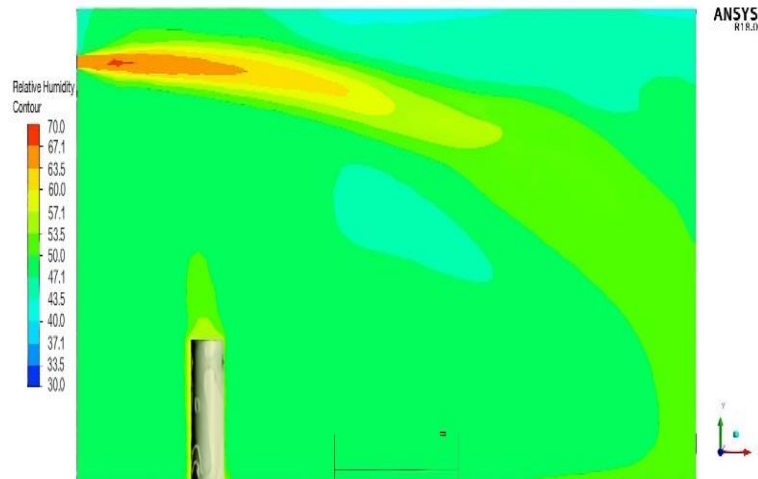


Figure 5.33: Relative Humidity contour, 2.0 m/s in the section (A).

IV. Velocity pattern without PCMs:

Figure 5.34 shows the velocity contour at section (A) with an inlet velocity of 2 m/s. The stream lines of the air flow tend to the last third of the room model, resulting in a reduction in speed delivery.

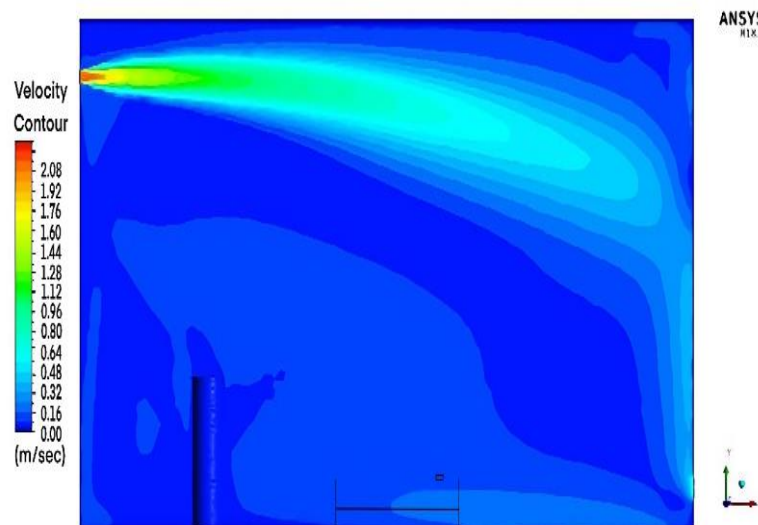


Figure 5.34: Velocity contour, 2.0 m/s in the section (A).

5.2.2 Heating protocol

5.2.2.1 Heating scenario in cold winter season

Tests were conducted with inlet velocities ranging from 0.5 m/s to 2 m/s, both with and without PCM_s, in cold winter conditions (T_{in} = 33 °C, inlet grill size 6 cm × 8 cm, outlet grill size 8 cm × 10 cm, and outdoor ambient temperature 12-16 °C).

A. Case study at inlet velocity mode 0.5 m/s

I. Temperature pattern without and with PCM_s:

Figures 5.35 and 5.36 show the temperature distributions without and with PCM_s at an inlet velocity of 0.5 m/s. Without using PCM_s, the results are not irregular within the conditioned area, especially in the middle of the model. It can be seen that the desired temperatures are achieved with the use of PCM_s, with the warm temperatures covering the entire room model, including the edges of the roof. Figure 5.37 shows the streamlines of the case study. Without PCM_s, some of the streamline bundles remain cold, while most streamline bundles quickly respond with the use of PCM_s. It can be noted that the temperature in the middle of the room is 30 °C, and 28 °C at the sides of the room, due to the flow vortex paths.

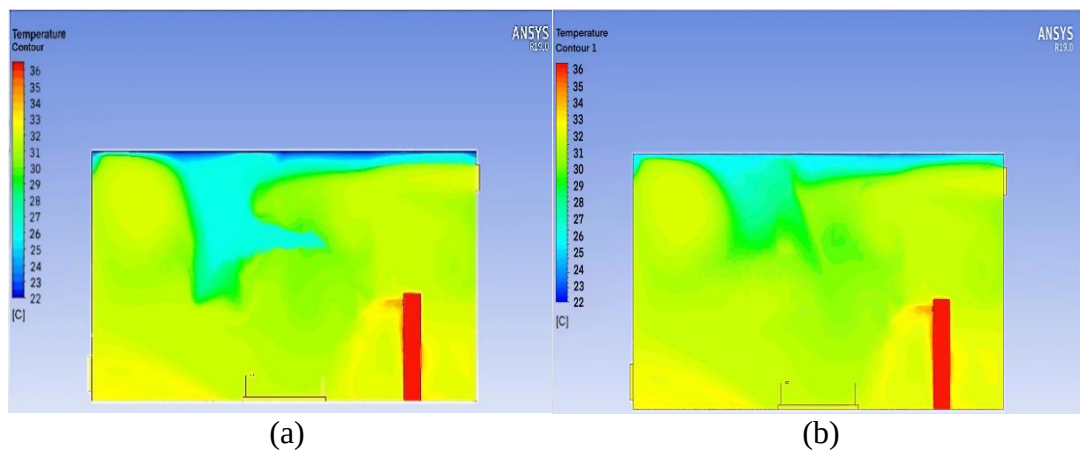
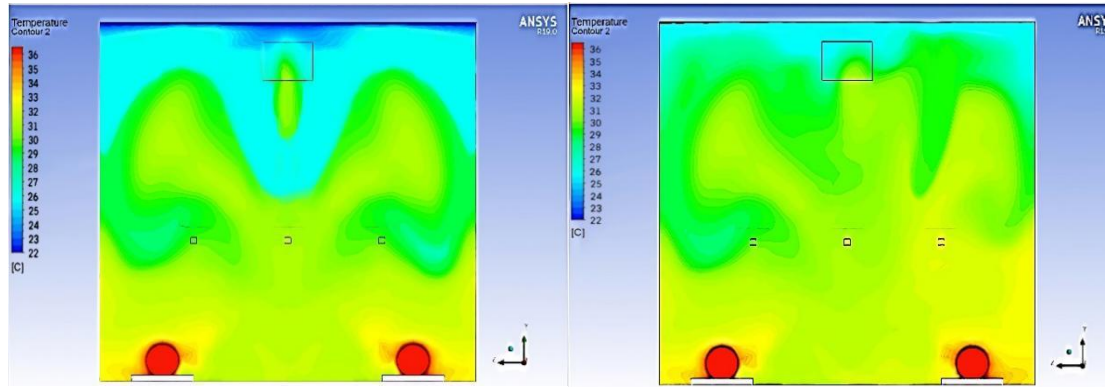


Figure 5.35: Temperature contour, 0.5 m/s in the section (A)

(a) Without PCM_s.

(b) With PCM_s.



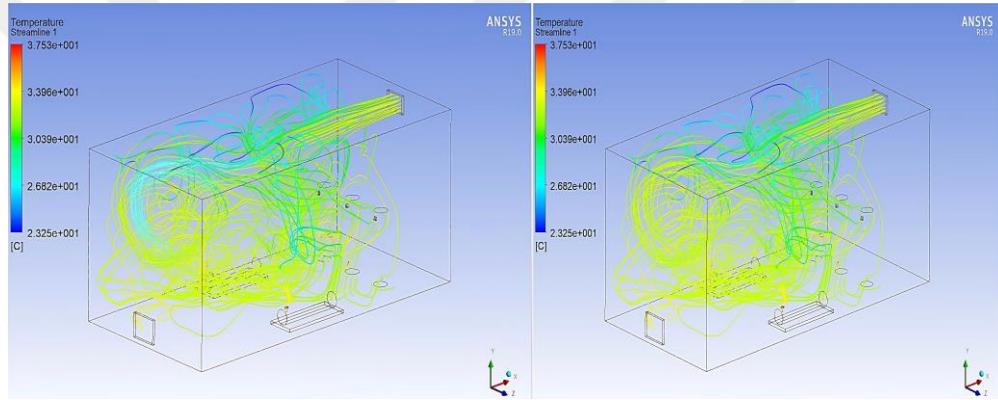
(a)

(b)

Figure 5.36: Temperature contour, 0.5 m/s in the section (B)

(a) Without PCM_s.

(b) With PCM_s.



(a)

(b)

Figure 5.37: 3-D Temperature streamline, 0.5 m/s in the room model.

(a) Without PCM_s.

(b) With PCM_s.

II. Carbon Dioxide (ppm) pattern with PCM_s:

Figure 5.38 shows the ppm of carbon dioxide in this case study, using only two layers of PCM_s at section (A). It can be noted that the ppm of CO₂ is normal and there is no risky situation. It is accumulated near the lying pseudo dummy. In Figure 5.39, it can be noted that the result indicates that there is no discomfort in breathing for the occupants, it is also with PCM system. It can be seen that the maximum value reaches 1170 ppm at the corner where the occupants are lying down, which normal due to the occupants' is breathing.

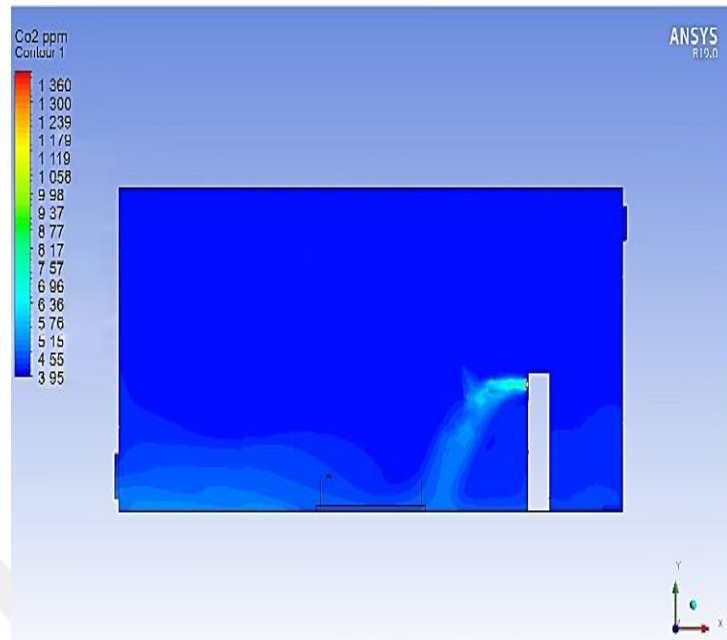


Figure 5.38: CO₂ Concentration contour, 0.5 m/s in the section (A).

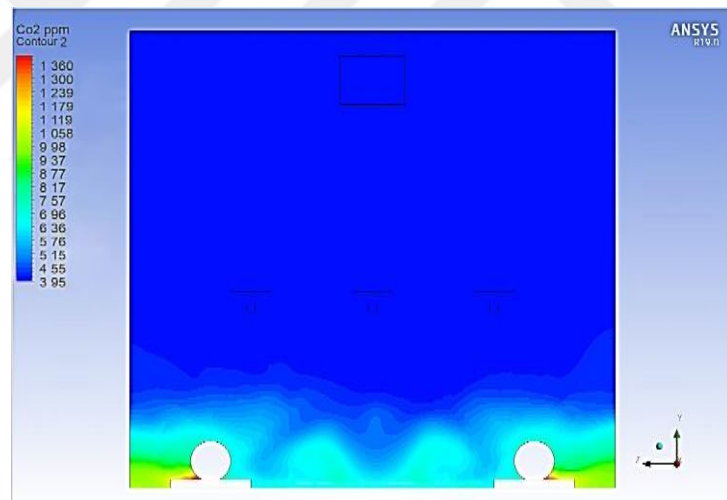


Figure 5.39: CO₂ Concentration contour, 0.5 m/s in the section (B).

III. Vapour volume fraction pattern with PCMs:

It is necessary to examine the water vapor percentage in the case study during the cold winter season because a lack of humidity can lead to dryness of the skin, which can cause skin diseases. The figures 5.40 and 5.41 show that the distribution of water vapor is acceptable at sections A and B.

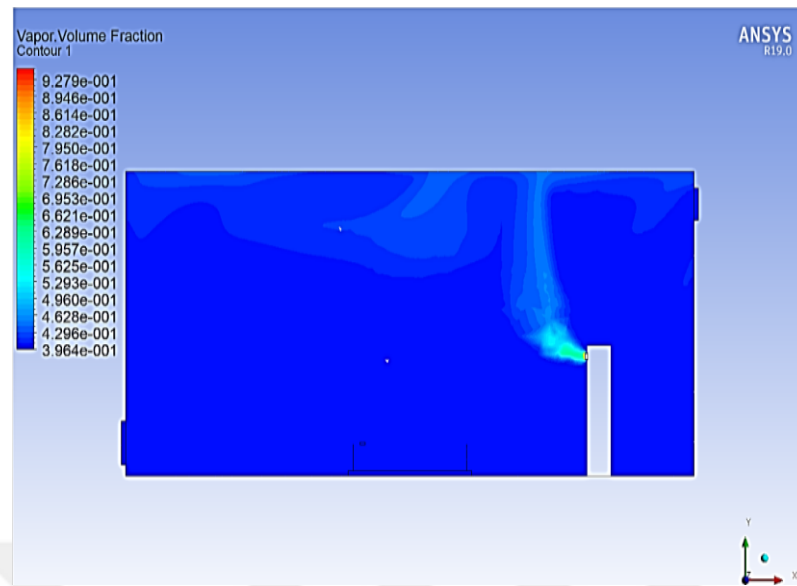


Figure 5.40: Vapour Volume Fraction, 0.5 m/s in the section (A).

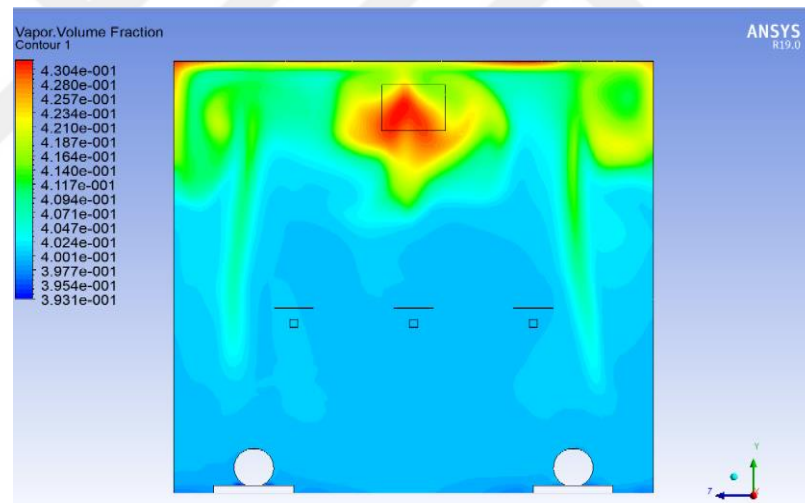


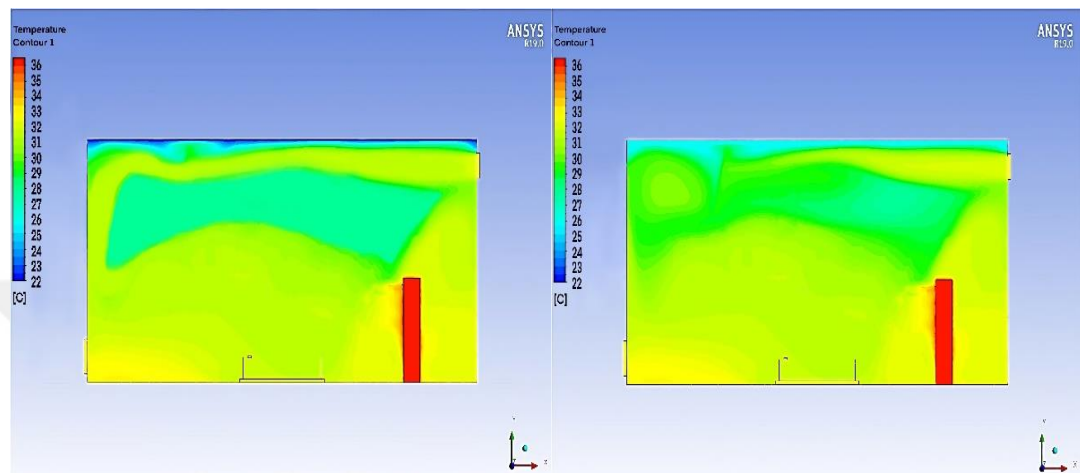
Figure 5.41: Vapour Volume Fraction, 0.5 m/s in the section (B).

B. Case study at inlet velocity mode 1m/s

I. Temperature pattern without and with PCM_s:

In this case study, an examination was conducted to show the temperature distribution with and without PCM_s. As shown in figures 5.42 and 5.43, both cases have similar temperature counters, with the most covered temperature being 30 °C.

Figure 5.44 shows that the inner vortexes were warmer in the test with PCM_s than in the test without PCM_s. The temperature is cooler on the upper sides of the inlet grill, but using PCM_s increases the temperature by 3 °C.



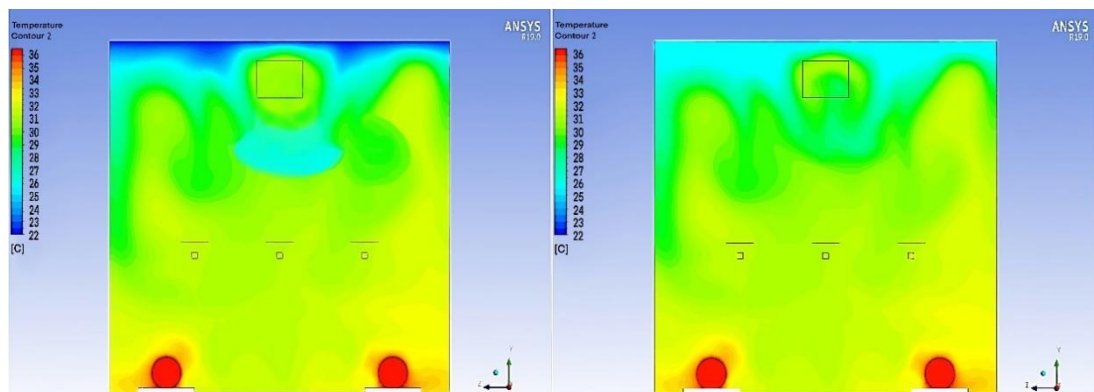
(a)

(b)

Figure 5.42: Temperature contour, 1.0 m/s in the section (A)

(a) Without PCM_s.

(b) With PCM_s.



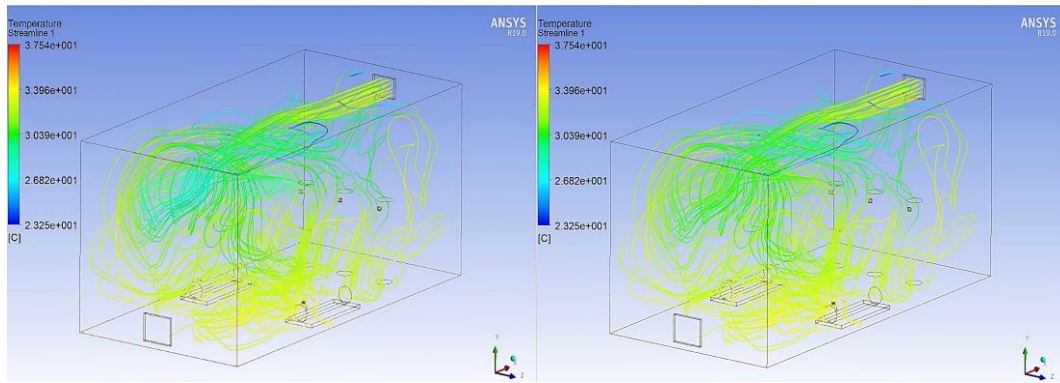
(a)

(b)

Figure 5.43: Temperature contour, 1.0 m/s in the section (B)

(a) Without PCM_s.

(b) With PCM_s.



(a)

(b)

Figure 5.44: 3-D Temperature streamline, 1.0 m/s in the room model.

(a) Without PCM_s.

(b) With PCM_s.

II. Carbon Dioxide (ppm) pattern with PCM_s:

Figures 5.45 and 5.46 show the ppm of carbon dioxide with an inlet velocity of 1m/s. The aggregated concentration of ppm is highest near the grill discharge and near the occupants' breathing zone, which is normal. These figures indicate that there is no danger or risk associated with this concentration of carbon dioxide.

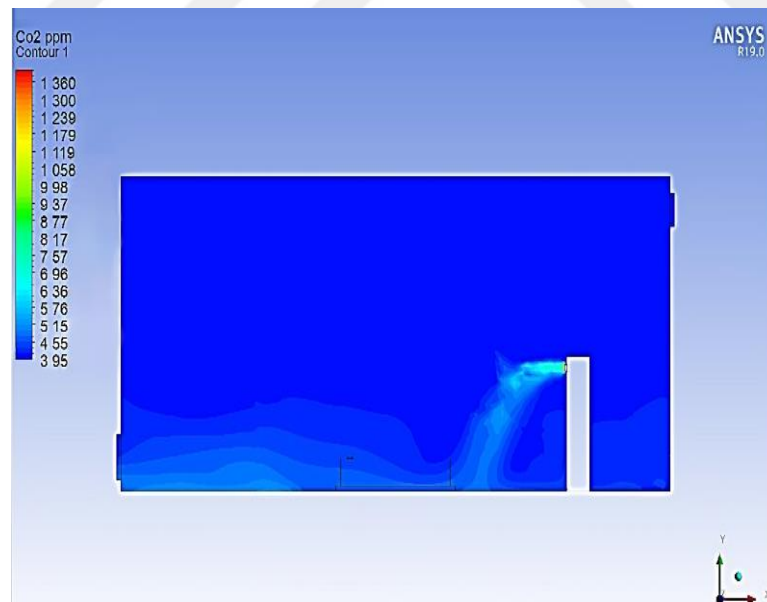


Figure 5.45: CO₂ Concentration contour, 1.0 m/s in the section (A).

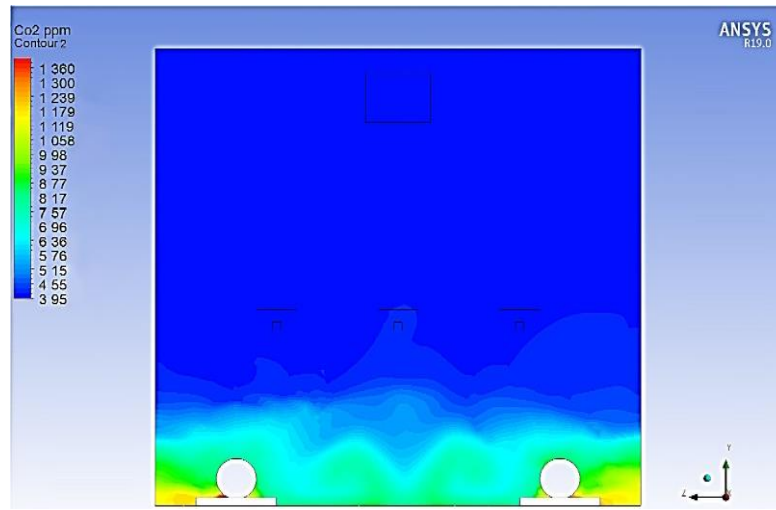


Figure 5.46: CO₂ Concentration contour, 1.0 m/s in the section (B).

III. Vapour Volume Fraction pattern with PCMs:

The vapor volume fraction was investigated in figure 5.47 at section A and figure 5.48 at section B. It can be seen that the water vapor levels are normal for the winter season, with only slight differences from previous cases.

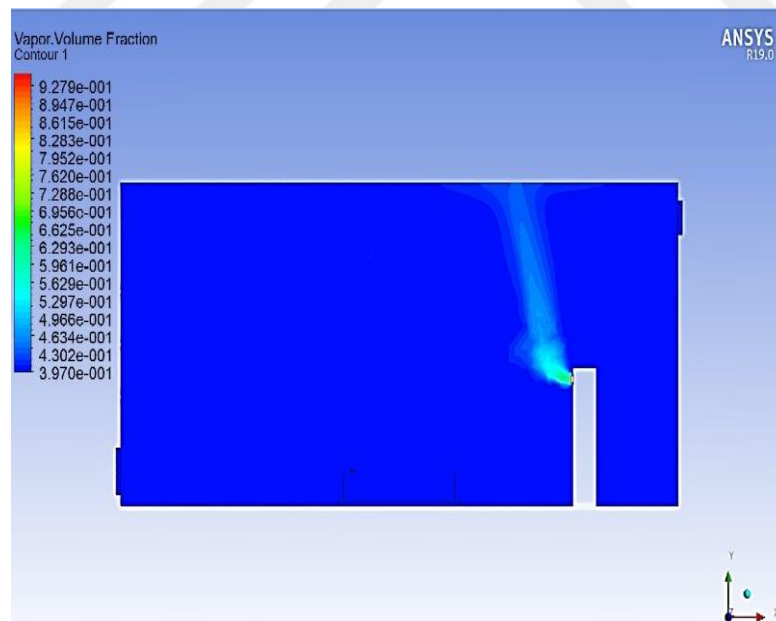


Figure 5.47: Vapour Volume Fraction contour, 1.0 m/s in the section (A).

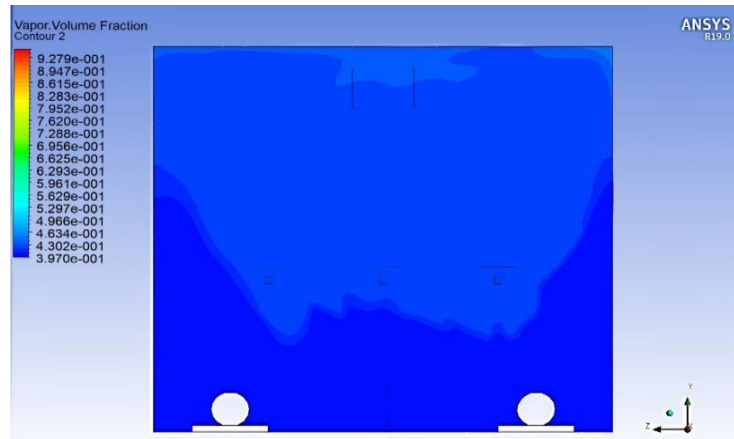
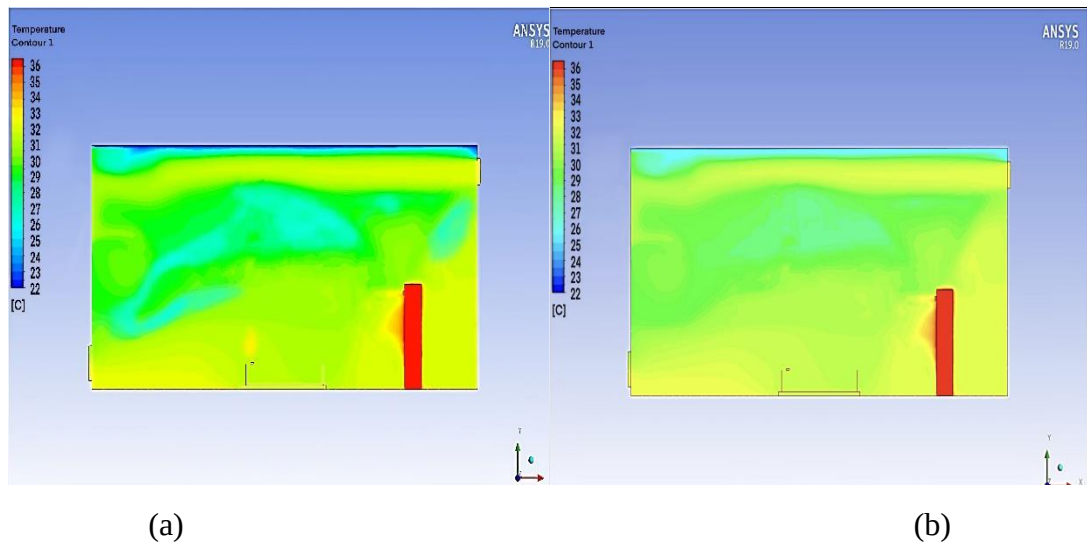


Figure 5.48: Vapour Volume Fraction contour, 1.0 m/s in the section (B).

C. Case study at inlet velocity mode 2.0 m/s

I. Temperature pattern without and with PCM_s:

Figures 5.49 and 5.50 show the temperature distribution at 2.0 m/s, and it is clear that the use of PCM_s leads to an improvement in comfort temperatures with a reduction in vortices, particularly at the interface vortices. Figure 5.51 shows the streamlines, and it can be seen that the use of PCM_s leads to an increase in comfort temperatures. In figure 5.50 (b), it can be seen that the temperature near the ceiling is 3 °C higher, going from 23 °C to 26 °C, due to the use of PCM_s.



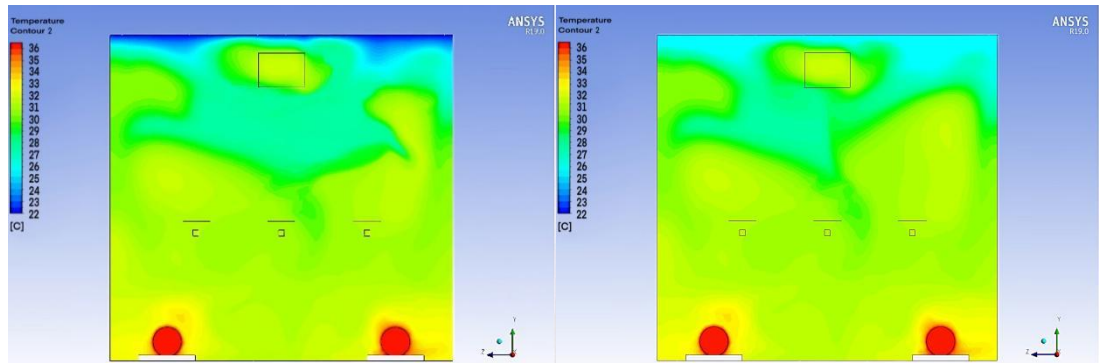
(a)

(b)

Figure 5.49: Temperature contour, 2.0 m/s in the section (A)

(a) Without PCM_s.

(b) With PCM_s.



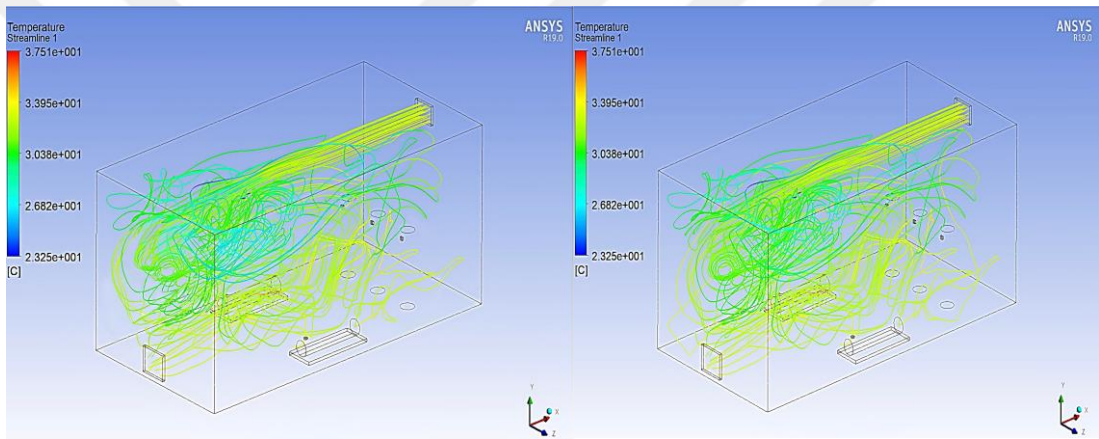
(a)

(b)

Figure 5.50: Temperature contour, 2.0 m/s in the section (B)

(a) Without PCM_s.

(b) With PCM_s.



(a)

(b)

Figure 5.51: 3-D Temperature streamline, 2.0 m/s in the room model.

(a) Without PCM_s.

(b) With PCM_s.

II. Carbon Dioxide (ppm) pattern with PCM_s:

Figures 5.52 and 5.53 show the ppm of carbon dioxide at an inlet velocity of 2 m/s. Both figures indicate that the ppm levels are normal, as seen in previous cases. The concentration of ppm is higher near the outlet grill due to the effect of the stream flow rate.

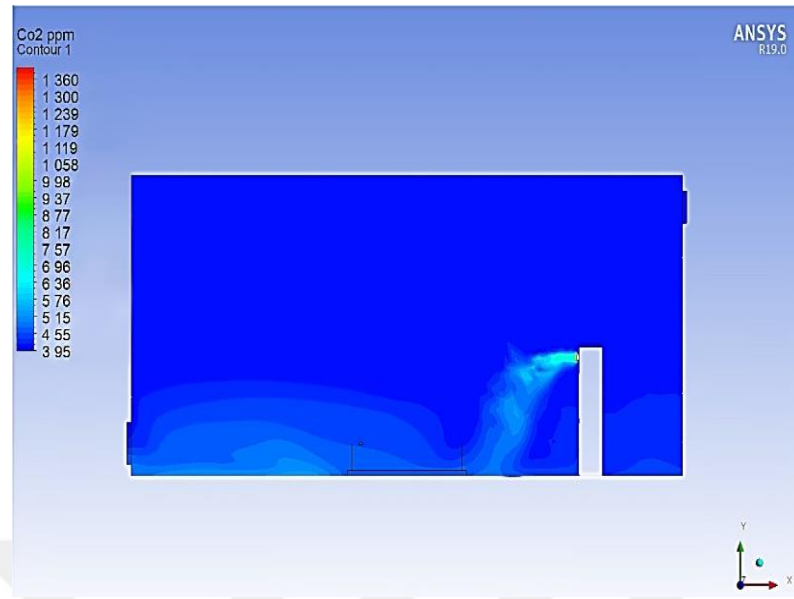


Figure 5.52: CO₂ Concentration contour, 2.0 m/s in the section (A).

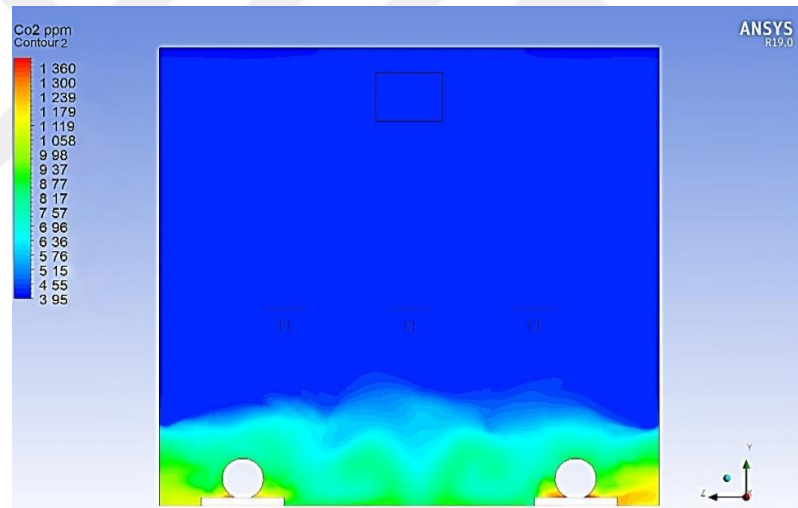


Figure 5.53: CO₂ Concentration contour, 2.0 m/s in the section (B).

III. Vapour Volume Fraction pattern with PCMs:

Figure 5.54 shows the vapor volume fraction for heating and an inlet velocity of 2 m/s at section A. It can be seen that the water vapor is concentrated near the ceiling and is less present near the occupants. Figure 5.55 indicates that the water vapor is concentrated on the ceiling and walls more so than other areas.

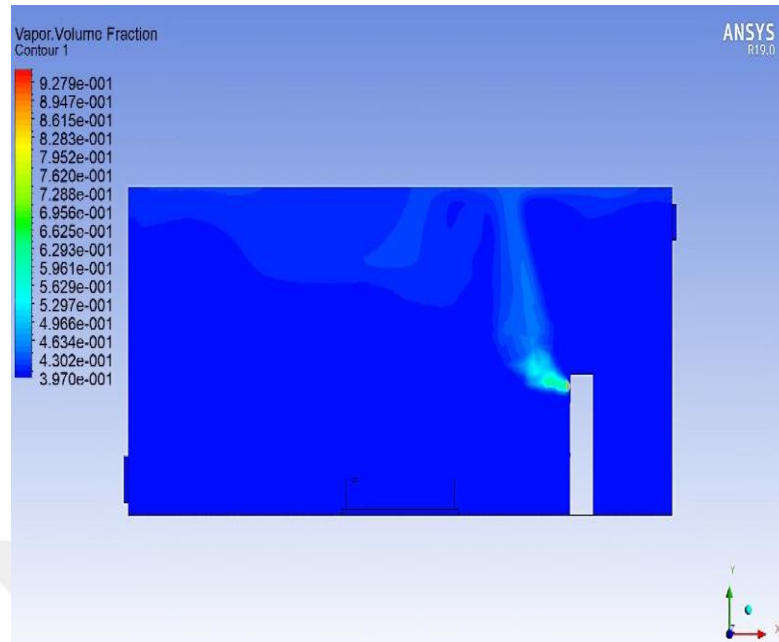


Figure 5.54: Vapour Volume Fraction contour, 2.0 m/s in the section (A).

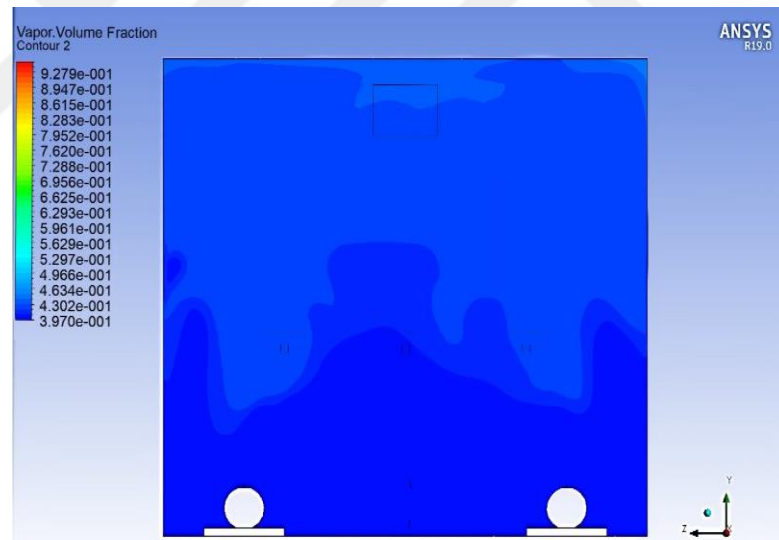


Figure 5.55: Vapour Volume Fraction contour, 2.0 m/s n in the section (B).

5.2.2.2 Heating ventilation scenario in autumn season

Simulations were conducted under the following boundary conditions: inlet velocities ranging from 0.5 m/s to 1 m/s, with and without PCM_s, in the winter season, with an inlet temperature of $T_{in} = 27\text{ }^{\circ}\text{C}$, inlet grill size of 4 cm $\times$ 6 cm, outlet grill size of 6 cm $\times$ 8 cm, and outdoor ambient temperature of 20 $^{\circ}\text{C}$.

A. Case study at inlet velocity mode 0.5 m/s:

I. Temperature pattern without and with PCM_s:

Figure 5.56 shows the results of the investigation into temperature distributions at an inlet velocity of 0.5 m/s. It can be seen that the temperature is more comfortable and stable with the use of PCM_s. Without PCM_s, the lower layers of the room have a cooler temperature, covering a larger area than the upper layers by 3 °C. When PCM_s are used, the cooler layers are reduced and the temperature in the layers increases.

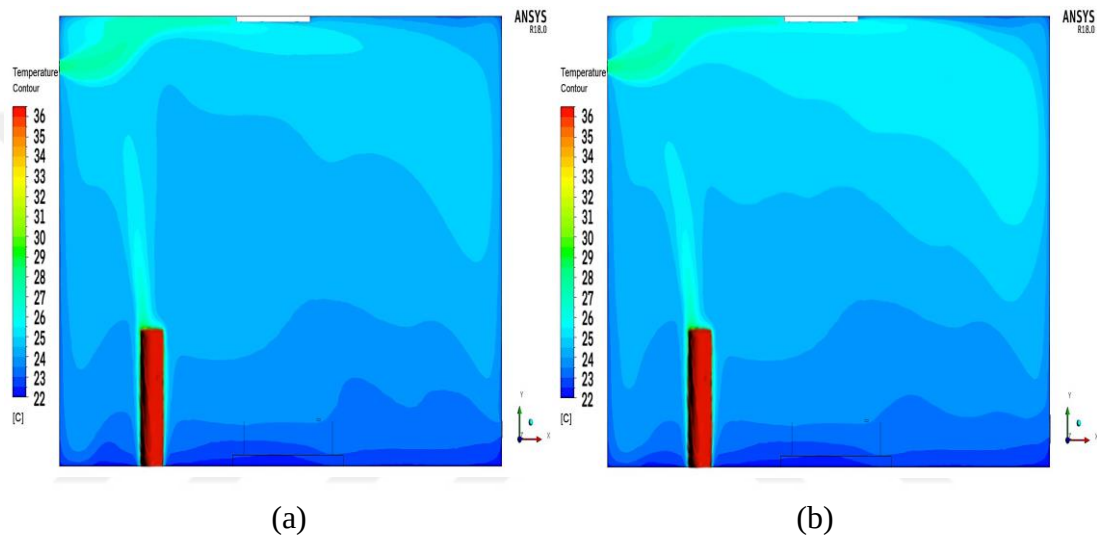


Figure 5.56: Temperature contour, 0.5 m/s in the section (A)

(a) Without PCM_s.

(b) With PCM_s.

II. Carbon Dioxide (ppm) pattern without PCM_s:

The ppm of carbon dioxide was investigated in the simulation program for an inlet velocity of 0.5 m/s. The results indicated that there is no risk at any point, as shown in figure 5.57, which shows the ppm levels inside the room model at section A. The maximum value reaches 580 ppm in the middle of the room.

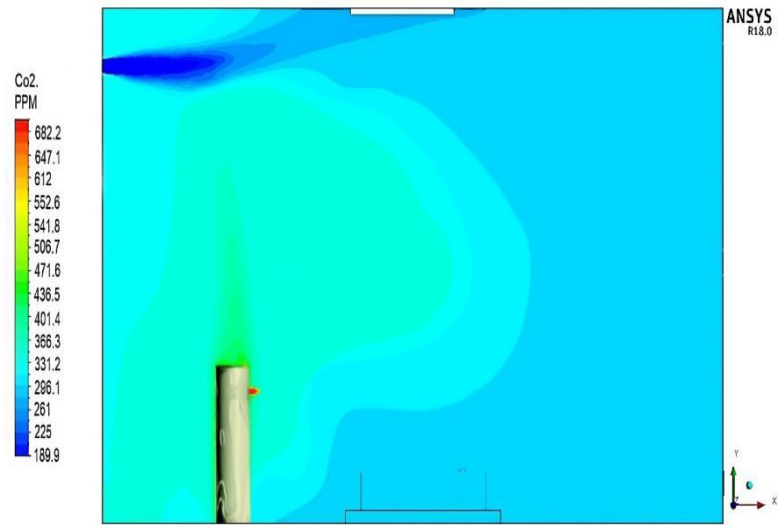


Figure 5.57: CO₂ Concentration contour, 0.5 m/s in the section (A).

III. Relative Humidity pattern without PCM_s:

The water vapor percentage was calculated using the simulation program, and the results showed that the concentration of water vapor is highest in the middle of the room model. All values are within the acceptable range according to ASHRAE requirements (40 ± 20 %), as shown in figure 5.58. It can be seen that the maximum value of 70 % is reached at one corner, but this does not hinder thermal comfort.

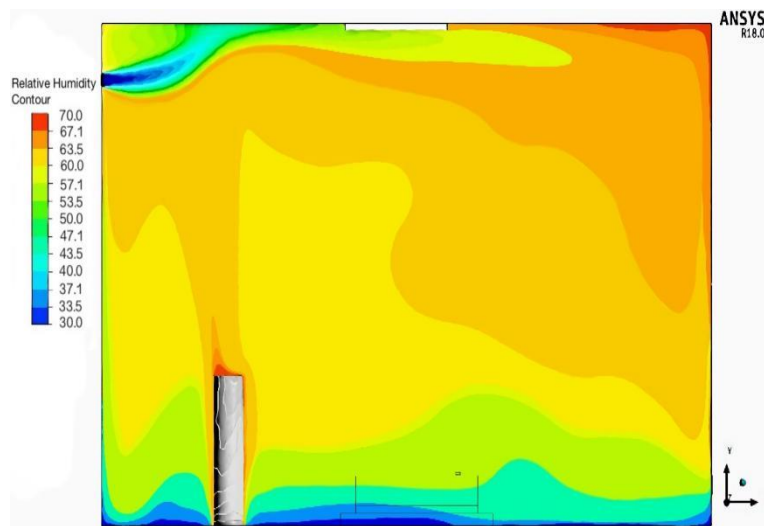


Figure 5.58: Relative Humidity contour, 0.5 m/s in the section (A).

IV. Velocity pattern without PCM_s:

Figure 5.59 shows the velocity at 0.5 m/s without PCM_s. It can be seen that there are many areas with low velocity, but this does not significantly affect the other parameters. The layers appear irregular, with velocities reaching 0.08 m/s in most positions.

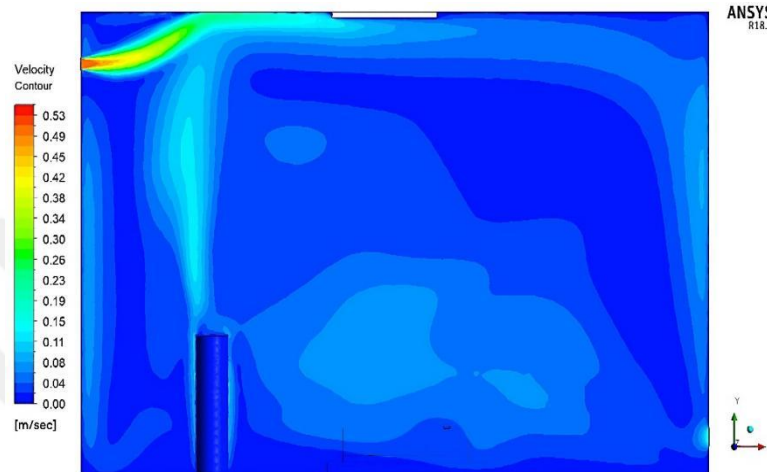


Figure 5.59: Velocity contour, 0.5 m/s in the section (A).

B. Case study at inlet velocity mode 1.0 m/s

I. Temperature pattern without PCM_s:

The temperature contour at 1.0 m/s was systematically examined to investigate the effect of the inlet velocity on the temperature. As shown in figure 5.60, comfortable temperatures are achieved in the indoor area.

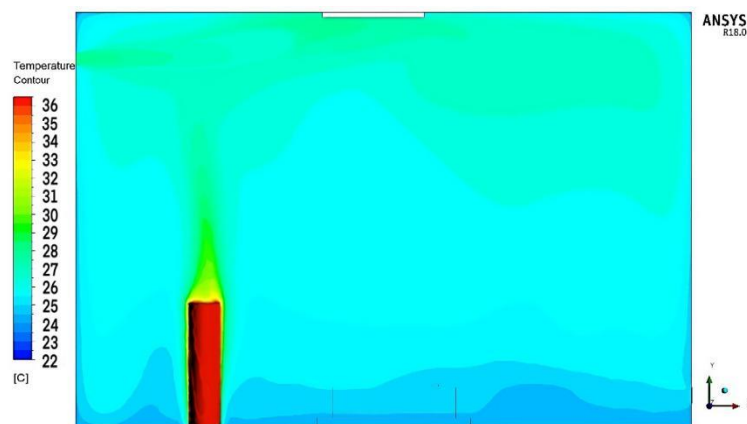


Figure 5.60: Temperature contour, 1.0 m/s in the section (A)

II. Carbon Dioxide (ppm) pattern without PCMs:

Figure 5.61 shows the ppm of carbon dioxide at the inlet velocity. In this case, the concentrations are acceptable and do not exceed 500 ppm.

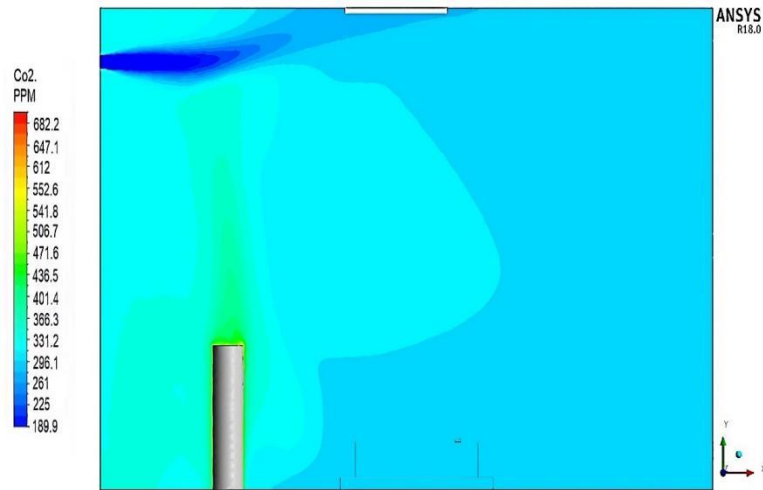


Figure 5.61: CO₂ Concentration contour, 1.0 m/s contour in the section (A).

III. Relative humidity pattern without PCMs:

Figure 5.62 shows the humidity or water vapor inside the room model. It can be seen that the concentration is highest in the middle of the room and near the occupants.

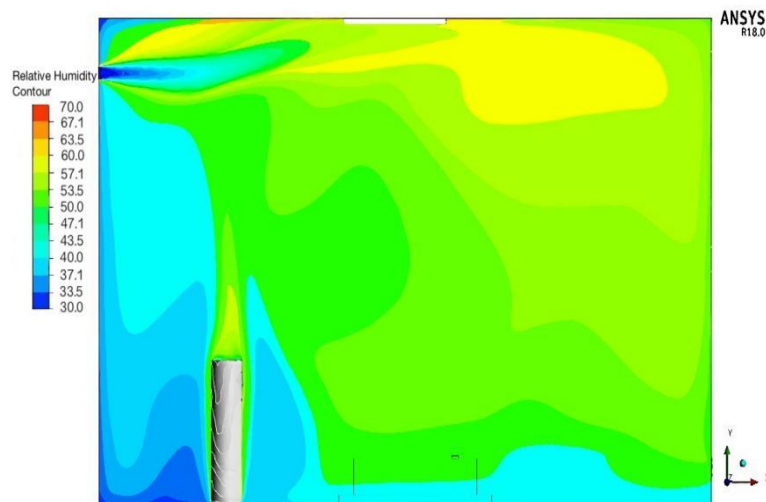


Figure 5.62: Relative Humidity contour, 1.0 m/s in the section (A).

IV. Velocity pattern without PCM_s:

Figure 5.63 shows the velocity distribution inside the room model at 1 m/s. It can be seen that the velocity in the indoor layers, particularly near the ceiling and walls, is higher than in other areas due to the impact of the stream flux.

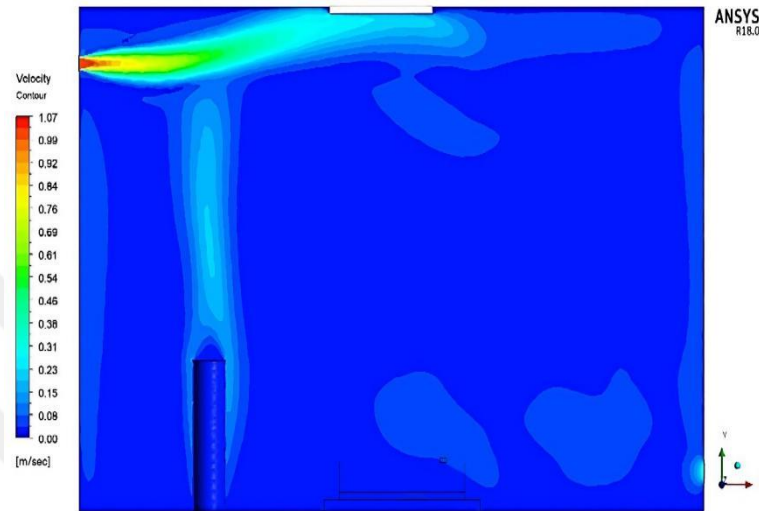


Figure 5.63: Velocity contour, 1.0 m/s in the section (A).

5.2.3 (Special Case study) Electricity cut-off scenario

Figure 5.64 shows the results of a dummy simulation where 4 % of carbon dioxide is exhaled from the lungs of inactive occupants. CO₂ is exhaled through the nose at a rate of 0.31 l/min (0.77 m/s) during sedentary activities. Figure 5.65 shows the results of a special case where the electricity is cut off in the room model for approximately 3 hours, resulting in an inlet flow rate of zero. The results show that this could lead to suffocation, as the concentration of ppm increases to 1400 ppm, which is sufficient to cause suffocation and death. This situation is very dangerous for the occupants, and it is necessary to take care and pay serious attention to prevent suffocation by ensuring that there is enough airflow in this type of prison hall.

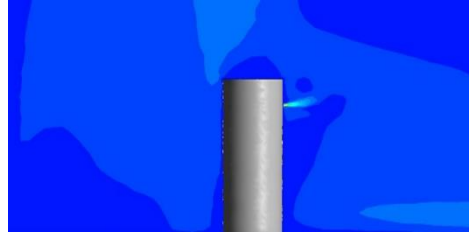


Figure 5.64: CO₂ emitted from the nose of the dummy.

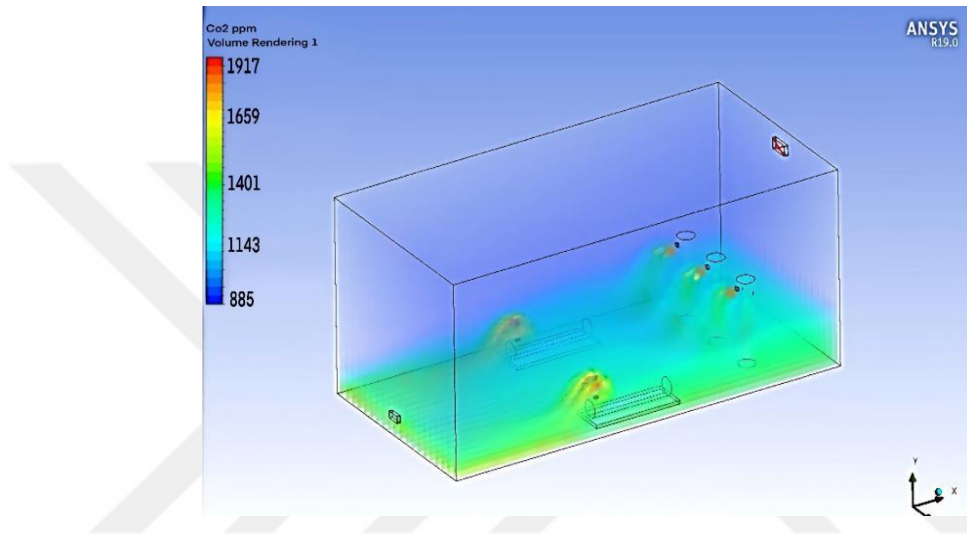


Figure 5.65: Special case, electricity cut-off on the space.

5.3 PCM_s temperaturer contour

Figure 5.66 shows the temperature contour with absorbent temperatures of the double layer in the summer scenario, with a high solar heat flux for three peak hours. The outdoor ambient temperature was 55 °C and the inlet velocity was 0.5 m/s. After half an hour from the start of the test, it can be seen that RRM₁ begins to charge the latent heat as TES, and then the latent heat is transferred to the lower layer. Figure 5.67 shows the temperature contour after an hour and a half, and it can be seen that the double layers are charged. Figure 5.68 shows the temperature contour after two hours and a half, and it can be seen that the double layers are charged and the melting process has begun. Figure 5.69 shows the temperature contour phase after 3 hours in the summer scenario, and it can be seen that the shifting of peak heat and the room ceiling are not affected during peak hours which is the perfect condition.

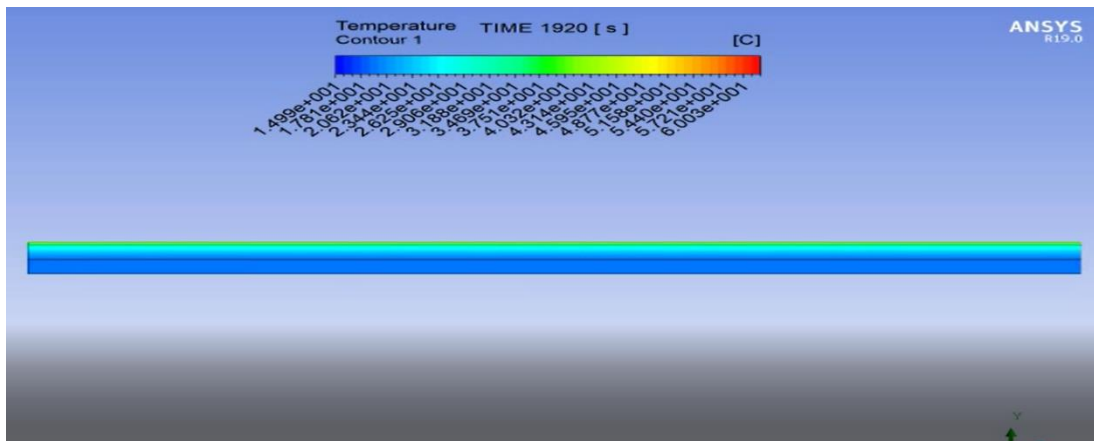


Figure 5.66: PCM_s temperaturer contour at o'clock 12:32 PM in summer scenareo.

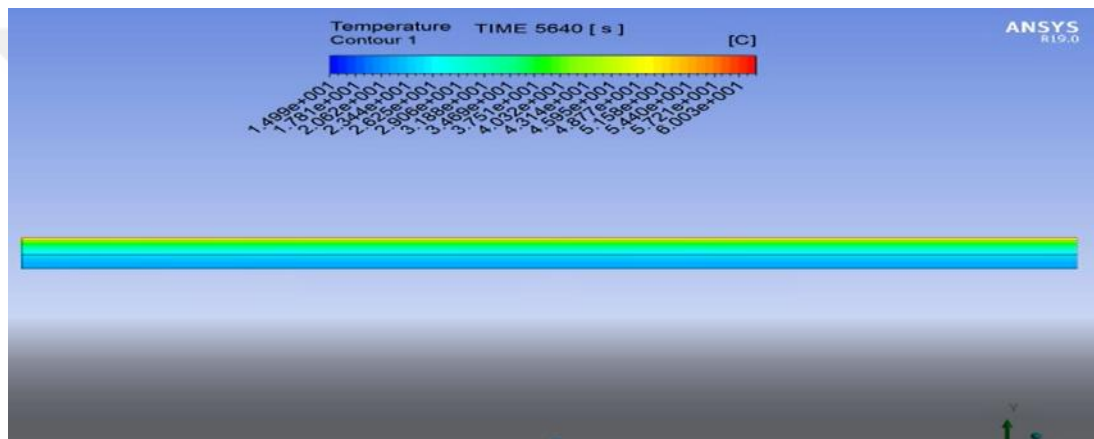


Figure 5.67: PCM_s temperaturer contour at o'clock 13:34 PM in summer scenareo.

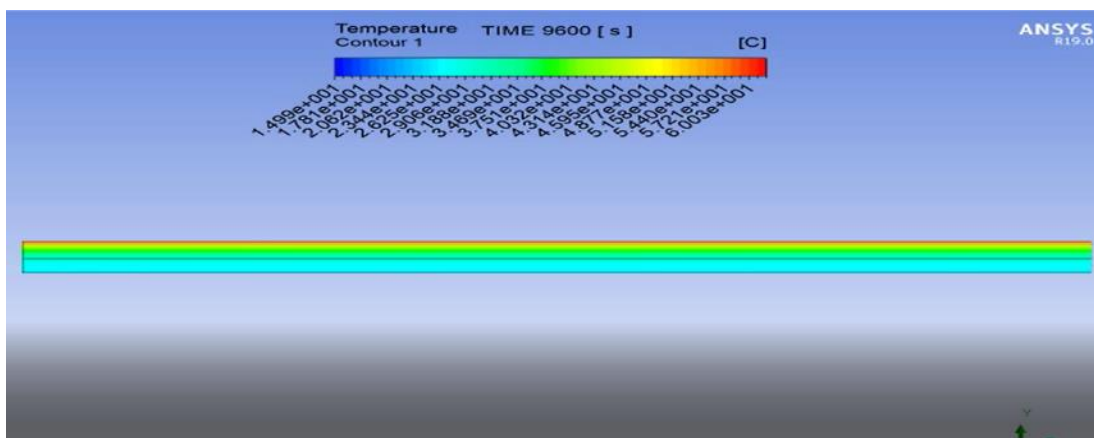


Figure 5.68: PCM_s temperaturer contour at o'clock 14:36 PM in summer scenareo.

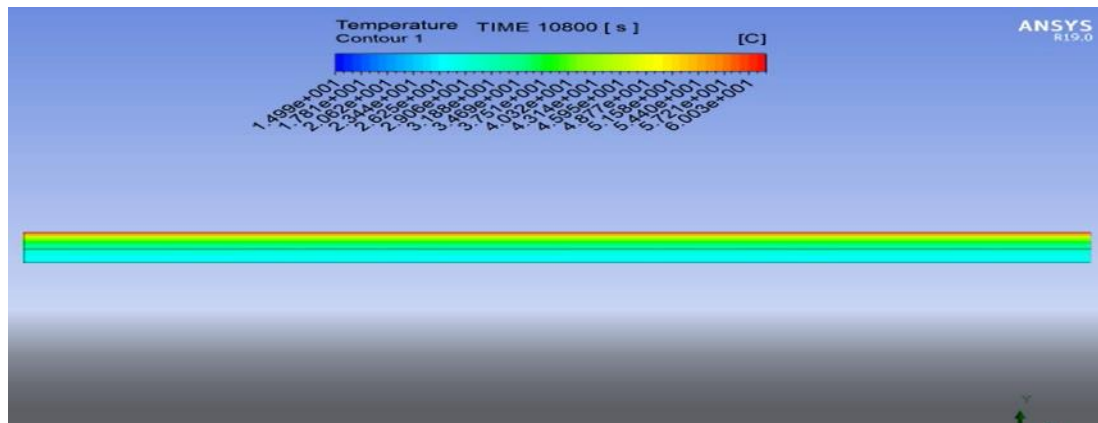


Figure 5.69: PCM_s temperatuer contour at o'clock 15:00 PM in summer scenareo.

Figure 5.70 shows the temperature contour for the same two layers with different melting points in the winter. It can be seen that the PCM_s are able to retain heat inside the space, allowing for thermal energy storage as a sustainable energy source.

All the above experiments which are implemented not taken the mass fraction or liquid motion of PCM_s in our calculations, it was neglected because paraffen wax panel has a slim thickness.

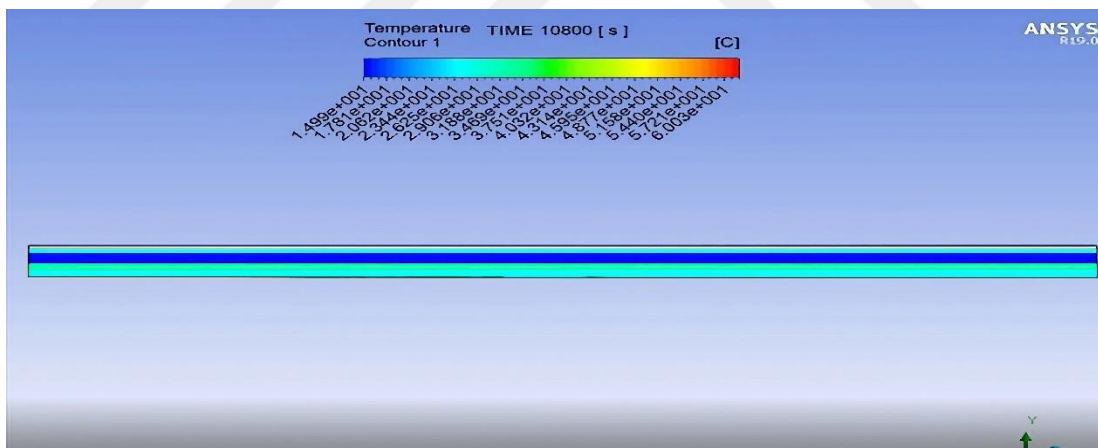


Figure 5.70: PCM_s temperatuer contour at o'clock 15:00 PM in winter scenareo.

5.4 Experimental and numerical results comparison

The experimental work, including the details of the test room layout and the use of thermocouples, is described in Chapter 4. The study was only conducted for the cooling scenario in August, for a sharp summer in Baghdad.

5.4.1 PCM_s Partition

One of the main goals of this research is to determine the thermal performance of different PCM_s with melting points at two layers, under hot and dry climatic conditions, in terms of energy efficiency and thermal comfort in crowded spaces. Two different compositions of local paraffin waxes were used, known as RRM₁ and RRM₂, which have melting points suitable for Iraq's hot and cold conditions, respectively. These PCM_s were used in roof construction since they are able to show solidification along with fusion, and were made of a mixture of soft wax (20 % for RRM₁ and 100 % for RRM₂) and crystal wax (80 % for RRM₁). The melting temperature and wax grade are closely related. Table 5.2 shows the properties of the RRM₁ and RRM₂ materials used in this study, and figures 5.71 and 5.72 show the dynamic curves of RRM₁ and RRM₂, respectively, obtained using a DSC experiment. In a DSC experiment, the heat flow to or from a sample is measured as it is heated or cooled.

Table 5.2: properties of the mentioned material of RRM₁, RRM₂.

Material	The proportion of paraffin waxes	Melting Temperature °C	ρ Kg/m ³ sold	ρ Kg/m ³ liquid	Flashpoint °C
RRM ₁	20% Soft Wax+80% Crystal Wax	40-55	1270	1180	177
RRM ₂	100% Soft Wax	19-37	785	749	256

The DSC curve of different PCM_s (RRM₁, and RRM₂) explains their behavior during the melting and freezing process. The RRM₁ starts melting in the range of 40-43 °C and the melting peak reaches at the temperature of 55 °C. The material at this temperature starts to charge when melting and discharging during solidification. RRM₂ melts at 20-21 degrees celsius and reaches melting peak around 30 °C, it charges when melting and discharges when solidifying.

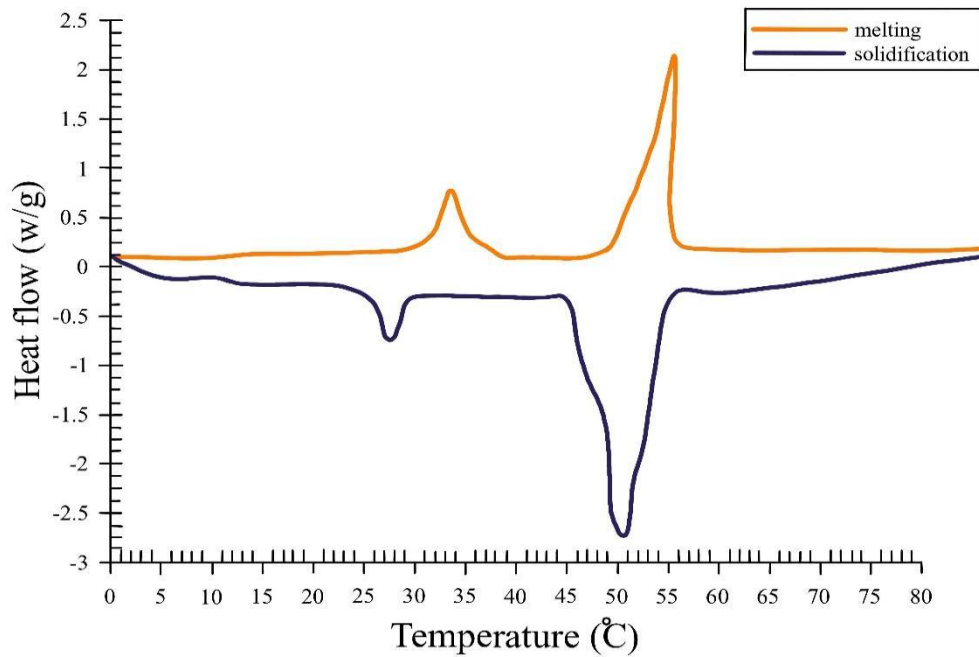


Figure 5.71: DSC curves for RRM₁.

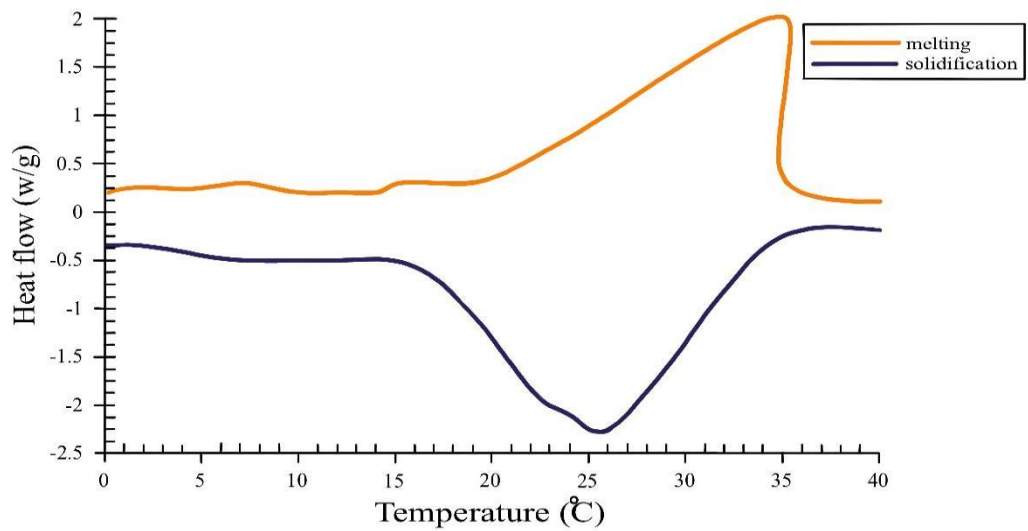


Figure 5.72: DSC curves for RRM₂.

Figure 5.73 shows the measured temperatures of the thermocouples. Six thermocouples were regularly distributed and fixed at the bottom, middle, and sides of the PCM panels to measure the temperatures at six points, allowing for the prediction

of the behavior of the paraffin inside the panels when exposed to solar heat flux during daylight.

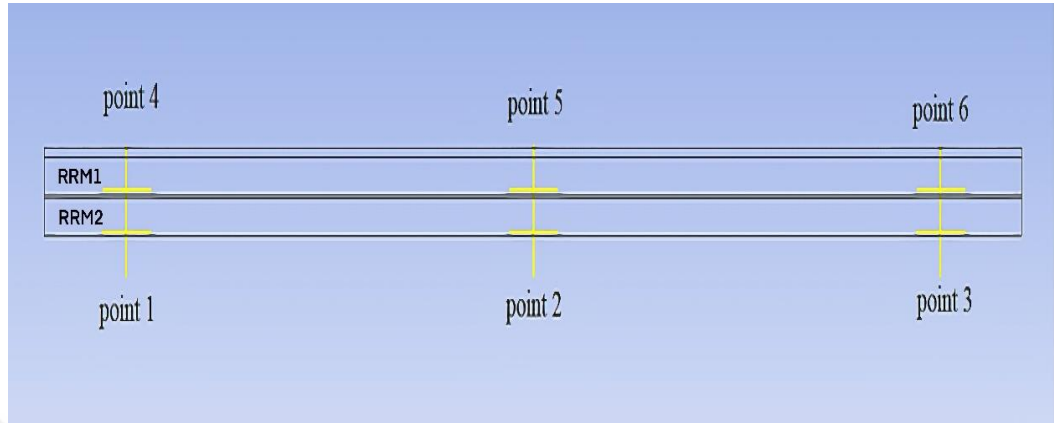


Figure 5.73: Specific location of thermocouple sensors in the PCM_s panels.

Figure 5.74 shows the temperature measurements for two groups of thermocouples, with experimental tests conducted in August for (10800) seconds and numerical tests conducted for the same duration. By comparing the experimental and theoretical results, it can be seen that the first three thermocouples, which measure the temperatures of paraffin RRM₂ in the panel, are very similar, while the second three thermocouples, which measure the temperatures of paraffin RRM₁ in the panel, are similar from the beginning of the test until the hundredth minute, after which they increase randomly. Figure 5.75 shows the results of the numerical tests only, and it can be seen that the thermal path is consistent with the temperature contour data and the differential scanning device.

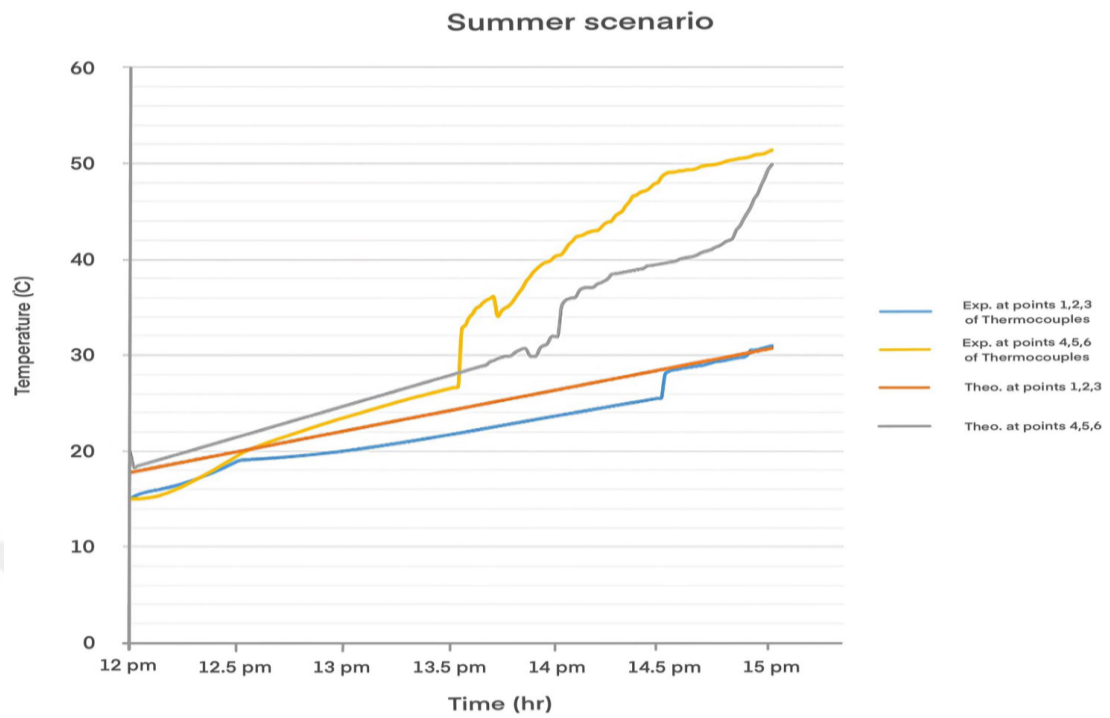


Figure 5.74: Experimental and numerical thermocouples measurement in panels at summer scenareo with 0.5 m/s.

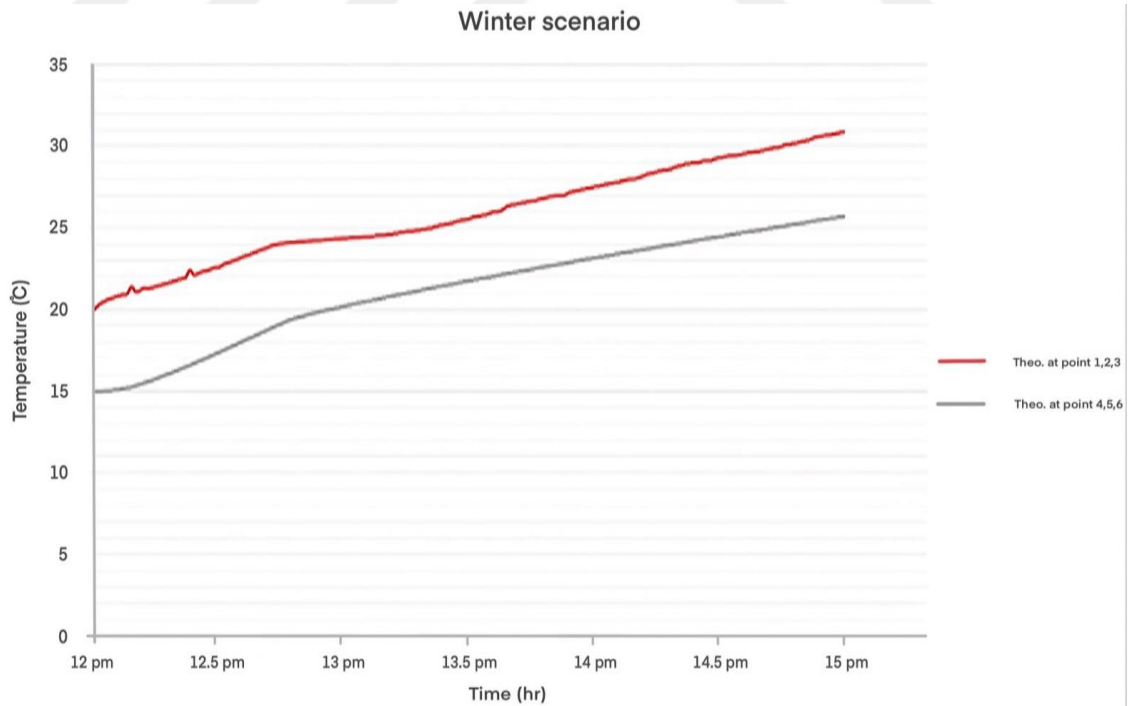


Figure 5.75: Numerical thermocouples measurement in panels at winter scenareo. with 0.5 m/s.

5.4.2 Indoor partition

Figure 5.76 shows the specific location of the 26 card sensors in the room model. All sensors are connected by virtual yellow lines for definition, which represent the surface level position of the card sensors at the three basic levels (ground, mid-room, and roof level). These lines help to compare the theoretical and experimental tests, which will be shown in the results.

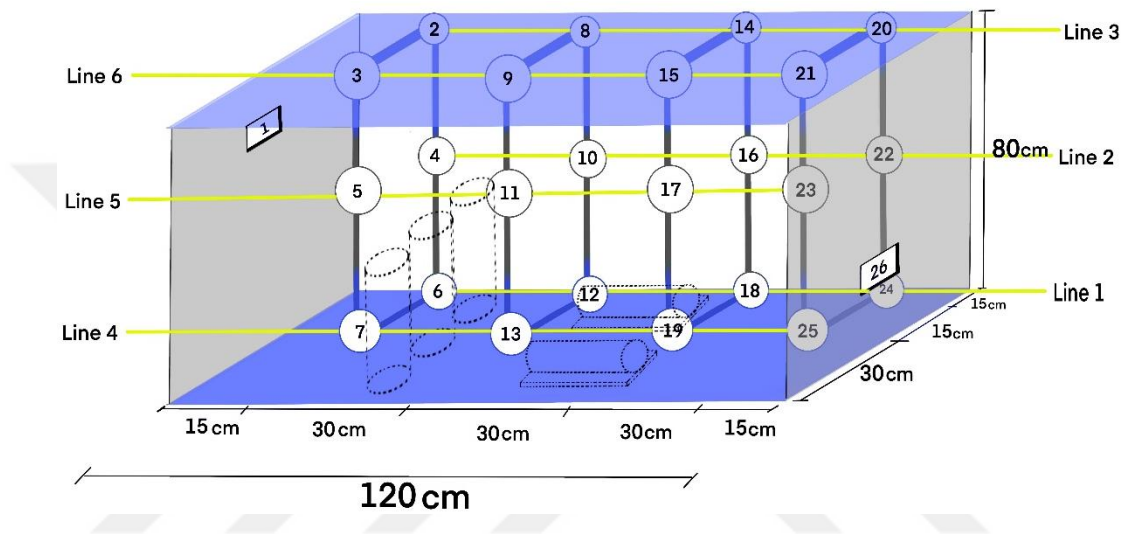


Figure 5.76: Specific location of multiple sensors in the room model.

Figure 5.77 shows the temperature contour with sensor numbers on different line positions, based on tests conducted under different protocols (cooling and heating), different scenarios (summer and winter seasons), inlet velocity mode (0.5 m/s). It can be noted that the readings of the measurements for the hypothetical lines (lines 1, 4 - 2, 5 and 3, 6) are analogous and similar because the room geometry is regular and symmetrical. In the summer scenario without PCM_s, the temperature distribution has a high range, especially on lines 3 and 6, due to their proximity to the ceiling. It can be seen from the temperature curves that the temperature interference is unstable at the same line, due to fluctuating vortexes. Additionally, this demonstrates that the inner surface of the ceiling is only minimally impacted by the surroundings as the PCM_s stored in the roof absorb all of the heat energy. The experimental results for IAQ in the summer scenario are approximately overlapped with the theoretical results.

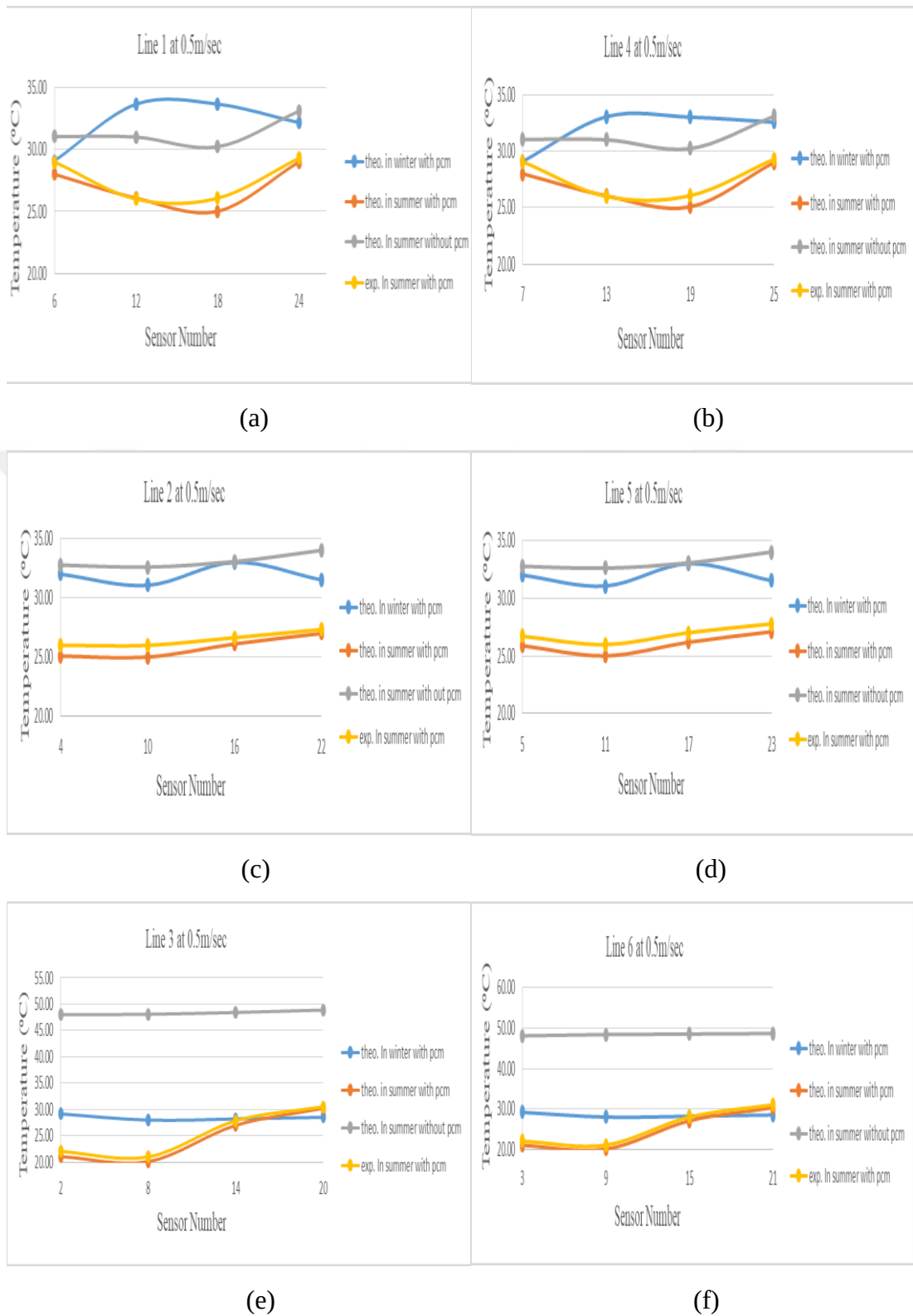


Figure 5.77: Temperatures contour with sensor numbers on the line positions at 0.5m/s, (a) Line1, (b) Line4, (c) Line2, (d) Line5, (e) Line3 and (f) Line6.

Figure 5.78 illustrates the contour of carbon dioxide in ppm with sensor numbers at various line positions. These tests were conducted using different protocols, including cooling and heating, and different scenarios, such as summer and winter seasons and an inlet velocity of 0.5 meters per second. The CO₂ pattern are convergent for lines 1, 4 - 2, 5 and 3, 6. Moreover, all of the results are within acceptable limits and pose no risk to the air-conditioned space. Additionally, the experimental and numerical results of ppm in the summer scenario with phase change materials (PCM_s) did not exceed 570 ppm, and did not exceed 710 ppm without (PCM_s). For the winter scenario with PCM_s, the results did not exceed 620 ppm. None of these results pose a danger to the space.

Figure 5.79 shows the contour of vapor volume fraction with sensor numbers at various line positions. These tests were conducted using different protocols, such as cooling and heating, and different scenarios, including summer and winter seasons and an inlet velocity of 0.5 meters per second. The vapor volume fraction pattern can be seen to oscillate between the lines and protocols, particularly in lines 2 and 5. However, the range of this parameter is technically acceptable and is limited between 0.39 and 0.57 for all protocols and scenarios.

Figure 5.80 illustrates the numerical values of temperature at the room ceiling with and without PCM_s for various scenarios and inlet velocity modes. It can be seen that when PCM_s are used on the top of the room roof, the temperature distribution is reduced. Additionally, it is important to observe that the peak temperature is observed to shift with the use of PCM_s. To validate the experimental values, tests were conducted in the summer scenario with PCM_s and different inlet velocity modes. The results are found to be significantly similar to the experimental values, with a small difference. This will be further discussed in Chapter 6. Figure 5.81 shows experimental results in August with three days of PCM_s use. The temperature measurement started at noon and continued until 3:00 PM. The temperature distribution across the roof structure is shown to increase with time due to the absorption of maximum heat energy by the PCM_s. From 1 PM to 2 PM, the heat transmission properties are observed to

have improved compared to the preceding time period. It can also be noted that there is a shift in the peak load for approximately one hour with the use of paraffin waxes.

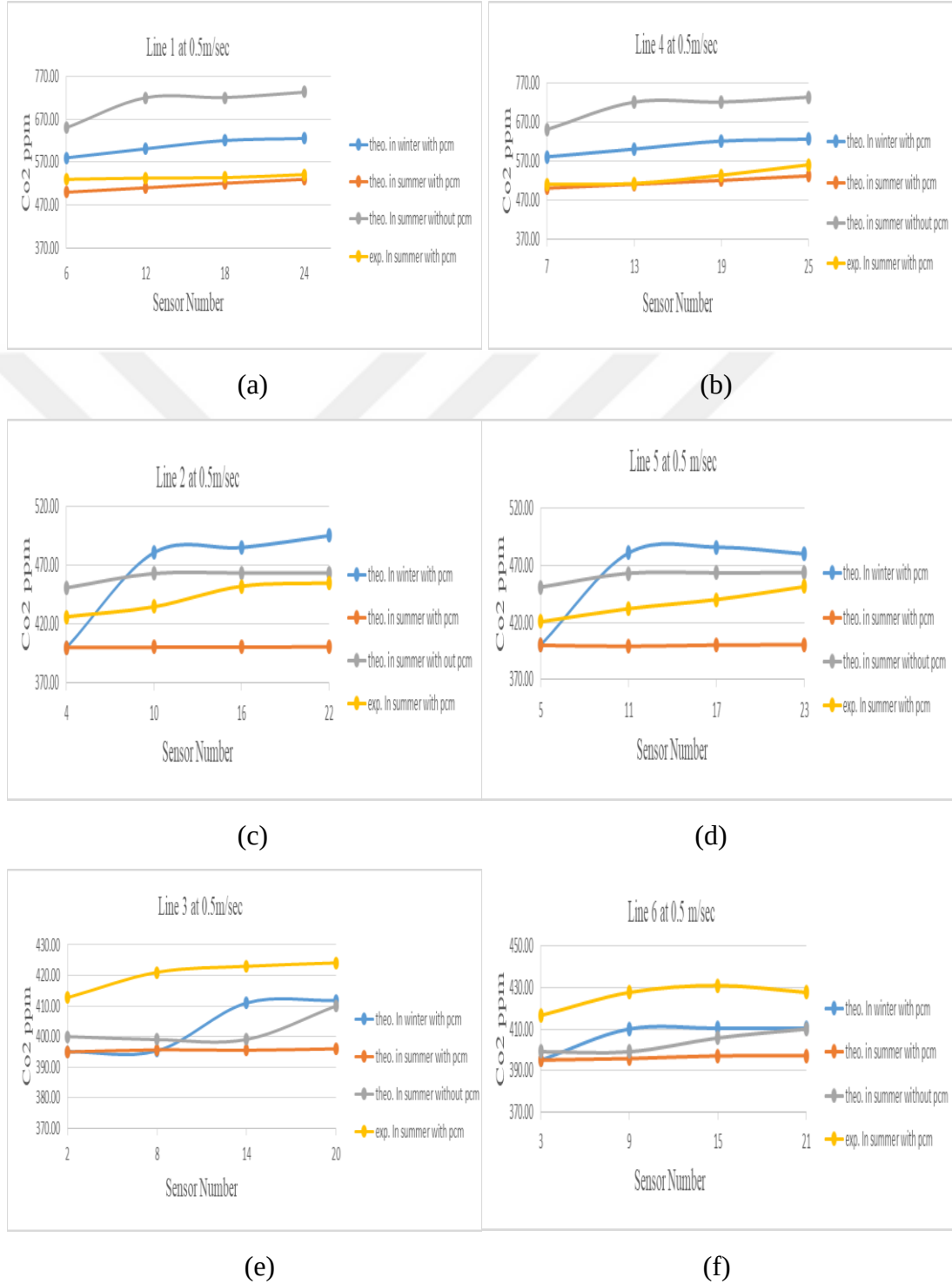


Figure 5.78: Carbon Dioxide distribution with sensor numbers on the line positions at 0.5m/s, (a) Line1, (b) Line4, (c) Line2, (d) Line5, (e) Line3 and (f) Line6.

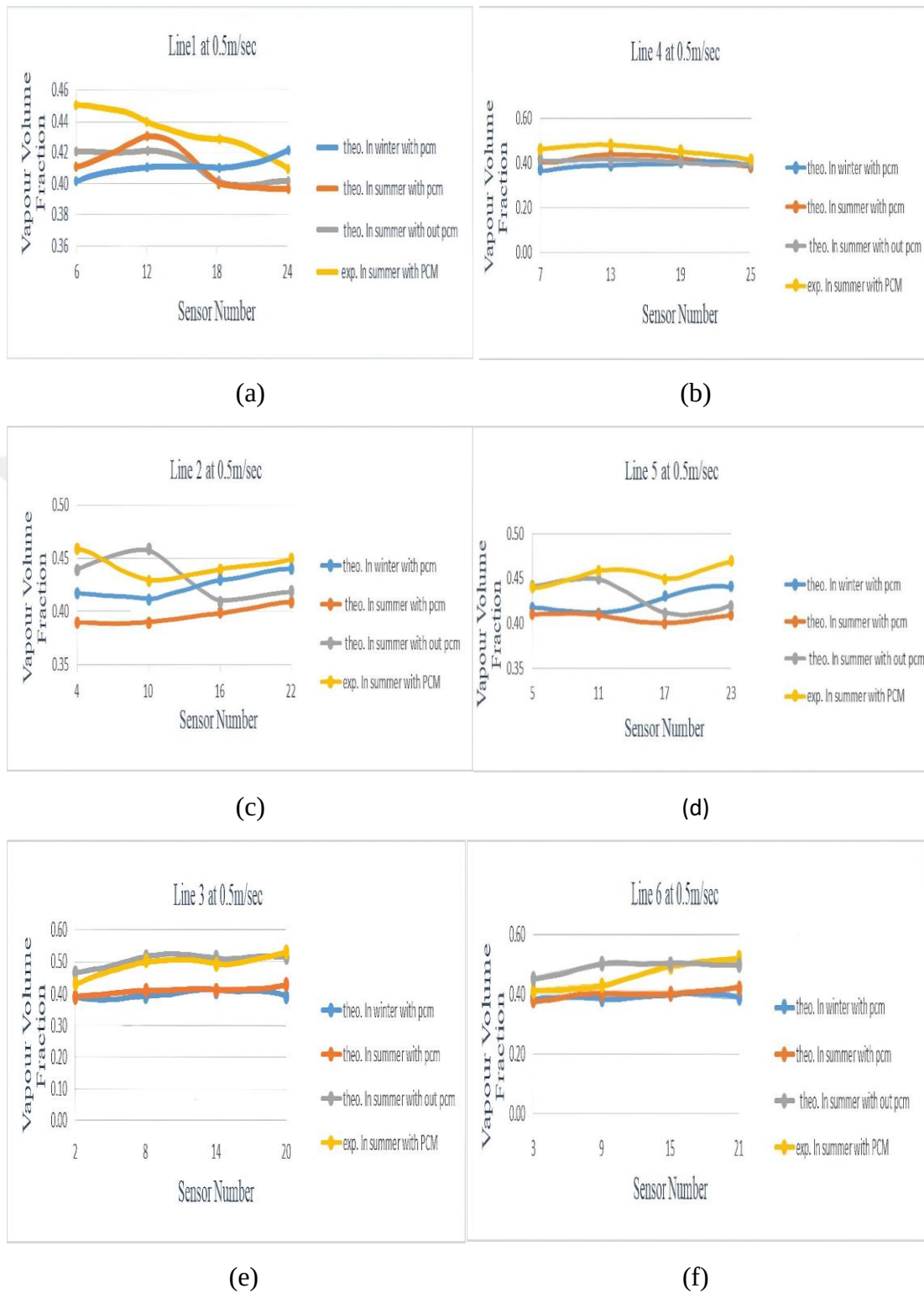


Figure 5.79: Vapour volume fraction with sensor numbers on the line positions at 0.5m/s, (a) Line1, (b) Line4, (c) Line2, (d) Line5, (e) Line3 and (f) Line6.

Table 5.3 is shown the comparison between the numerical and experimental valuable data in the test room for cooling protocol, summer scenario and 0.5 m/s as a mode.

Table 5.3: Numerical and experimental valuable data in the test room.

Numerical with PCMs						Experimental with PCMs					
Scenario mode	ACH	Pattern	Average values			Scenario mode	ACH	Pattern	Average values		
			Line 1-4	Line 2-5	Line 3-6				Line 1-4	Line 2-5	Line 3-6
Summer 0.5m/s	1.5	Temp-°C	27.0	26.5	30.2	Summer 0.5m/s	1.5	Temp-°C	28.0	27.6	27.0
		CO ₂ ppm	540	400	395			CO ₂ ppm	570	455	425
		Vapour Fraction	0.39	0.41	0.42			Vapour Fraction	0.42	0.44	0.45

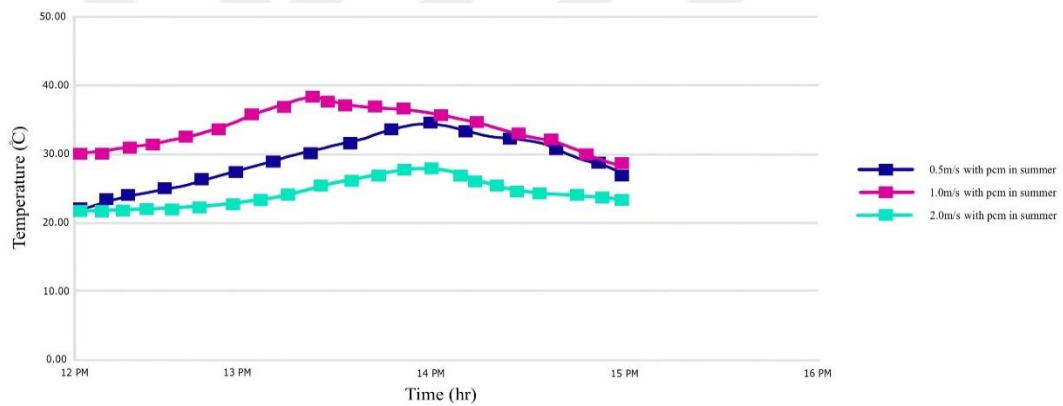


Figure 5.80: Numerical values of temperature for room ceiling with PCMs in summer for different inlet velocity modes.

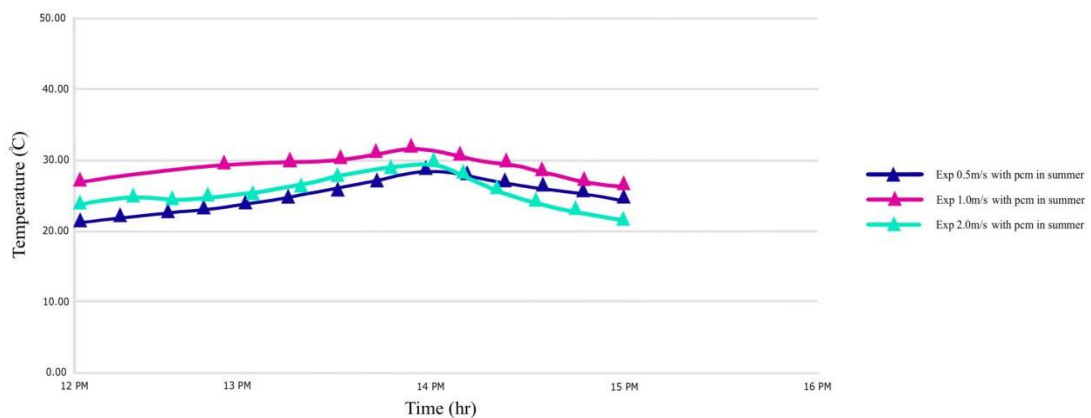


Figure 5.81: Experimental values of temperature for room ceiling with PCMs for summer scenario and different inlet velocity modes.

5.5 Energy saving

Figure 5.82 presents the results of an experimental study on energy consumption for a prison quarry model. This test was conducted using the cooling protocol in the summer scenario and an inlet velocity of 0.5 m/s. First, the test was conducted without PCM_s and the thermostat was set to a temperature of 26 °C with an inlet air temperature of 16 °C. It was found that the energy consumption was high for 12 hours, with a full electric consumption of more than 1.75 kWh. When the HVAC device's compressor was turned off, it was observed that the inside ambient temperature was lower than the set point. The test was then repeated with PCM_s, with the thermostat set to a temperature of 26 °C and an inlet air temperature of 16 °C. The HVAC compressor was found to be operating from 6:00 AM to 7:00 AM, then shutting down from 7:00 AM to 10:00 AM, before resuming operation afterwards. The total energy consumption for this case was 29.5 kW/24 hr without PCM_s and 15.6 kW/24 hr with PCM_s.

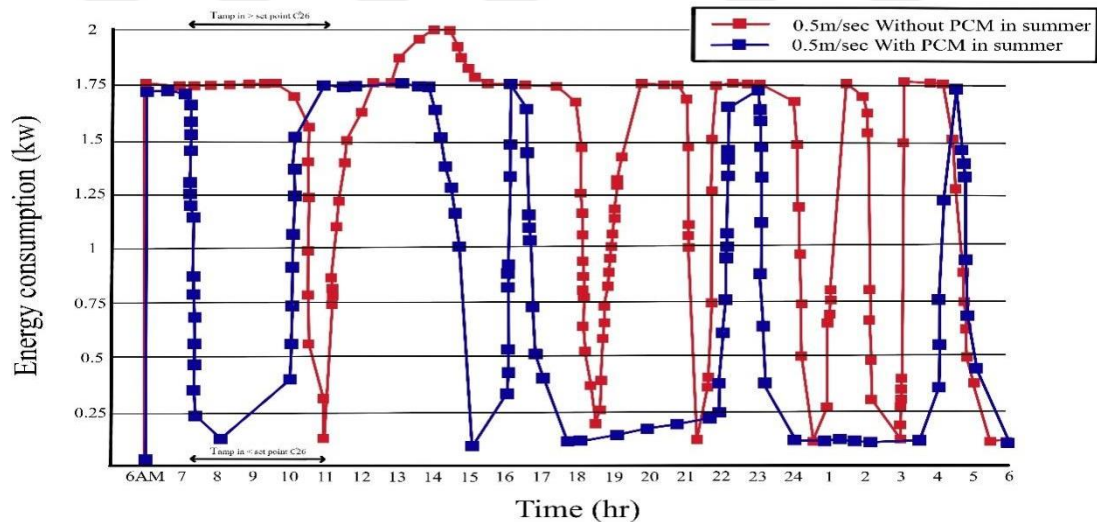


Figure 5.82: Experimental energy consumption with and without PCMs at 0.5m/s mode, in summer scenario for one day at August.

Figure 5.83 presents the results of an experimental study on energy consumption under the same boundary conditions as the previous test, except with an inlet velocity

of 2.0 m/s. It can be seen that the compressor is working harder in the case without PCM_s, with three peak load zones of high energy consumption. In contrast, the case with PCM_s shows stability and balance without significant fluctuations in peak energy consumption.

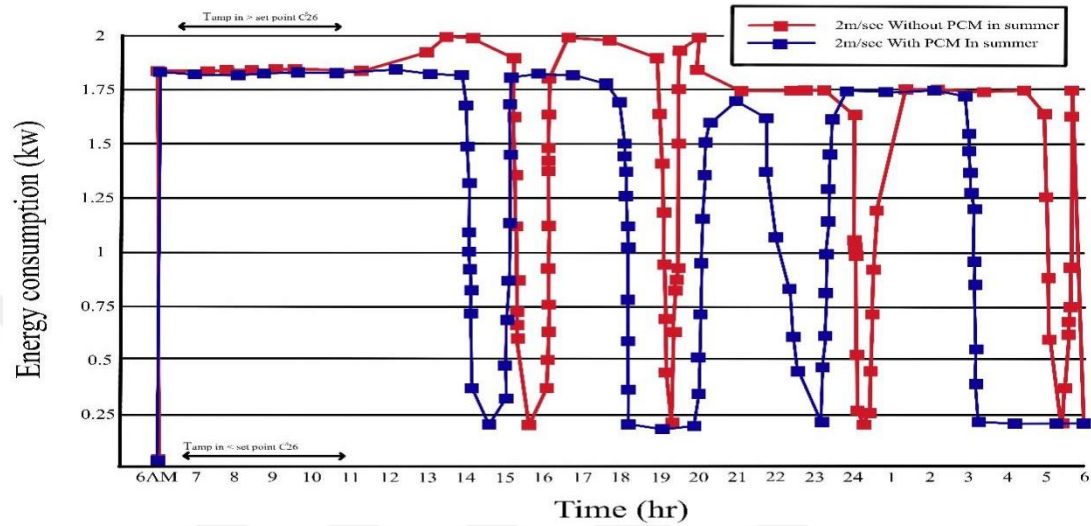


Figure 5.83: Experimental energy consumption with and without PCM_s at 2.0 m/s mode, in summer scenario for one day.

Figure 5.84 illustrates the experimental energy consumptions in the cooling protocol with and without the use of PCM_s for different scenarios and modes. It can be observed that the use of special paraffin wax always results in a decrease in energy usage. In the heating protocol, it is known from ASHRAE standards that energy consumption is approximately one-third of that in the cooling protocol. From the numerical simulations of temperature distribution cases, it can be seen that the use of PCM_s is particularly useful in the heating protocol. Figure 5.85 shows the percentage of energy savings with the use of PCM_s. It can be seen that the energy consumption is reduced by 47.2 % for an inlet velocity of 0.5 m/s, 23 % for 1.0 m/s, and 17.9 % for 2.0 m/s in the summer. In the single case of cold ventilation with an inlet velocity of 0.5m/s, energy consumption is reduced by 38.9 %. These values are based on one month of data and assume constant boundary conditions for all days of the month.

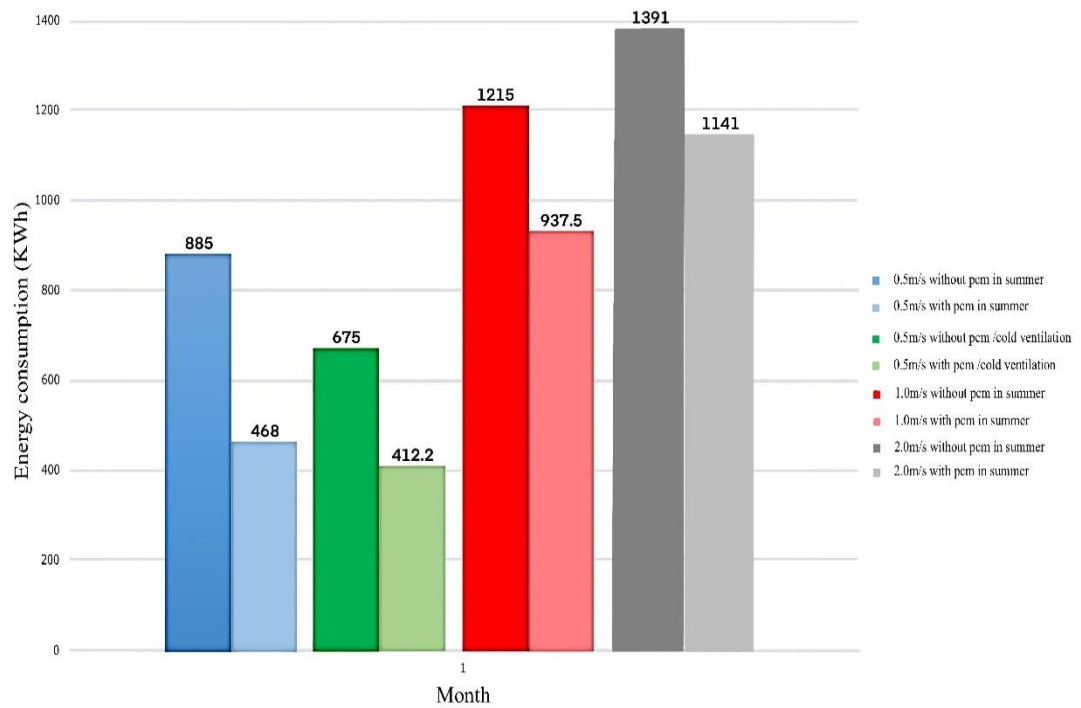


Figure 5.84: Experimental energy consumption with and without PCM_s for different scenarios and inlet velocity modes, for one month.

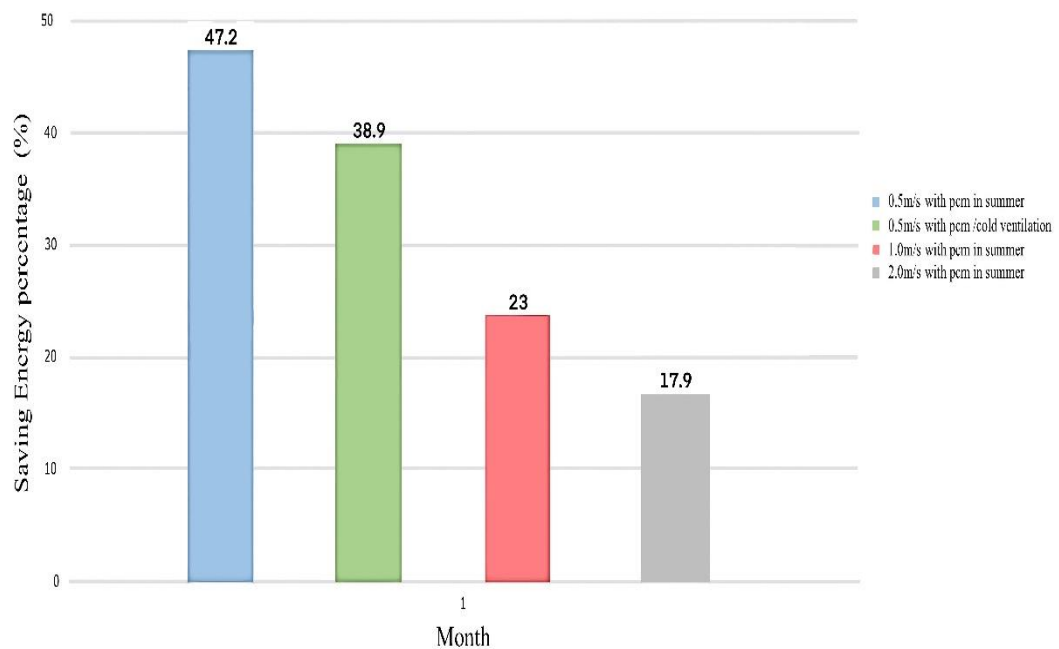


Figure 5.85: Saving energy percentage with PCM_s, for different scenarios and inlet velocity modes, for one month.

5.5.1 Billing price saving

The selling price and cost price is calculated to see the saving value in money when PCM_s used, Figure 5.86 shows the cost as per latest ministry of electricity billing criteria in Iraq, it is considered that the cost is (0.12) USD for the first (5000) kwh consumption. This figure of one small prison quarry at one month only.

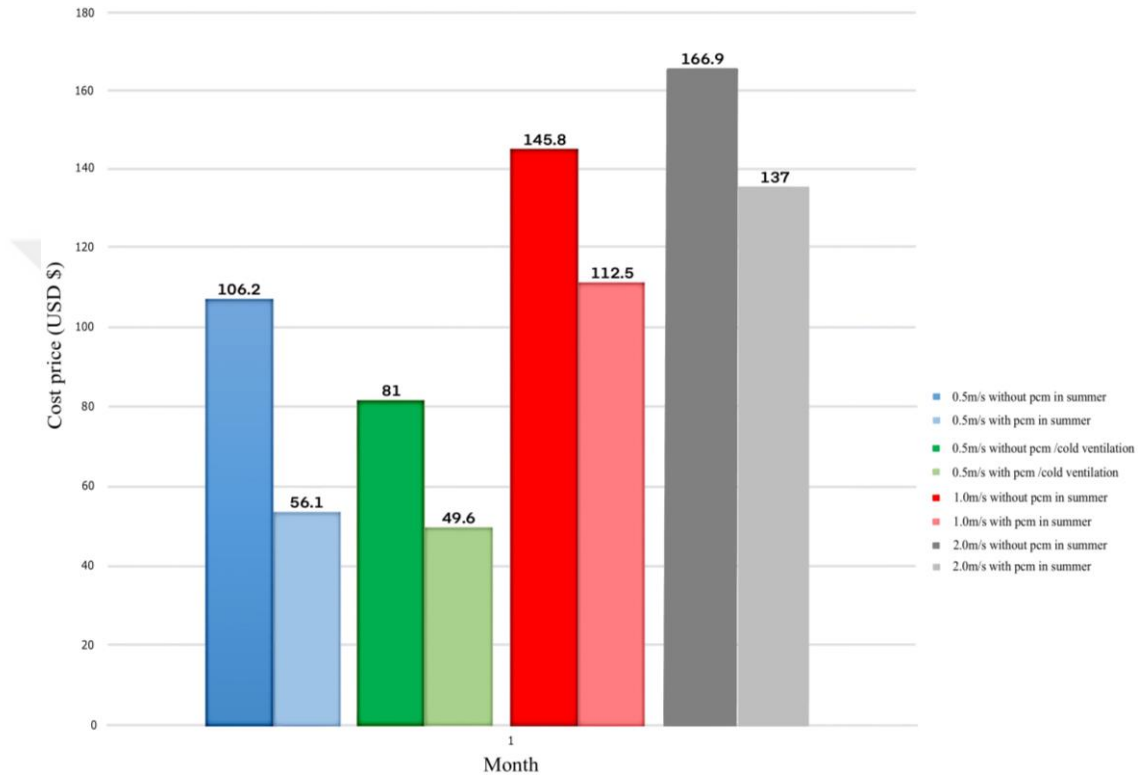


Figure 5.86: Total cost in USD for different case study for one month.

CHAPTER 6

CONCLUSIONS

6.1 Introduction

In this chapter, the conclusions of the study are presented and summarized throughout the dissertation in the form of a list. Suggestions for further study in this field are also provided.

6.2 Conclusion

6.2.1 Scale model experiments

1. Two new types of PCM_s have been tested for their thermal performance and found to be effective in reducing the temperature inside a space during the cooling process and minimizing temperature fluctuations. Moreover, they are found to be responsible for good thermal storage during cooling protocol and also they are good with keep thermal heat in winter scenario.
2. It was observed that the configuration without PCM_s in the roof allowed for more solar radiation to enter the room due to the high thermal conductivity of the roof.
3. The configuration was tested in the climate of Baghdad, Iraq using a prison quarry model. The use of PCM_s in the roof resulted in a reduction in energy consumption of 47.2 %, 23 %, 17.9 % during the summer at inlet velocities of 0.5, 1, and 2 m/s, respectively, and 38.9 % for cooling ventilation at an inlet velocity of 0.5 m/s.
4. The numerical analysis showed that along with other inlet velocities, using an inlet velocity of 0.5 m/s resulted in improved temperature and velocity distribution for this special case.
5. Both numerical and experimental analyses showed that CO₂ concentrations remained within safe levels for all cases in the prison quarry. However, it is important to note that prolonged loss of electricity could lead to dangerous levels of CO₂ due to the risk of suffocation for occupants.

6. The velocity of the air was evenly distributed and moved slowly near the ground, resulting in comfortable temperatures for all velocity patterns. It was determined that an inlet velocity of 0.5 m/s was the optimal choice as it resulted in acceptable noise levels and the best overall temperature and air displacement in this particular model.
7. The contour of relative humidity in the space was within the recommended range for thermal comfort and remained relatively consistent, with acceptable fluctuations.
8. The use of ventilation with a Louvers diffuser of 10" x 14" improved indoor air quality to meet recommended standards. Hence it is said that, selected diffuser provides a good cfm inside the room model.
9. A new type of local paraffin composition was prepared with the goal of creating energy-efficient buildings with high thermal performance. These materials are cost-effective, easily accessible, and have excellent physical and thermal properties.
10. Paraffin PCM_s have a low fire risk and a wide range of melting points and have been shown to save energy in buildings as a successful passive cooling material.
11. It is important to consider the local climate when selecting PCM_s as the temperature at which the phase change occurs may not be effective in different climate zones with varying daily temperature ranges.
12. The implementation of this new chemical as PCM_s in building structures is highly suitable for hot climates due to its low heat flux, reduced temperature fluctuations, and safety features for HVAC systems.
13. The experimental study investigated the thermal performance of a PCM system for space cooling in the climate of Iraq, both numerically and experimentally for both cooling and heating scenarios.
14. There was good agreement between the experimental and numerical (Fluent codes) analysis for thermal comfort considerations.
15. Possible reasons for the discrepancy between numerical and experimental results include:

- a) The dimensions of the computational domain.
- b) Nonuniformity in the inlet mass flow rate of the grill diffuser, which was assumed to be constant for each grill in the model.
- c) Experimental data points were taken from concealed zones, leaving large portions of the experimental space without data.
- d) The computational grid was much finer than the experimental test grid.
- e) The time lag between the observed and simulated results of the temperature difference, as well as the effect of the underlying assumptions of the model.

6.3 Suggestion for future work

It is common for numerous failed attempts and inquiries to precede ground-breaking discoveries. As such, the issues raised by a study are just as important as the findings themselves and can lead to further research for validation or exploration of a hypothesis or technique. In the previous section, the conclusions of the study were discussed, and this section presents ideas for future research advancements.

1. Further testing with different mixtures of PCM_s could be conducted to determine the most effective material for cooling applications and confirm the results of the initial test.
2. Future research could focus on the effects of the thermo-physical properties of RRM₁ and RRM₂, installation methodology, location, and number of cycles on the performance of these materials, as well as the positions for using PCM_s in room walls.
3. Investigating the impact of using PCM_s in bricks on heat gain caused by the melting of the PCM_s inside the bricks before it enters the building through the roof or walls.
4. Examining the influence of variations in outside ambient conditions for each month, the heat transfer coefficient on the exterior surface of the roof, and the thickness of the PCM panels.
5. Validating the tests with a full-scale model constructed at the Technology University in Baghdad.

6. Collaborating with electrical experts to determine the cost-effectiveness of using an energy-efficient system to generate electricity in different locations could be a useful tool.
7. Passive cooling methods, such as the use of latent heat for thermal energy storage, are an attractive alternative to traditional cooling systems and can effectively increase the thermal dormancy of building casing, reducing temperature fluctuations and improving thermal comfort for inhabitants.



REFERENCES

- [1] Yunus A. Çengel, and Afshin Jahanshahi Ghajar."Heat and Mass Transfer: Fundamentals & Applications". *McGraw Hill Education journal*, 2015.
- [2] Knibbs, Luke D., et al. "Room ventilation and the risk of airborne infection transmission in 3 health care settings within a large teaching hospital." *American journal of infection control* 39.10 pp.866-872, 2011.
- [3] Lu, Jianyun, et al. "COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, *Emerging infectious diseases* 26.7 , p.1628, 2020.
- [4] Rothe C, Schunk M, Sothmann P, Bretzel G, Froeschl G, Wallrauch C, et al. Transmission of 2019-n CoV Infection from an Asymptomatic Contact in Germany. *N Engl J Med*. 382(10):970-1, 2020.
- [5] Atul Sharma, V.V.Tyagi, C.R.Chen , D. Buddhi, "Review on thermal energy storage with phase change materials and application", *Renewable and Sustainable Energy Reviews*, 13 , pp.318–325, 2009.
- [6] Dincer, Ibrahim. "On thermal energy storage systems and applications in buildings." *Energy and buildings*, vol. 34.4, pp.377-388, 2002.
- [7] Balaji, N. C., Monto Mani, and B. V. Venkatarama Reddy. "Thermal performance of the building walls." *Preprints of the 1st IBPSA Italy conference Free University of Bozen-Bolzano*. vol. 346, 2013.
- [8] Šujanová, Paulína, et al. "A healthy, energy-efficient and comfortable indoor environment, a review." *Energies* 12.8, p.1414, 2019.
- [9] American Society of Heating, et al. "Ventilation for acceptable indoor air quality".. *American Society of Heating, Refrigerating and Air-Conditioning Engineers*, vol.p.6,1, 2007.
- [10] Shakir and Abdul Khaliq. "Thermal Comfort Modelling of an Open Space (Sport Stadium)". *Masters dissertation*, university of Glasgow, UK, 2010.
- [11] Emmanuella, Madu, and Halil Zafer Alibaba. "The assessment of indoor thermal comfort in a building: A case study of lemar, salamis road, famagusta, cyprus." *International Journal of Civil and Structural Engineering*.vol. 6, Issue 2, pp.109-127, March 2019.
- [12] Auliciems, Andris, and Steven Vajk Szokolay. "Thermal comfort Passive and Low Energy" *Architecture International in association* .The University of Queensland, second revised edition, vol 108 p.219, 2007.

- [13] Cho, J., "Investigation on the contaminant contour with improved ventilation system in hospital isolation rooms: Effect of supply and exhaust air diffuser configurations ". *Journal Applied thermal engineering*, 2019.
- [14] Tanabe, Shinichi, and Kenichi Kimura. "Effects of air temperature, humidity, and air movement on thermal comfort under hot and humid conditions" No. conference - 9406105, *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.*, Atlanta, GA (United States), 1994.
- [15] Hensen; J.L.M., "A comparison Of Coupled Solution for Temperature and Air Flow in a Building". In *ASHRAE Transactions*, vol. 105:2, pp. 962-969, 1999
- [16] Musat R., Helerea E., "Parameters and Models of the Vehicle Thermal Comfort" *Acta Universitatis Sapientiae, Electrical, and Mechanical Engineering*, 1, pp.215-226, 2009.
- [17] Appah-Dankyi J., Koranteng C., "An assessment of thermal comfort in a warm and humid school building at Accra", *Ghana Advances in Applied Science Research*, pp. pp.535-547, 2012.
- [18] Kumar A., Singh I. P., Sud S. K., "An approach towards development of PMV based thermal comfort smart sensor", *International Journal on Smart Sensing and Intelligent Systems*, pp.621-632, 2010.
- [19] Alahmer, A., et al. "Effect of relative humidity and temperature control on in-cabin thermal comfort state: Thermodynamic and psychometric analyses." *Applied Thermal Engineering*, 14-15 pp.2636-2644, 2011.
- [20] Alam S., Ghosh A., "Selection of cotton fabrics for optimal comfort properties using multi-criteria decision making", *Journal of textile and apparel technology and management*, pp.1- 8 , 2013.
- [21] Abhishek R., Balachander R., "Thermal comfort in a closed space based on closed loop temperature control" in *Department Of Electrical Engineering National Institute , Technology Rourkela*, 2010.
- [22] Alwetaishi, Mamdooh S. "Impact of building function on thermal comfort: A review paper." *American Journal of Engineering and Applied Sciences*, 9, pp.928-945, 2016.
- [23] Alfredo Fernandez-Gonzalez and Afzal Hossain" cooling performance and energy savings produced by a roof pond in the United States southwest" *Solar Energy*, pp.65-78, 2010.

- [24] Kharrufa, Sahar N., and Yahyah Adil. "Roof pond cooling of buildings in hot arid climates." *Journal of Building and Environment* 43.1 pp.82-89, 2008.
- [25] Sinan Mazin Hazim, "The Effect of Phase Change Material Section on the Convection Heat Transfer Coefficient", *M.Sc. Thesis*, Technical College/Baghdad, 2011.
- [26] L. F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, and A. I. Fernandez, "Materials used as PCM in thermal energy ' storage in buildings: a review," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp.1675–1695, 2011.
- [27] Hiebler, S., Mehling, H., Helm, M. and Schweigler, C. "Latent Heat Storage with Melting Temperature 29 °c Supporting a Solar Heating and Cooling System". In Proc. 11th Int. Conf. *Therm Energy Storage Effstock*, 2009.
- [28] D. Zhao, and Y. Tian, "Review on thermal energy storage with phase change materials (PCM_s) in building applications," *Applied Energy*, vol. 92, pp.593–605, 2012.
- [29] Hawlader, M. "Encapsulated Phase Change Materials for Thermal Energy Storage: Experiments and Simulation". *International Journal of Energy Research*, 26.2, pp.159–171, 2002.
- [30] Choi, Won-Chang, et al. "Feasibility of using phase change materials to control the heat of hydration in massive concrete structures." *The Scientific World Journal* , pp.734-744, 2014.
- [31] Farid, Mohammed M., et al. "A review on phase change energy storage: materials and applications." *Energy conversion and management* 45.9-10 pp.1597-1610, 2004.
- [32] Wakilaltojjar S. M., Saman W., "Analysis and modeling of a phase change storage system for air conditioning applications", *Appl. Thermal Engineering*, 21, pp.249-263, 2001.
- [33] Alkan C., Sari A., Karaipekli A. and Uzun, O. "Characterization and Thermal Properties of Microencapsulated Phase Change Material for Thermal Energy Storage". *Solar Energy Materials and Solar Cells*, 93(1), pp.143–147, 2009.
- [34] Alawadhi E. M. "Using Phase Change Materials in Window Shutter to Reduce the Solar Heat Gain". *Energy and Buildings*, 47, pp.421–429, 2012.

[35] Esvar Subramanian, "Integrating phase change materials in building materials: Experimentation, Characterization and numerical simulation" *MSc thesis of Materials Science and Engineering*, Clemson University, May 2011.

[36] Sarı, A. "Thermal Reliability test of some fatty acids as PCMs used for solar thermal latent heat storage applications". *Energy Conversion and Management*, 44(14), pp. 2277–2287, 2003.

[37] Malekipirbazari, M., Sadrameli, S. M., Dorkoosh, F. and Sharifi, H. "Synthetic and Physical Characterization of Phase Change Materials Microencapsulated by Complex Coacervation for Thermal Energy Storage Applications" *International Journal of Energy Research*, 38(11), pp.1492–1500, 2014.

[38] CLARK, E. "Phasing out Mass", Internet:
<http://solartoday.org/2014/03/phasingout-mass/>, january.13, 2014 [may.15, 2014].

[39] Regin, A. F., Solanki, S. C. and Saini, J. S. "Heat Transfer Characteristics of Thermal Energy Storage System using PCM Capsules: A Review". *Renewable and Sustainable Energy Reviews*, 12(9), 2008.

[40] K. Gungor, M. Airah, and N. Disney, —"Guide to air change Effectiveness", I .Ecolibrium mode, *Indoor air ISSN*, 0905-6947pp.33-39, 2013.

[41] KC Noh, JS Jang and MD Oh, I. I. "Engineering, —indoor air quality and thermal comfort in the lecture room with-way cassette air conditioner and ventilation system", *Building and Environment*, vol.42, pp.103-743, 2005.

[42] Bhattacharyya, S., et al., "A novel CFD analysis to minimize the spread of COVID-19 virus in hospital isolation room". *Chaos, Solitons & Fractals*, 139, p. 110294, 2020.

[43] Bendjelloul, G., et al., "Impact of admission to high-risk isolation room on patients and healthcare workers perceptions: A qualitative cross-assessment Approach. *Medecine et Maladies Infectieuses*", *Free PMC article*, 2020.

[44] Lipinski, T., et al., "Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings". *International Journal of Thermofluids*, p. 100045, 2020.

- [45] J. Xamán, J. Arcea, G. Álvarez a, Y. Cháveza “Laminar and turbulent natural convection combined with surface thermal radiation in a square cavity with a glass wall” *International Journal of Thermal Sciences* 47 pp.1630–1638, 2008.
- [46] Frank Pedersen, Klaus Hansen, Kim Bjarne Wittchen“Combining building thermal simulation methods and LCA methods” *Nordic Symposium on Building Physics NSB2008* (Vol. 2, pp. 605-611). Technical University of Denmark (DTU), 2008.
- [47] Jørgen Rose, Andreas Lahme, Niels Uhre Christensen, Per Heiselberg, Magne Hansen, and Karl Grau, "Numerical Method For Calculating Latent Heat Storage In Constructions Containing Phase Change Material", *Building Simulation*, p.431, 2009.
- [48] Samira Haghshenaskashani, Hadi Pasharshahi, "Simulation of Thermal Storage Phase Change Material in Buildings", *World Academy of Science, Engineering and Technology* 58, 2009.
- [49] Jegadheeswaran, S., and Sanjay D. Pohekar. "Performance enhancement in latent heat thermal storage system: a review." *Renewable and Sustainable energy reviews*. 13.9 pp.2225-2244, 2009.
- [50] Tabares-Velasco, Paulo Cesar, Craig Christensen, and Marcus Bianchi. "Verification and validation of Energy Plus phase change material model for opaque wall assemblies." *Building and Environment*, V.54, pp.186-196, 2012.
- [51] O. Bamodu, T. Yang, and D. Halim, "True Smart and Green City , International Forum on Urbanism Numerical Investigation of Thermal Comfort in an Office Room with 4-Way Cassette Air Conditioner" , *8th Conference of the International Forum on Urbanism*, 2009 .
- [52] Yang, Chao, Gideon Susman, and Mark Dowson. "Energy Plus model of novel PCM cooling system validated with installed system data." *Proceedings of Sim Build* 6.1, 2016.
- [53] E. Procedia, “A numerical simulation of air distribution in an office room ventilated by 4-way cassette air-conditioner” ., | *EnergyProcedia*, vol.105, pp.2506–2511, 2017.

[54] Elfeky, K. E., Ahmed, N., & Wang, Q.” Numerical comparison between single PCM and multi-stage PCM based high-temperature thermal energy storage for CSP tower plants”. *Applied Thermal Engineering*, 139, pp.609-622, 2018.

[55] Bayomy, A., Davies, S., & Saghir, Z.” Domestic Hot Water Storage Tank Utilizing Phase Change Materials (PCMs): Numerical Approach”. *Energies*, 12(11), 2170, 2019.

[56] Mao, Q., Chen, H., & Yang, Y. “Energy storage performance of a PCM in the solar storage tank” *Journal of Thermal Science*, 28(2), pp.195-203, 2019.

[57] Bhattacharyya, S., et al., “A novel CFD analysis to minimize the spread of COVID-19 virus in hospital isolation room”. *Chaos, Solitons & Fractals*, 139: p. 110294, 2020.

[58] Lu, Y., M. Oladokun, and Z. Lin, “Reducing the exposure risk in hospital wards by applying stratum ventilation system”. *Building and Environment*, 183, p. 107204, 2020.

[59] Juan Bohórquez-Ordenes, Andrés Tapia-Calder.” Methodology to reduce cooling energy consumption by incorporating PCM envelopes: A case study of a dwelling in Chile”*Departamento de Construção Civil Thermal Simulation Analysis Service*, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 21941-909, Brazil, 2020.

[60] Maurizio Detommaso, Antonio Gagliano, Luigi Marletta and Francesco Nocera, "Effectiveness of VIPs and PCMs on the energy performance and thermal comfort in buildings", *IEEE International Conference on Environment and Electrical Engineering*, 2020.

[61] Alawadhi E. M. “Using Phase Change Materials in Window Shutter to Reduce the Solar Heat Gain” *Energy and Buildings*, 47, pp.421–429, 2012

[62] Hossein inasab, S., & Lay, E. N. “Critical Modeling & Exergy Analysis of Multi-Phase Change Materials Storage System” *Journal of Chemical Product and Process Modeling*, 13(1), 2017.

[63] Nagappan, B., Alagu, K., Devarajan, Y., & Munuswamy, D. B. "Energy and exergy analysis of multi-temperature PCMs employed in a latent heat storage system and parabolic trough collector" *Journal of Non-Equilibrium Thermodynamics*, p. 43(3) 2021.

[64] Abu-Hamdeh, N. H., & Alnefaie, K. A." Assessment of thermal performance of PCM in latent heat storage system for different applications" *Solar Energy*, 177, pp.317-323, 2019.

[65] Zhibin Wu, Nianping Li, Pawel Wargocki and Jingqing Peng. "Field study on thermal comfort and energy saving potential in 11 splitair-conditioned office buildings in Changsha, China", *Energy journal*, College of Civil Engineering, Hunan University, Changsha, 410081, 2019.

[66] Ahmet Yüksel, Müslüm Arıcı, Michal Krajčák and Hasan Karabay, "Experimental investigation of thermal comfort and CO₂ concentration in mosques: A case study in warm temperate climate of Yalova, Turkey", *Sustainable Cities and Society*, Yalova University, 2019.

[67] Qudama Al-Yasiri, and Márta Szabo, "Energetic and thermal comfort assessment of phase change material passively incorporated building envelope in severe hot Climate: An experimental study". *Doctoral School of Mechanical Engineering*, Hungarian University of Agriculture and Life Sciences, Szent István campus, Páter K. u. 1, Gödöllő H-2100, Hungary, 2022.

[68] I. B. Munksgaard, and I. A. I. R. Issn, —"Air flow and particle control with different ventilation systems in a classroom", *PMID: 12756014* || pp.200– 204, 2003.

[69] T.Karimipناه, H.B.Awbi, C.Blomqvist, and M.Sandberg, "Effectiveness of confluent jets ventilation system for classrooms", *Conference: Indoor Air*, University of Gävle.June pp. 2–9, 2005.

[70] Anastasios Markopoulos, "PCM performance optimization in building s using active cooling systems" *MSc thesis in Energy Systems and the Environment*, University of Strathclyde engineering, 2008.

[71] A. Durmuş, A. Daloğlu, "Numerical and Experimental Study of Air Flow by Natural Convection in a Rectangular Open Cavity: Application in a Top Refrigerator" *Experimental Heat Transfer*, 21:pp. 281–295, 2008.

[72] Lamberg, Piia, Reijo Lehtiniemi, and Anna-Maria Henell. "Numerical and experimental investigation of melting and freezing processes in phase change material storage." *International Journal of Thermal Sciences* 43.3 pp.277-287, 2004.

[73] Rady, Mohamed. "Thermal performance of packed bed thermal energy storage units using multiple granular phase change composites." *Applied energy* 86.12 pp.2714-2720, 2009.

[74] Agyenim, Francis, et al. "A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS)." *Renewable and sustainable energy reviews* 14.2 pp.615-628, 2010.

[75] Mandilaras, I., Stamatiadou, M., Katsourinis, D., Zannis, G. and Founti, M. "Experimental Thermal Characterization of a Mediterranean Residential Building with PCM Gypsum Board Walls". *Building and Environment*, 61, pp.93–103, 2013.

[76] Mushtaq, T. H., Q. M. Ahmed, and M. H. Hasanain. "Experimental and numerical study of thermal performance of a building roof including phase change material (PCM) for thermal management." *Global Advanced Research Journal of Engineering, Technology and Innovation* 2.8 pp.231-242, 2013.

[77] Stalin, M., Krishnan, S. and Barath, P. "Cooling of Room with Ceiling Fan using Phase Change Materials". *Proceedings of the World Congress on Engineering, researge gate*, 2013.

[78] Li, Bin, Xiaoqiang Zhai, and Xiwen Cheng. "Experimental and numerical investigation of a solar collector/storage system with composite phase change materials." *Solar Energy* 164 pp.65-76, 2018.

[79] Salih, S. M., Jalil, J. M., & Najim, S. E. "Experimental and numerical analysis of double-pass solar air heater utilizing multiple capsules PCM" *Renewable Energy IDEAS*, 2019.

[80] Gohar Gholamibozanjani, Mohammed Farid, "A comparison between passive and active PCM systems applied to buildings". *Chemical and Materials Engineering*, University of Auckland, Private Bag 92020, Auckland, New Zealand, 2020.

- [81] Seyedmostafa Mousavi, Behzad Rismanchi, Stefan Brey, and Lu Aye, "PCM embedded radiant chilled ceiling: A state-of-the-art review" *Renewable Energy and Energy Efficiency Group*, The University of Melbourne, VIC 3010, 2021 Australia.
- [82] Jatatileke C.L. "The Influence of Prandtl-Number and Surface Roughness on the Resistance of the Laminar Sub-Layer to Momentum and Heat Transfer Progress in Heat and Mass Transfer", *Abaqus Analysis* vol. 1, pp.193-329, 2016.
- [83] Chen Q. "Indoor Air Flow, air Quality and Energy Consumption of Buildings", *PhD. Thesis, Delft*. University of Technology, the Netherlands, 1988.
- [84] Awbi H.B., and Hatlon A. "Convection Heat Transfer in Rooms", *Building and Environment*, vol.29, pp.80-96, 1996.
- [85] S. C. Turner et al., *ASHRAE STANDARD*, Thermal Environmental Conditions for Human Occupancy, 1 vol. 2010, 2011.
- [86] N. Mahyuddin and H. Awbi, "The spatial distribution of carbon dioxide in an environmental test chamber", 1 *Build. Environ.* vol. 45, no. 9, pp.1993–2001, 2010.
- [87] A. Bakker, —"Lecture 1 - Introduction to CFD Applied Computational Fluid Dynamics", 1 *Fluid Dyn.* no. 2002, pp.1–25, 2006.
- [88] Hoffmann K.A., "Computational Fluid Dynamics for Engineers", University of Texas, *Engineering Education System*, 1989.
- [89] Hussin H.M. " Prediction of Buoyant Flow inside a Heated Enclosure", *Msc. Thesis*, Al-Rafidain University, Military College of engineering.S. 2013.
- [90] Rodi W, "Examples of Turbulence Models Incompressible Flow", *AIAA J, ARC*, vol.20, No.7, p. 879, 2012.
- [91] Beausoleil-Morrison I, "The Adaptive Coupling of Heat and Air Flow Modeling within Dynamic Whole Building Simulation", *PhD Thesis*, University of Strathclyde, Glasgow, UK, 2000.

[92] ASHRAE Handbook, Fundamentals (SI) “physical Properties of materials”, U.S.patent, Chapter 36, 1997.

[93] A. Merimanov, “Numerical solutions for a Stefan problem” *Research Article*, Walter de Gruyter, *on the one dimensional Stefan problem*, Berlin, 2016.

[94] D. Poulikakos “Conduction Heat Transfer”, U.S.patent, NJ, Section 2, 2017.



APPENDIX (A)
ACTUAL PICTURES



Figure A.1: Rig frame.



Figure A.2: Glass wall insulation.



Figure A.3: Supply and return grills.

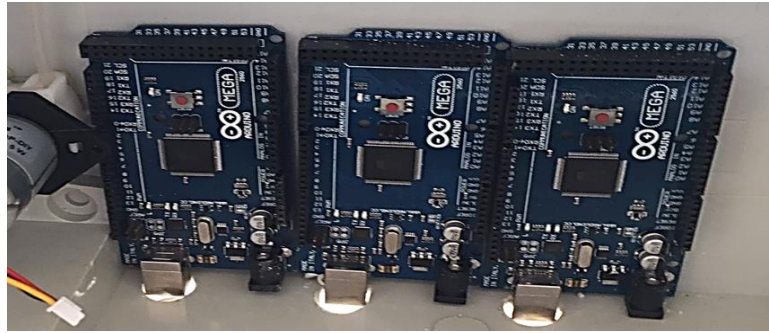


Figure A.4: Arduino microcontrollers.

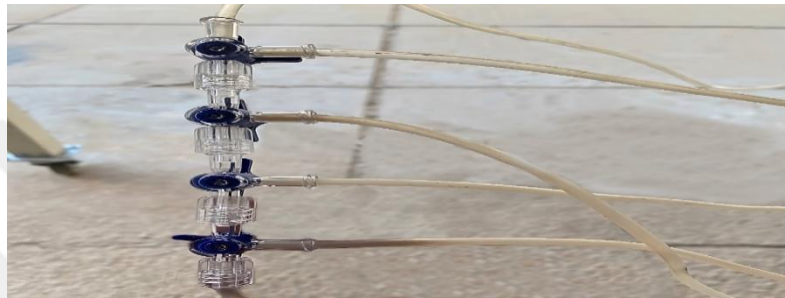


Figure A.5: Fitting segmentation.

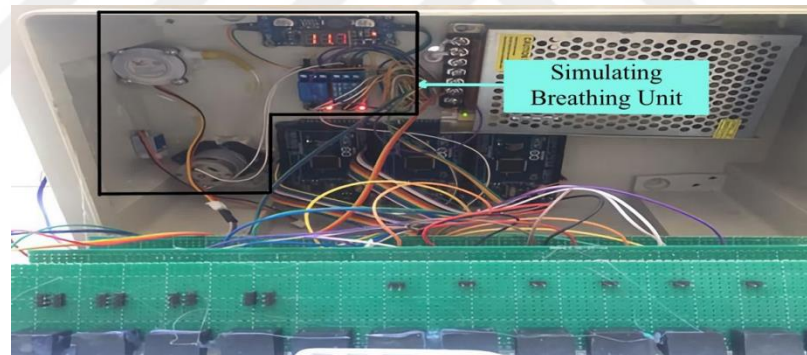


Figure A.6: Arduino box.

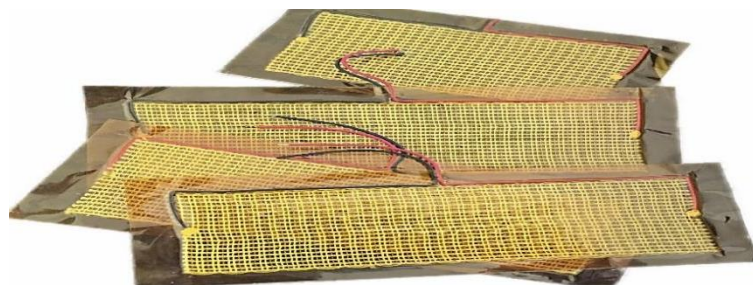


Figure A.7: Thermal pad.

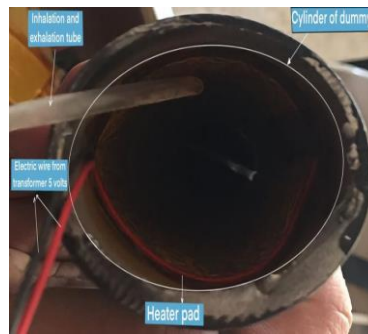


Figure A.8: Heater pad inside the bogus dummy.

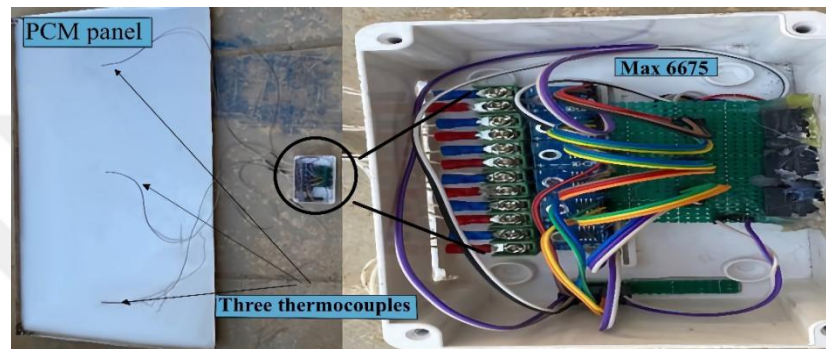


Figure A.9: Max 6675 device with panel thermocouples.



Figure A.10: Arduino board with power supply.



Figure A.11: The design of the actual prototype model.



Figure A.12: Paraffin waxes stage of pouring.



Figure A.13: The complete prototype model ready for testing before putting the around insulator.



Figure A.14: Put PCM to panel.



Figure A.15: Actual prison quarry.

APPENDIX (B)

CARRIER HAP SOFTWARE

B.1 Launder and Spalding Constants

Table B.1: Constants of turbulence model.

C_1	C_2	C_D	σ_k	σ_ε
1.44	1.92	0.09	1.0	1.3

B.2 HAP Data sheet

Prison quarry -- DATA SHEET

09/06/2022 1:29 PM	Space Input Data	Fadhil Asaad Al Malaki ~~Dr. Rahim Jafari~~ ~~Dr. Hasaneen Mohammed.~~
-----------------------	-------------------------	--

Cooling load

1. General Details:

Floor Area **11.52** m²
 Avg. Ceiling Height . **3.2** m
 Building Weight **5.1** kg/m²

1.1. OA Ventilation Requirements:

Space Usage **CORRECTIONAL FACILITY: Cells**
 OA Requirement 1 **7.50** L/s/person
 OA Requirement 2 **0.00** L/(s-m²)
 Space Usage Defaults **ASHRAE Standard 62-2001** for comfortable.

2. Internals:

2.1. Overhead Lighting:

Fixture Type **Recessed**
(Unvented)
 Wattage **10.00** W/m²
 Ballast Multiplier ... **1.00**
 Schedule **24 hour**

2.2. Task Lighting:

Wattage **0.00** W/m²
 Schedule **None**

2.4. People:

Occupancy **5.0 People**
 Activity Level **Sedentary Work**
 Sensible **82.1**
 W/person
 Latent **79.1**
 W/person
 Schedule **off 1 hour Thurs.**

2.5. Miscellaneous Loads:

Sensible **5000** W
 Schedule **off 1 hour Thurs.**
 Latent **1000** W
 Schedule **off 1 hour Thurs.**

2.3. Electrical Equipment:

Wattage **0.00** W/m²
Schedule **None**

3. Walls, Windows, Doors:

Exp	Wall Gross Area (m ²)	Window 1 Qty.	Window 2 Qty.	Door 1 Qty.
E	7.68	0	0	0
S	15.36	0	0	0
W	7.68	0	0	0
N	15.36	0	0	1

3.1. Construction Types for Exposure E

Wall Type **Stucco + 203mm common brick + 13mm gypsum plaster**

3.2. Construction Types for Exposure S

Wall Type **Stucco + 203mm common brick + 13mm gypsum plaster**

3.3. Construction Types for Exposure W

Wall Type **Stucco + 203mm common brick + 13mm gypsum plaster**

3.4. Construction Types for Exposure N

Wall Type **Stucco + 203mm common brick + 13mm gypsum plaster**

4. Roofs, Skylights:

Exp	Roof Gross Area (m ²)	Roof Slope (deg.)	Skylight Qty.
H	11.52	0	0

4.1. Construction Types for Exposure H

Roof Type **Default Roof Assembly**

5. Infiltration:

Design Cooling .. **2.00** ACH

Design Heating .. **2.00** ACH

Energy Analysis .. **2.00** ACH

Infiltration occurs slightly only when the fan is off.

6. Floors:

Type **Floor above Conditioned Space**

(No additional input required for this floor type).

7. Partitions:

(No partition data).

Figure B.1: Carrier HAP software for cooling load calculation.

Table B.2: SOLAR RADTION DATA SHEET

Parameter: Global R. (W/m²)

Month: 8 Year: 2022

	006	007	008	009	010	011	012	013	014	015	016	017	018	019
1	3	112	179	344	505	605	600	670	670	681	557	362	200	33
2	1	109	203	376	530	618	695	700	708	647	512	304	157	20
3	7	92	141	317	472	580	649	752	823	612	492	285	149	33
4	-	64	211	377	558	626	686	950	955	700	448	283	122	10
5	21	148	168	349	505	588	662	912	760	610	446	281	126	3
6	19	142	178	334	496	567	650	910	823	593	470	308	146	16
7	2	115	173	324	489	582	655	991	876	635	535	364	187	32
8	-	49	224	376	555	610	672	972	900	614	467	289	122	4
9	15	158	201	363	530	597	690	912	865	624	476	284	160	22
10	5	147	231	403	519	675	761	823	801	671	547	330	139	32
11	-	67	242	413	579	693	736	747	709	580	404	125	22	-
12	-	89	185	345	508	638	780	860	799	559	396	278	104	6
13	8	106	256	397	547	645	785	1099	866	601	423	282	98	-
14	13	137	180	348	510	623	950	1100	908	582	417	265	118	-
15	5	116	290	338	501	625	770	970	954	626	468	307	153	13
16	-	85	166	330	483	618	717	1000	899	604	452	289	132	150
17	1	108	179	353	514	652	780	1090	863	572	390	222	46	-
18	33	193	329	510	607	648	800	910	805	522	473	203	-	-
19	15	124	161	337	484	619	786	922	799	614	456	282	139	8
20	-	79	158	326	482	604	743	954	864	611	451	260	119	9
21	-	91	156	330	482	679	740	910	823	681	453	286	119	-
22	-	116	286	340	490	608	721	963	955	664	476	333	133	10
23	-	38	156	321	483	617	701	981	861	622	470	295	125	-
24	-	94	167	329	480	611	888	1000	800	683	471	293	130	2
25	-	57	226	362	559	643	708	1001	890	536	356	199	44	-
26	-	144	321	324	481	601	704	990	877	582	422	265	101	-
27	-	84	156	228	485	636	710	911	800	595	434	272	102	-
28	-	84	151	328	482	600	699	900	900	570	392	250	107	4
29	-	77	149	327	470	614	698	887	788	638	501	158	16	-
30	-	59	163	343	513	684	752	884	745	632	474	300	129	-
31	-	93	171	354	518	648	723	881	736	617	439	256	131	-

Table B.3: OPET from Meteorological Authority

(OPET) OF (EERC)

Parameter: Temperature °C

month: 8 year: 2022

	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	00
1	34	34	33	32	31	30	27	35	37	39	42	44	45	45	45	45	43	40	40	38	36	36	36	34
2	34	33	32	31	31	31	33	36	38	41	42	42	45	46	46	45	45	43	40	38	37	36	35	36
3	34	34	33	33	31	35	31	33	34	37	40	42	47	44	43	44	43	40	38	35	31	31	34	34
4	34	31	31	31	29	30	31	36	39	42	43	45	45	46	45	45	43	39	34	34	32	31	31	30
5	26	30	28	26	27	28	30	33	35	38	40	44	48	43	45	42	41	40	37	35	35	35	34	32
6	33	32	32	31	31	30	30	33	36	38	39	48	51	44	46	41	40	39	36	35	34	34	34	33
7	32	31	37	31	31	31	32	33	34	36	38	48	49	46	47	42	40	39	37	36	33	33	34	34
8	33	31	31	30	29	29	30	32	35	37	38	49	53	45	45	40	39	37	34	32	32	32	32	32
9	31	31	30	30	29	29	31	34	37	39	45	50	52	44	47	41	39	38	36	36	35	34	33	32
10	32	31	31	30	29	31	33	33	34	36	38	47	49	48	45	39	39	37	35	34	34	33	31	31
11	31	30	29	29	27	28	30	33	35	36	38	41	50	49	46	43	41	40	37	35	35	34	33	33
12	33	32	30	30	29	28	29	31	34	36	38	43	51	49	47	40	40	39	39	37	35	33	33	32
13	29	30	28	29	29	31	30	33	35	38	41	48	54	51	47	45	41	41	40	39	38	35	33	32

Energy and Environment Research /Center Station/ Al-Jadriyah-Baghdad

APPENDIX C

HARDWARE SPECIFICATIONS

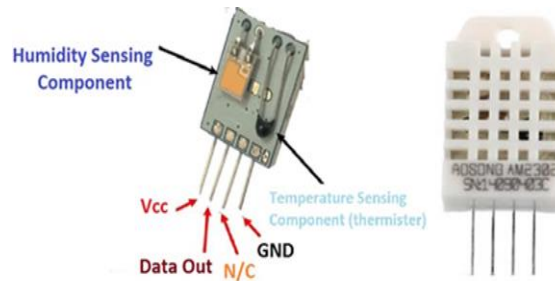


Figure C.1: Temperature & Humidity sensing.

Table C.1: Technical specification of DHT22.

Model	DHT22
Power supply	3.3-6V DC
Output signal	Digital signal via signal-bus
Sensing element	Polymer capacitor
Operating range	Humidity 0-100%RH; temperature -40~80Celsius
Accuracy	Humidity $\pm 2\%$ RH(Max $\pm 5\%$)RH; temperature $\leq \pm 0.580$ Celsius
Resolution or sensitivity	Humidity 0.1% RH; temperature 0.1Celsius
Repeatability	Humidity $\pm 1\%$ RH; temperature ± 0.2 Celsius
Humidity hysteresis	$\pm 0.3\%$ RH
Long-term Stability	$\pm 0.5\%$ RH/year
Sensing period	Average: 2 sec
Interchangeability	Fully interchangeable
Dimensions	Small size 14×18×5.5mm; big size 22×28×5mm



Figure C.2: Hot wire Anemometer.

Table C.2: Data sheet of yk-2005AH.

FEATURES

* Combination of hot wire and standard thermistor, deliver rapid and precise measurements even at low air velocity value.	Data Output	RS 232 PC serial interface.
* Slim probe, ideal for grilles & diffusers.	Operating Temperature	0 to 50 °C.
* Air velocity : m/S, Ft/min, Km/h, Knot, Mile/h,	Operating Humidity	Less than 80% R.H.
* Air flow : CMM (m ³ /min.) and CFM (ft ³ /min.).	Power Supply	DC 1,5 V battery (UM3) x 4 PCs, (Heavy duty type).
* Air temperature (°C, °F)	* main instrument	DC 9V adapter input. @ AC/DC power adapter is optional.
* Type K/ Type J thermocouple thermometer.	Power Supply	DC 3V silver battery.
* Real time data logger, build in clock (hour-min.-sec, year-month-date).	* clock module	Type : CR2032.
* Auto data record, 16,000 Data logger no.	Power Current	Approx. DC 21.5 mA @ Main instrument.
* Wide sampling time adjustment range from two seconds to 8 hours 59 minutes 59 seconds.		Approx. DC 70 mA @ Main instrument. + Hot wire probe.
* Zero adjustment.	Weight	515 g/ 1.13 LB. @ Battery is included.
* Can default auto power off or manual power off.	Dimension	Main instrument : 203 x 76 x 38 mm Telescope Probe : Round, 12 mm Dia x 280 mm (min. length). Round, 12 mm Dia x 940 mm (max. length).
* Can default the air velocity, air flow, Temp. unit.	Accessories Included	Instruction manual..... 1 PC Telescope Probe.....1 PC DC 3V silver battery, CR2032..... 1 PC Carrying case.....1 PC
* Air flow measurement can set the area dimension.	Optional Accessories	Type K thermocouple probe. AC to DC 9V adapter. RS232 cable/UPCB-02, USB cable/USB-01 Data Acquisition software, SW-U801-WIN. Data Logger software, SW-DL2005.
* Large LCD with multiple display.		
* Data hold, record max. and min. reading.		
* Microcomputer circuit provides special function & offer high accuracy.		
* Air Temp. used thermistor sensor, fast response time.		
* Power by UM3 (1.5 V) x 4 batteries or DC 9V adapter.		
* RS232 computer interface.		
* Separate probe, easy for remote measurement.		
* Applications : Environmental testing, Air conveyors, Flow hoods, Clean rooms, Air velocity, Air balancing, Fans/motors/blowers, Furnace velocity, Refrigerated case, Paint spray booths.		



Figure C.3: MQ-2 sensor.

Table C.3: Technical Specification of MQ-2.

Model No.			MQ-2
Sensor Type			Semiconductor
Standard Encapsulation			Bakelite (Black Bakelite)
Deduction Gas			Combustible gas and smoke
Concentration			300-10000ppm (Combustible gas)
Circuit	Loop Voltage	V_C	$\leq 24V$ DC
	Heater Voltage	V_H	$5.0V \pm$
	Load Resistance	R_L	Adjustable
Character	Heater Resistance	R_H	$31\Omega \pm \Omega$ (Room Tem.)
	Heater Consumption	P_H	$\leq 900mW$
	Sensing Resistance	R_S	$2K\Omega - 20K\Omega$ (in 2000ppm C_3H_8)
	Sensitivity	S	$R_S(\text{in air}) / R_S(1000ppm \text{ isobutene}) \geq 5$
	Slop	a	$\leq 0.6(R_{5000ppm} / R_{3000ppm} CH_4)$
Condition	Temp. Humidity		$20^\circ C \pm 2^\circ C : 65\% \pm 5\% RH$
	Standard test circuit		$V_C: 5.0V \pm 0.1\pm;$ $V_H: 5.0V \pm 0.1V$
	Preheat time		Over 48 hours



Figure C.4: MG-811 sensor.

Table C.4: Technical Specification of MG-811.

Features	Sensors		
	Temperature/Humidity : RHT03	Luminosity:TSL256 1	CO ₂ Concent ration: MG811
Power supply	3.3-6.0 V	2.7-3.3 V	6.0 V
Measurement range	T:[-40; 80]°C H:[0; 100]%	[0; 40,000] Lux	[350; 10,000] ppm
Sensitivity	T:0.1°C H:0.1%	1Lux	Variable
Accuracy	T:0.1°C H:0.1%	Not available	Not availabl e
Preparation time	0.5 s	0-1 s	30-60 s
Response time	0.5 s	0-1 s	15-30 s
Communications	Digital	12	Analog

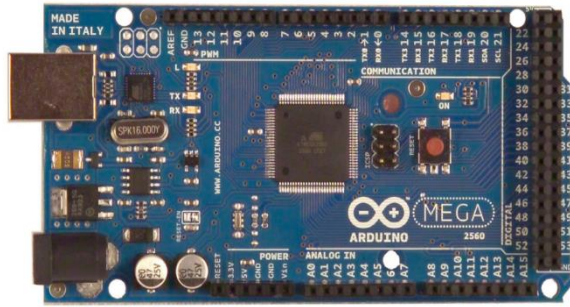


Figure C.5: Arduino mega 2560.

Table C.5: Technical specification of Arduino Mega 2560.

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage(recommended)	7-12V
Input Voltage(limits)	6-20V
Digital I/O Pins	54(of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O pin	40 mA
DC Current for 3.3V pin	50 mA
Flash Memory	256 KB of which 8 KB used by boot loader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz



Figure C.6: Power supply.

Table C.6: Technical specification

Output voltage	DC 12V
Output voltage control range	11V-13.8V
Output current	20A
Output power	240W
Input voltage	100-240VAC/50Hz/60Hz
Operation temperature	-10 °C to +50 °C
Storage temperature	-20 °C to +60 °C
Shell material	Metal case/aluminum base
Ambient Humidity	0-95% Non-Condensation
Dimensions	199×110×50mm
Weight	740 g
Protection	Shortage, Overload, over Voltage

**Figure C.7:** Infrared thermometer, model GM700**Table C.7:** Infrared thermometer specification

Temperature range	Accuracy	Resolution
-50~700°C(-58~1292)°F	0~700 °C(32~1292) °F : +/-1.5 °C(2.7) °F OR 1.5 % -50~0 °C(-58~32) °F : ++/-3 °C(+/-5 °F) Whichever is greater	0.1 °C OR 0.1 °F



Figure C.8: Air conditioning laboratory unit, A660/15611.



Figure C.9: TPS- 500, device.



Figure C.10: Weighed specimen sample



Figure C.11: DSC device

APPENDIX D

BREATHING SYSTEM

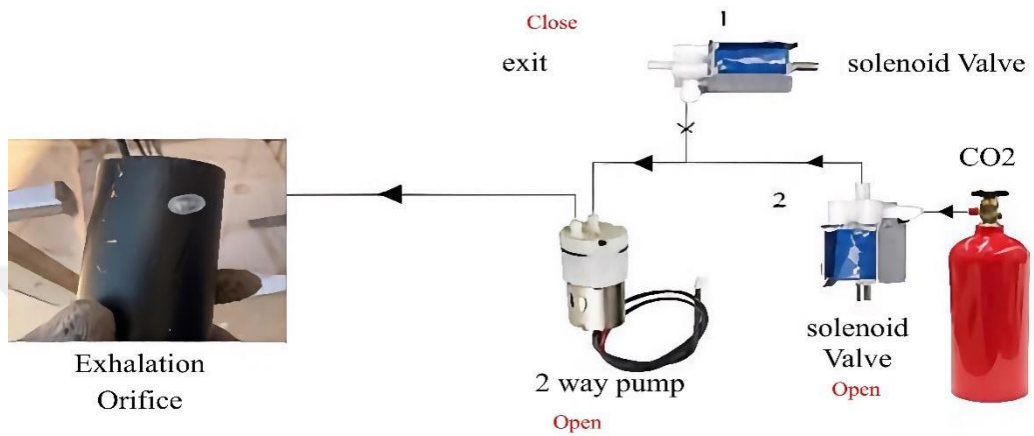


Figure D.1: Exhalation mode for pseudo dummy.

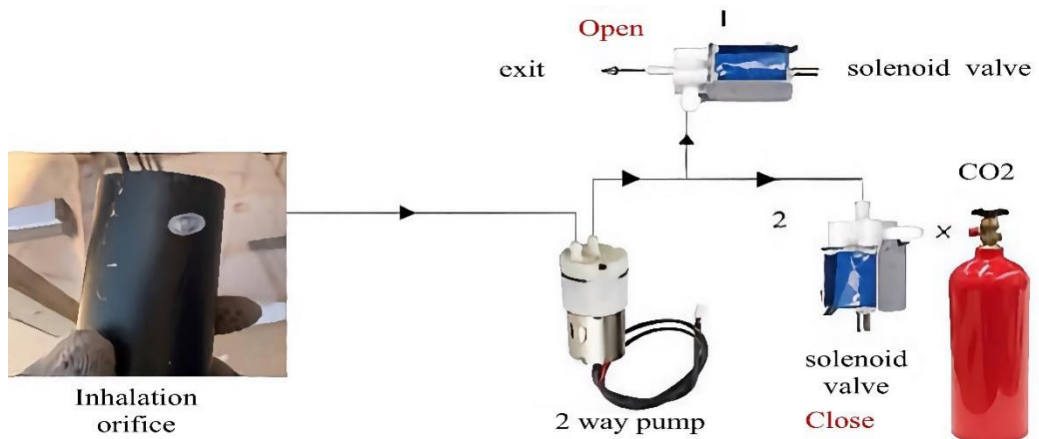


Figure D.2: Inhalation mode for pseudo dummy.

APPENDIX E

LIST OF PUBLICATION

- **Numerical Evaluation of Thermal Comfort, IAQ Indices, and TES for the Improvement of the Energy Performance in Crowded Area.**

[Al-Malaki, F., Jafari, R.](#)

IICETA 2022 - 5th International Conference on Engineering Technology and its Applications, IEEE 2022, pp. 6–13

- **Investigation of the Effectiveness of PCM on the Energy Saving, Thermal Comfort and Indoor Air Quality in Overcrowded Area, Submitted.**