ENERGY SAVING POTENTIAL OF BUILDINGS INTEGRATED WITH PHASE CHANGE MATERIAL IN HOT, ARID CLIMATE ZONE

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DECLARATION

I hereby, declare that this manuscript, entitled "Energy saving potential of buildings integrated with phase change material in hot, arid climate zone", is the result of my own work except for quotations and citations which have been duly acknowledged.
I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

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Abstract

Phase change materials are used to decrease energy cost, dependency on fossil fuels and make the buildings energy efficient. The main aim of this study is to carry out parametric study in BWh zone of Koppen-Geiger climate classification in order to evaluate the hypothesis that a single PCM or a group of PCMs (in the narrow) can be used for the whole BWh climate zone. Hence, the energy performance of two-storey PCM integrated residential building located in eight different cities (Abu- Dhabi, Dubai, Faisalabad, Mecca, Jodhpur, Nouakchott, Cairo and Biskra) from BWh Koppen-Geiger classification was evaluated using the most representative building envelope. Also, the impact of meteorological

factors like temperature, wind speed, relative humidity, solar radiance on energy saving have been evaluated. Numerical simulations were performed with thirteen different phase change ranges in DesignBuilder software, which uses EnergyPlus as its calculation engine. According to the test results, the optimum PCMs were able to reduce the temperature fluctuations and the maximum temperature reduced by up to 4.64C. The monthly energy savings results showed that different PCMs were found to be optimum in different months of the year. Except for Cairo and Biskra,

the optimum PCM were close to the cooling set points suggesting that in dry climate region, PCM with higher melting points perform better. For the selected

cities, the energy consumption reduction varied from 17.97 to 34.26%. For a given volume of PCM, energy efficiency increased with the increase in the surface area and decrease in the thickness of PCM layer. From bivariate correlation analysis, it was found that the increase in wind speed, temperature and solar radiation resulted in the increase in the energy savings while the increase in relative humidity resulted in the decrease in energy saving values. Conclusively, the incorporation of PCM in residential building located in dry climate (BWh) is feasible.

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Table of contents

Abstract 3

Acknowledgements 5

List of Abbreviations & Symbols viii8

List of Tables 9

List of Figures 10

Chapter 1 - Introduction 11
- 1.1. Background 11
- 1.2. Research objectives 12
- 1.3. Research novelty 13

Chapter 2 – Literature review 14
- 2.1. PCM 14
- 2.2 Sensible and latent heat 15
- 2.2. Research investigations 16

Chapter 3 – Methodology 20
- 3.1. Research methodology 20
- 3.2. Simulation details 21
- 3.3. BWh climate zone 23
- 3.4. Building envelope 26
- 3.5. HVAC system 32
- 3.6. Validation 33

Chapter 4 – Results and discussion 35
- 4.1 Effect of PCMs on Monthly Energy savings 35
- 4.2 Effect of Optimum PCM on Thermal performance (HVAC switched on) 40
- 4.3 Selection of Optimum PCM 49
- 4.4 Annual energy consumption and Energy savings 51
- 4.5 Assessment of different Thickness 54
- 4.6 Assessment of Surface Area on Energy Savings 55
- 4.7 Impact of wind speed, temperature, solar radiation and relative humidity on energy savings 57

Chapter 5 – Conclusion and Recommendations 61

References.. 64

List of Abbreviations & Symbols

ATFR	Average temperature fluctuation reduction
ECR	Energy consumption reduction
ES	Energy saving
CondFD	Conduct Finite Difference
HVAC	Heating, ventilation & air conditioning
PCM	Phase change material

List of Tables

Table 3.1 Description of selected cities in BWh climate classification 26

Table 3.2. Thermophysical characteristics of building materials 31

Table 4.1 Annual Energy savings and Energy consumption reduction for all cities 53

Table 4.2 Energy savings as a function of PCM thickness 55

Table 4.3 Mean monthly meteorological values for Abu-Dhabi, Dubai, Jodhpur and Mecca 57

Table 4.4 Correlation coefficients for selected cities 59

List of Figures

Figure 2.1. Latent heat curve 16

Figure 3.1 Research methodology 21

Figure 3.2 Koppen-Geiger climate classification map 23

Figure 3.3 Average values of temperature and precipitations for BWh climate zone 24

Figure 3.4 Koppen-Geiger BWh climate zone 24

Figure 3.5 Map showing selected cities in BWh climate zone 25

Figure 3.6. Model of a Two-story residential house 27

Figure 3.7 Wall composition 28

Figure 3.8 Roof composition 29

Figure 3.9 Details of Wall, Roof, Intermediate and ground floor 30

Figure 3.10 Enthalpy-temperature graph for PCM20-32 32

Figure 3.11 Single room model 33

Figure 3.12 Validation results 34

Figure 4.1. Monthly energy savings results for all cities. 39

Figure 4.2 Temperature profiles for all cities in months with highest energy savings 44

Figure 4.3. Temperature profiles for all cities in months with lowest energy savings 47

Figure 4.4 Temperature profiles for January in Cairo and Biskra 49

Figure 4.5 Annual energy required for heating and cooling of residential house located in Cairo and Biskra 51

Figure 4.6. Annual energy required for heating and cooling of residential house located in Mecca, Abu-Dhabi, Jodhpur and Dubai 52

Figure 4.7. Relationship between energy savings in Dubai and Mecca for different PCM surface area with constant volume 56

Chapter 1 - Introduction

1.1. Background

The recent reports of worldwide energy consumption state that buildings consume about 40% of total energy consumed in the world [1]. It is also known that about 80 percent of energy is extracted from combustion of fossil fuels to provide energy for heating, cooling and lightning in commercial and residential buildings [1]. Moreover, their usage is directly linked to emission of carbon dioxide and other harmful gases, contributing to human health aggravation, environmental pollution and climate change effects, such as global warming. Hence, the grow of energy consumption, depletion of natural resources and related environmental issues are the driving factors encouraging scientists, engineers and contractors to use renewable energy resources and adopt sustainable building style [2, 3]. One of the solutions, which has attracted researchers and engineers, is the incorporation of phase change materials (PCM) into building envelopes to improve buildings energy efficiency and thereby reducing the environmental influence of energy use [4-8].

Various researchers have evaluated the energy efficiency and thermal performance of PCM integrated building in different parts of the world. However, the detailed investigation regarding the thermal performance, monthly and yearly energy saving potential and optimization of PCM integrated building in eight different cities of BWh climate classification, has not been evaluated yet. Another novelty of this research is that the construction details including wall, roof, floor and foundation composition of the building and the thermal comfort range was chosen according to local practice. The effect of PCM layer with different thickness and surface area on the energy saving potential was also evaluated. Finally, bivariate correlation analysis was performed to find relationship between energy savings, wind speed, temperature, solar radiation and relative humidity.

1.2. Research objectives

This research considers the performance of PCM integrated building in the hot dry climate zone. The main aim is to carry out parametric study and consider how PCM could decrease energy consumption and find optimum PCM range for BWh climate zone. So, the performance of the PCM integrated building could evaluated by following objectives:

- To evaluate monthly and annual energy savings of PCM integrated building in eight different cities;
- To determine thermal performance for months with the highest and lowest energy savings;
- To find optimum PCM among several PCMs (20-32) for each city;
- To make surface and thickness comparison;

- To determine the influence of meteorological parameters on PCM performance.

1.3. Research novelty

The main goal of this research was to carry out parametric study in BWh zone of Koppen-Geiger climate classification in order to evaluate the hypothesis that a single PCM or a group of PCMs (in the narrow) can be used for the whole BWh climate zone. Hence, eight different cities from BWh climate were chosen. The detailed investigation regarding the thermal performance, monthly and yearly energy saving potential and optimization of PCM integrated building in eight different cities of BWh climate classification, has not been evaluated yet. Another novelty of this research is that the building envelope and thermal comfort range were chosen according to local practices and guidelines. Also, the impact of meteorological factors like temperature, wind speed, relative humidity, solar radiance on energy saving have been evaluated.

Chapter 2 – Literature review

Background information about PCM like types of PCM, incorporation methods, explanation of how PCM works in terms of sensible and latent heat are described in this section. Moreover, due to the aim of this study to consider the performance of PCM incorporated building in hot dry climate, the studies which have been observed the PCM integrated buildings in different countries and climates have been mentioned in this section.

2.1. PCM

PCM is a material that keep energy in the form of latent heat [9]. Phase change could be different types such as solid-liquid, solid-solid, solid-gas and others. Each of them has different advantages, however solid-liquid is more attractive as thermal energy storage system since it has high latent heat, small volume change and economy [10]. PCM in the form of solid-liquid decreases cooling or heating demand by melting or solidifying processes which allows to absorb or release the heat. Overall, there are three main groups of PCM due to the composition:

Inorganic: hydrated salts, metallics;

Organic: paraffins, sugar alcohol, glycols, plant and bio-based;

Eutectics: organic-organic, inorganic-organic, inorganic-organic.

Inorganic PCM have several advantages like high thermal conductivity, non-flammable. Nevertheless, along with the advantages it has some disadvantages such as corrosiveness, high volume change, chemical instable. Organic PCM has high specific heat compare to inorganic, low-cost, non-corrosive, able to be recycled and has small volume difference during the phase change cycle. However, it has low thermal conductivity and are slightly flammable. Thermal-physical properties of eutectic PCM is limited due to the lack of test data [11].

Also, there are different PCM incorporating methods, so PCM could be directly incorporated or by immersion, encapsulation, shape-stabilization and form stable composite PCMs.

2.2 Sensible and latent heat

Charging and discharging process happens under certain temperature which is called phase change point. When the temperature reaches the melting point, the PCM starting to melt and absorb the heat. PCM works as the sensible heat storage device after it is completely melted. When the temperature achieves the freezing point, PCM starts to solidify and releases the stored heat. Figure 2.1 shows how PCM works. PCM is 5 to 14 times more effectively store energy compare to the sensible storage materials like masonry and rock [12].

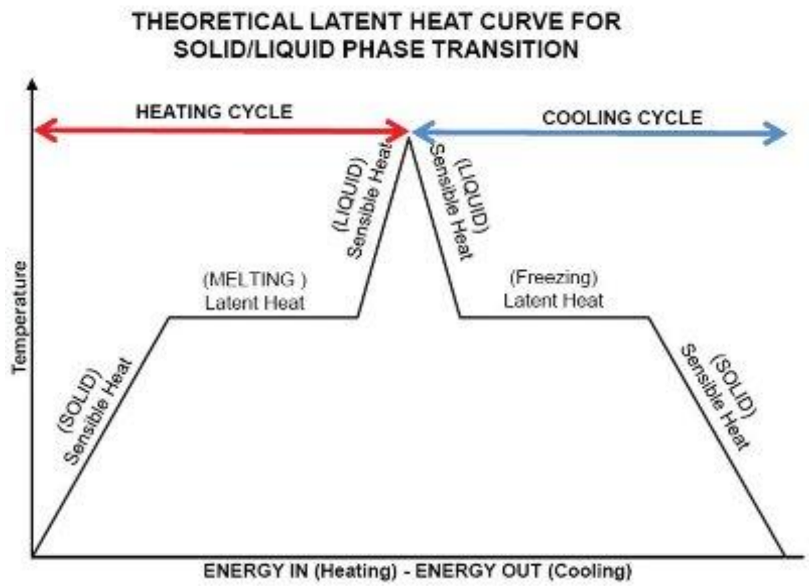


Figure 2.1. Latent heat curve [12]

2.2. Research investigations

Various researchers have investigated the energy saving and thermal performance of PCM integrated building in different parts of the world [13-19]. Mi et al. [20] considered the energy saving potential of 3 storey PCM integrated office building located in five different cities of China. The simulations were performed in DesignBuilder software with PCM27 having melting temperature of 27^{o}C. From simulation results, the performance of PCM integrated office building in Shenyang and Zhengzhou located in cold region and Changsha, which has hot summer and cold winter, was prominent. Based economic analysis, it was pointed out that the application of PCM in Hong Kong and Kunming is not feasible. The thermal performance and energy saving potential of house model integrated with PCM was evaluated by Alam et al. [21] in EnergyPlus for eight different cities of Australia. The considered cities were Canberra, Darwin, Hobart, Melbourne, Perth, Sydney, Adelaide and Brisbane. For the studied PCM integrated house model, the annual energy saving varied from 17 to 23% except for Darwin city. It was concluded that the performance of PCM is highly dependent on local weather, thickness of PCM layer; it's location in building, surface area and thermostat range. The energy saving potential of a detached house integrated with PCM23, PCM25 and PCM27 in London was evaluated for current and future climate scenarios (2050 and 2080) during summer period [22]. The influence of PCM thickness was also considered. From simulation results, PCM 25^{o}C with 48mm thickness and an air gap of 25mm were found to be optimum. It was concluded that for current weather scenario, the performance of PCM is very limited. However, the performance of PCM becomes dominant in 2080. Lei et al. [23] assessed the performance of PCM integrated simplified cubic model (3m x 3m x 2.8m) for tropical Singapore. For the benchmark study, where 10 mm layer PCM 28^{o}C was added to outside surface of the walls, the reduction in heat gains varied from 21 to 32%. Moreover, from parametric study, the performance of PCM in the exterior wall surface was found to be superior when compared to interior wall surfaces. The environmental performance and energy saving potential of typical flat located in Hong Kong was evaluated in EnergyPlus using PCM having melting point of 21.7^{o}C [24]. Through computer simulations, the PCM integrated flat was able to save 2.9% of air-conditioning load annually. The payback period of 91 years made the PCM integrated flat economically unfeasible. However, an energy payback of 23.4 years made the building environmentally feasible. For Tlemcen city located in Algeria, Selka et al. [25] investigated the dynamic thermal behavior of a two-story building integrated with PCM by using two-dimensional model. The researchers pointed out that the internal temperature could decrease by 6˚C to 7˚C by the utilization of PCMs in walls.

In the recent past, several researchers have performed the energy analysis of PCM integrated buildings located in different climate zones. For example, Soares et al. [26] evaluated the energy saving potential of lightweight steel frame single zone room incorporated with PCM-drywalls in two main Climate zones (C: Warm temperate and D: Snow) and found that the efficiency of PCM drywalls was optimum in Mediterranean climate. Marin et al. [27] performed numerical simulations to evaluate the energy saving potential of lightweight single zone building integrated with PCM in different climate zones. Test results showed that PCM has energy saving potential in arid and warm temperate climate while the energy saving potential of PCM in tropical and snow main climate areas was limited. In the recent past, optimization techniques have become popular for sustainable building design [28, 29]. Saffari et al. [30] used single-objective optimization technique to optimize the performance of PCM integrated midrise building located in different climate zones and found that PCM with higher melting point (PCM26) perform better in cooling dominant climate while PCM with lower melting point (PCM20) perform better in heating dominant climate.

Chapter 3 – Methodology

Research methodology has been described in detail in this section. The features of selected software and simulation details along with equations which have been used in the research have been mentioned in this chapter. Also, the description of selected climate region and cities, the selection of the building envelope and the final version of wall, roof, ground and intermedia floor compositions have been discussed. The sections like simulation details, building envelope, BWh climate region, HVAC system and validation are widely discussed in this chapter.

3.1. Research methodology

Diagram (Figure3.1) represents the research methodology of this study. The first step of this research was the literature review which have been mentioned in previous chapter. Main factors on which study should be focused have been determined based on literature review. After, literature review the climate zone and cities have been selected for further investigations. Further, the model in Designbuilder have been validated in order to be sure that it can be used for simulations. Then, model properties like building envelope, comfort range, HVAC system and others have been determined, also based on literature review. After, fixing all necessary properties, simulations have been started. The performance of

PCM integrated building have been evaluated in terms of monthly energy savings and thermal performance. Selection of optimum PCM for each selected city have been done based on annual energy savings. Afterwards, assessment of thickness and surface area on PCM performance have been evaluated and optimum thickness have been determined. Finally, correlation analysis has been done in order to investigate how meteorological parameters such as wind speed, solar radiation, temperature and relative humidity could influence on PCM performance. Overall, conclusion due to the results have been done.

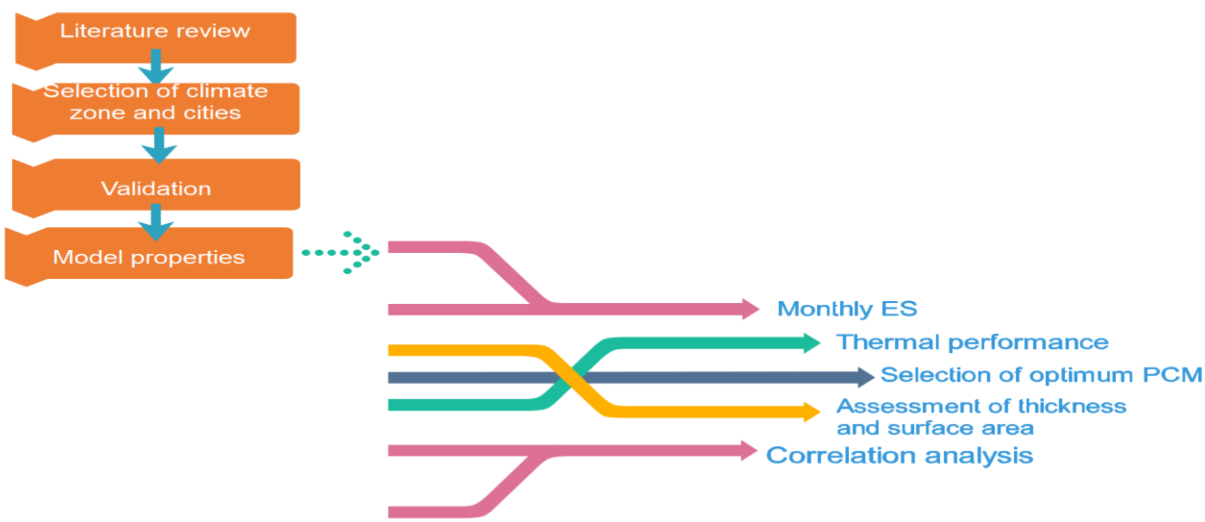


Figure 3.1 Research methodology

3.2. Simulation details

The simulations were performed by using DesignBuilder software, which is recognized as the most extensive and powerful graphical user interface for EnergyPlus [31]. In this research, CondFD was used as it able to simulate the materials with variable thermal properties including PCM. The thermal transfer and storage processes of PCM was taken into account by employing one-dimensional conduction finite difference solution as the heat balance algorithm. To account for phase change energy, this algorithm applies an implicit finite difference scheme combined with an enthalpy-temperature function to account for phase change energy.

$$\frac{\rho C_p \Delta x (T_{i,new} - T_{i,old})}{\Delta t} = \frac{k(T_{i-1,new} - T_{i,new})}{\Delta x} + \frac{k(T_{i+1,new} - T_{i,new})}{\Delta x} \quad (3.1)$$

where ρ-density (kg/m^3), Δx- thickness (m), T- temperature (k), i-node being modeled, Cp-specific heat capacity (kJ/kg K), k- thermal conductivity (kW/m K), Δx- time step (s), i + 1- adjacent node to inside of construction, i – 1- adjacent node to outside of construction,.

In each iteration, the specific heat capacity for the PCM is updated by the following equation:

$$C_P = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \quad (3.2)$$

All simulations were performed by following the guidelines given by Tabares-Velasco et al. for PCM simulations in EnergyPlus [32,33]. The main guidelines were regarding time step and node space. Time step should be less or equal 3 min (in this research 2 min time step have been used) and smaller node space was suggested.

3.3. BWh climate zone

The Koppen-Geiger climate classification (Figure 3.2) is one of the most widely known and used climate classifications. Koppen classification system subdivides world climate into five major types represented by Capital letter (A: equatorial, B: arid, C: warm temperature, D: snow and E: polar). Further subdivision is represented by a second small case letter, which distinguishes specific seasonal characteristics of precipitation and temperature (f: fully humid, s: summer dry, w: winter dry, m: monsoonal). To further represent variation in climate, a third small case letter was added to the code (a: hot summer, b: warm summer, c: cool summer, d: extremely continental, h: hot arid, k: cold arid). The detailed description can be found in Chen and Chen [34].

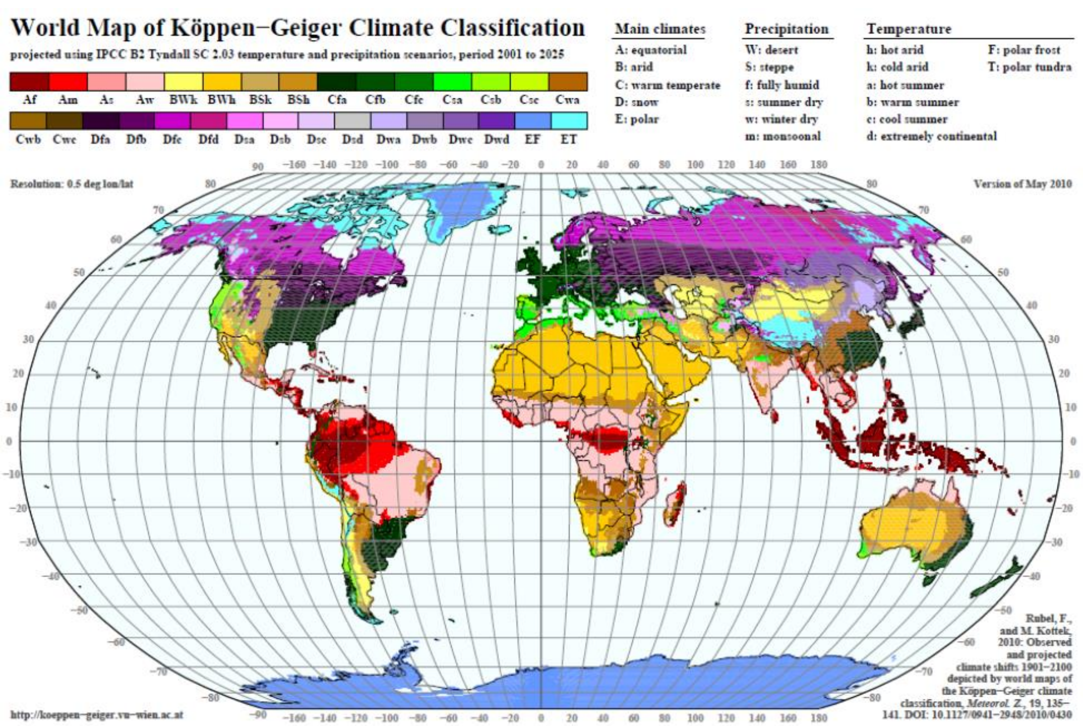


Figure 3.2 Koppen-Geiger climate classification map [35]

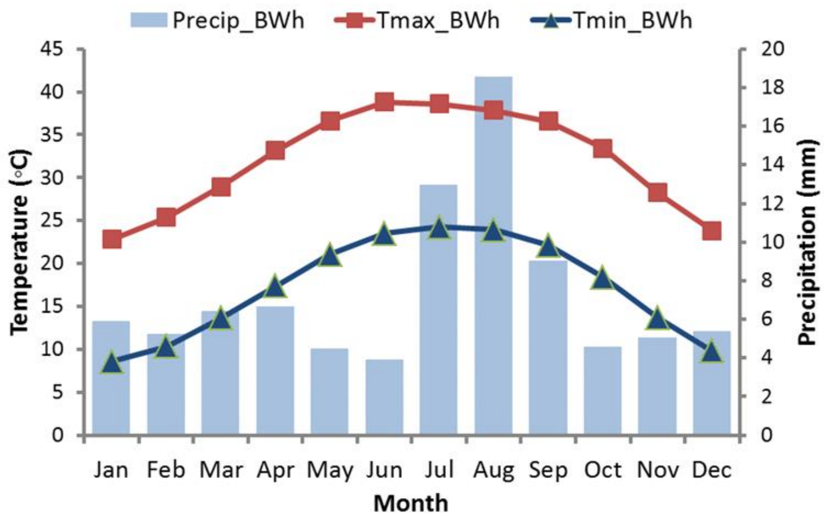


Figure 3.3 Average values of temperature and precipitations for BWh climate zone [36].

In this research, we have chosen BWh climate zone, which represent a hot desert climate. The climate is generally hot, sunny and dry year-round. In summer, the maximum temperature of over 40 °C are common while in winter the temperature seldom falls below freezing point. The average monthly temperature and precipitations values for BWh region are given in the Figure 3.3 [36].

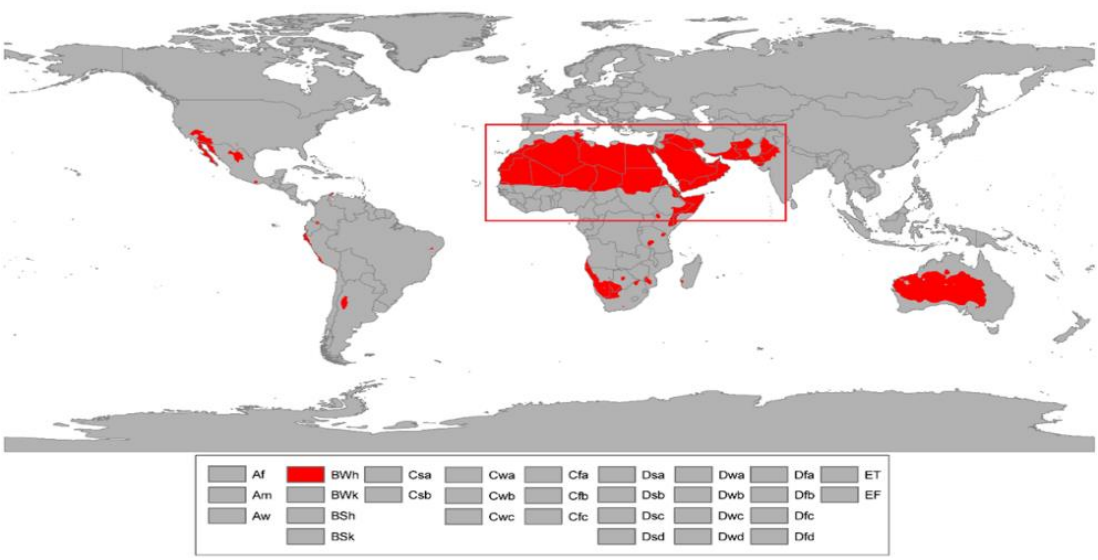


Figure 3.4 Koppen-Geiger BWh climate zone [37]

Eight cities Abu-Dhabi, Biskra, Cairo, Dubai, Faisalabad, Jodhpur, Mecca and Nouakchott located in BWh climate classification were selected (Figures 3.4-3.5). The selection of the cities was based on two main criteria. The first criteria was to cover the whole BWh climate zone and hence the cities located in different countries were chosen while the second criteria was to select the city based on its significance in terms of economy, status and population. The description of the selected cities is given in Table 3.1.

Figure 3.5 Map showing selected cities in BWh climate zone

Table 3.1 Description of selected cities in BWh climate classification

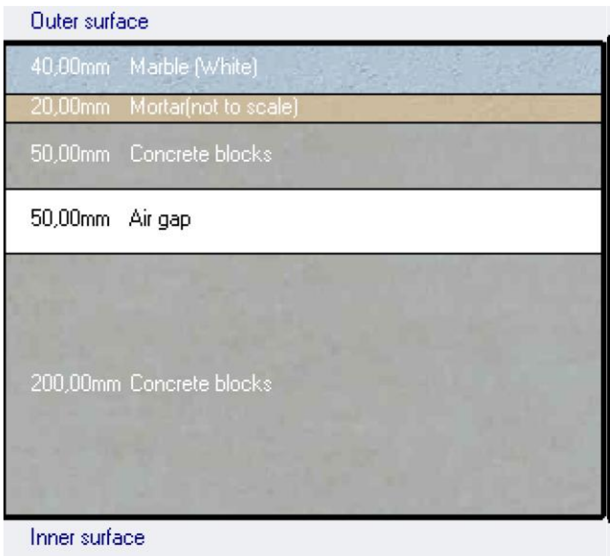
Climate zone	Country	City	Latitude	Longitude	Elevation (m)	Average highest temperature for hottest month (°C)	Average lowest temperature for coldest month (°C)
BWh	United Arab Emirates	Abu-Dhabi	24.28	54.22	6	42.9	13.2
		Dubai	25.03	55.1	3	41.3	14.2
	Algeria	Biskra	34.51	5.43	115	40.9	6.1
	Egypt	Cairo	30.03	31.14	23	34.7	9
	Pakistan	Faisalabad	31.43	73.1	508	41	4.8
	India	Jodhpur	26.16	73	237	41.4	9.6
	Saudi Arabia	Mecca	21.25	39.49	333	43.8	18.8
	Mauritania	Nouakchott	18.05	15.58	10	36.4	13.7

3.4. Building envelope

In this research, a two-story residential house as shown in Figure 3.6 was considered for simulation. The house has a rectangular layout having floor area of 9.15m x 12.2m and height of 5.2m. The windows having size of 2.1m x 2.1m are installed at 1m above the floor level while the door having size of 1.2m x 2.1m is placed on the south side.

Figure 3.6. Model of a Two-story residential house

Different building envelope are being used in BWh climate zone. In Saudi Arabia, the wall consists of marble, mortar, concrete block, air gap and concrete block [38] while in India the wall consists of cement plaster on both the sides of the wall and a dense concrete sandwiched between the cement plaster [39]. In Egypt, the wall is made of red brick and covered by mortar on both sides of the wall [40] (Figure 3.7). The roof composition in Saudi Arabia consists of ceramic tiles, mortar, sandstone, foam insulation, asphalt insulation, reinforced concrete, concrete blocks, plaster [38], in India, the roof consists of cement plaster, reinforced concrete, cement plaster [39] while in Egypt, the roof composition is cement tile, mortar, sandstone and reinforced concrete [40] (Figure 3.8). As mentioned earlier that research is focus on carring out parametric study in BWh zone of Koppen-Geiger climate classification in order to evaluate the hypothesis that a single PCM or a group of PCMs (in the narrow) can be used for the whole BWh climate zone. Hence, the most common/representative construction details, whose thermophysical are known, was selected. The thermophysical properties along with the details of construction of building elements used in this research are represented in Table 3.2 and Figure 3.9 respectively [38-40].

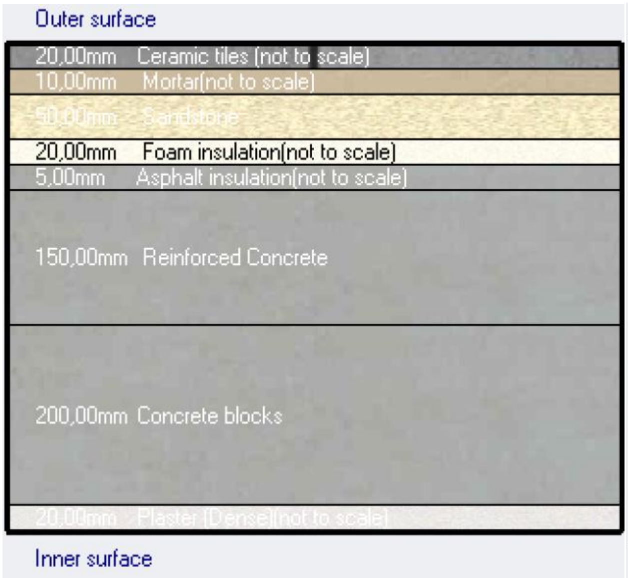


a)Saudi Arabia

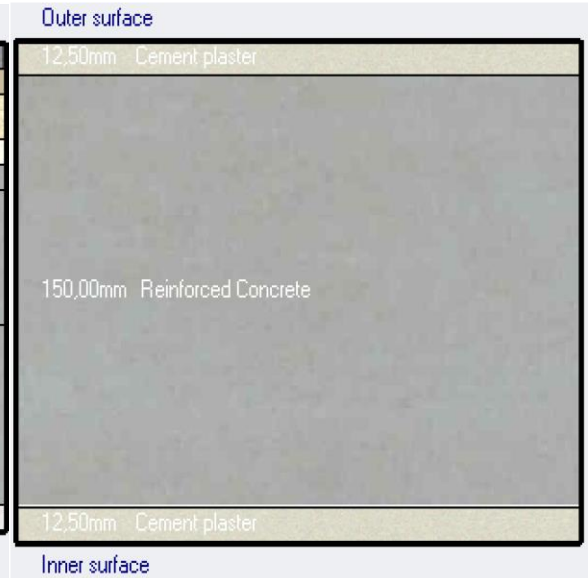
b)India

c)Egypt

Figure 3.7 Wall composition



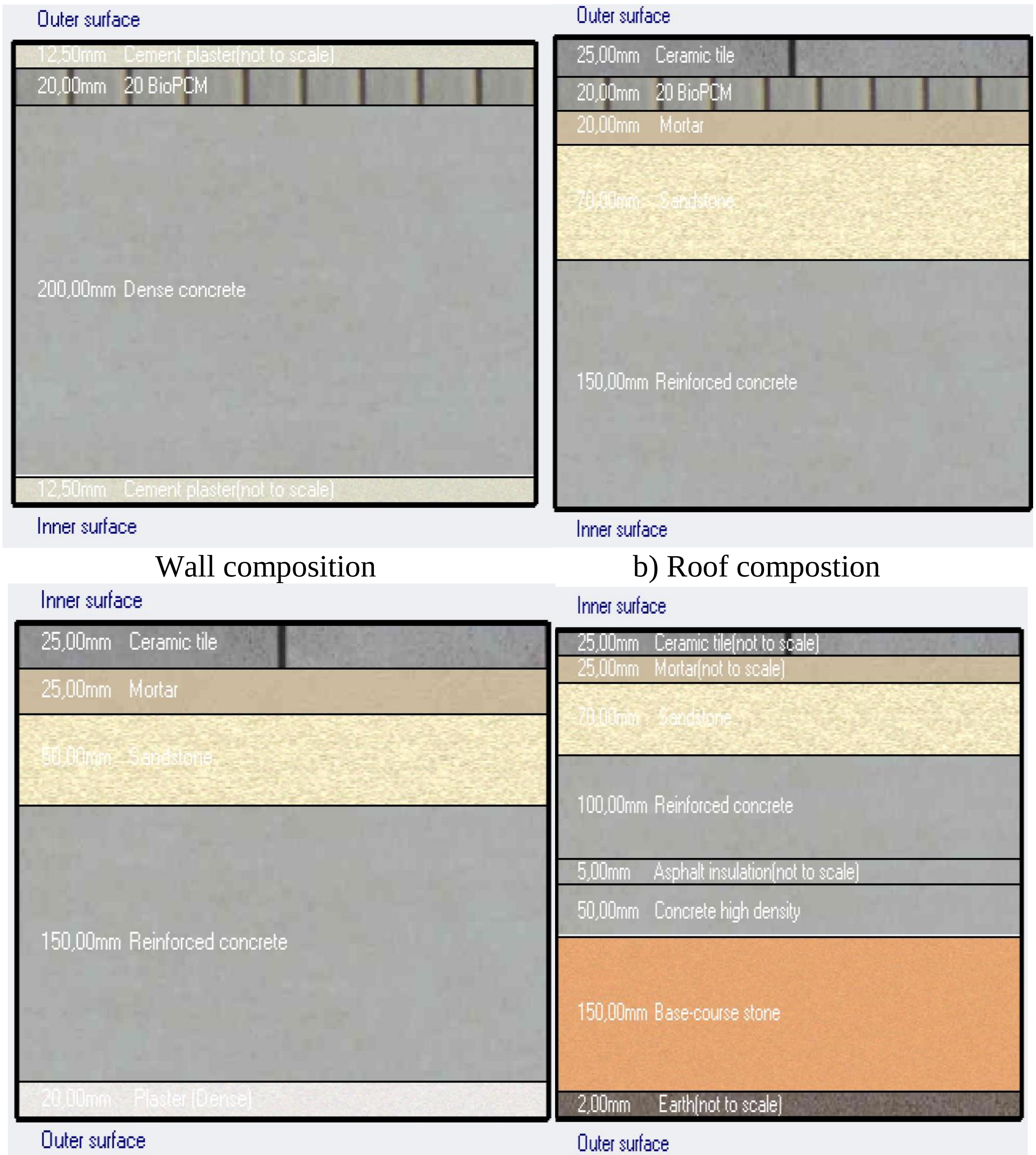
Saudi Arabia



b) India

c)Egypt

Figure 3.8 Roof composition



Wall composition b) Roof compostion

c) Intermediate floor d) Ground floor

Figure 3.9 Details of Wall, Roof, Intermediate and ground floor

Table 3.2. Thermophysical characteristics of building materials [38-40]

Material	Thickness (mm)	Density (kg/m^3)	Conductivity (W/m K)	Specific heat (J/kgK)
Roof				
Ceramic tile	25	2300	1.3	840
PCM	20	860	0.2	1970
Mortar	20	2800	0.88	896
Sandstone	70	2200	1.83	712
Reinforced concrete	150	2300	2.3	1000
Wall				
Cement plaster	12.5	1762	0.721	840
PCM	20	860	0.2	1970
Dense concrete	200	2410	1.74	880
Cement plaster	12.5	1762	0.721	840
Intermediate floor				
Ceramic tile	25	2300	1.3	840
Mortar	25	2800	0.88	896
Sandstone	50	2200	1.83	712
Reinforced concrete	150	2300	2.3	1000
Plaster (dense)	20	1300	0.5	1000
Ground floor				
Ceramic tile	25	2300	1.3	840
Mortar	25	2800	0.88	896
Sandstone	100	2200	1.83	712
Reinforced concrete	100	2300	2.3	1000
Asphalt insulation	5	2100	0.7	1000
Concrete high density	50	2400	2	1000
Base-course stone	150	2000	1.4	1000
Earth	2	1460	1.28	880

In this research, BioPCMs with melting point ranging from 20°C (PCM20) to 32°C (PCM32) were considered. Here, PCM20 means that the melting point of PCM is 20°C. This means that PCM20 would complete the phase change cycle in between 18°C and 22°C. The phase change of PCM was taken into consideration enthalpy-temperature curve as given in [21]. For all other PCMs, the enthalpy-temperature curves were taken by shifting the curve according to PCM melting range. Figure 3.10 shows the enthalpy temperature curves for all PCMs.

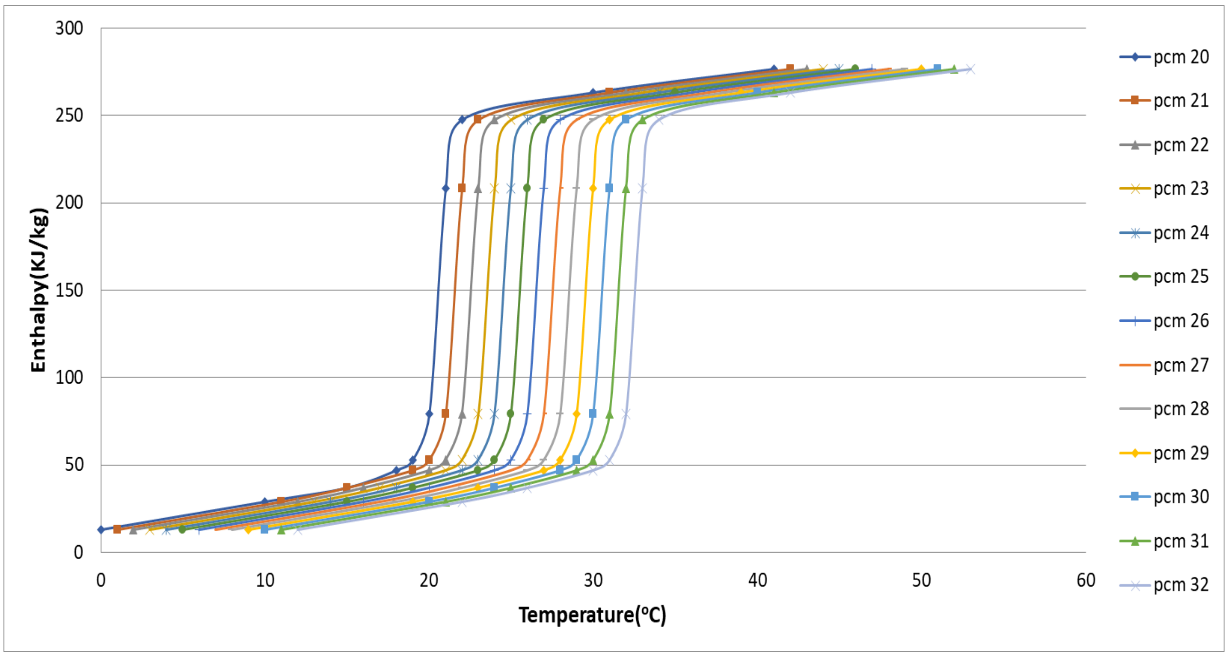


Figure 3.10 Enthalpy-temperature graph for PCM20-32

3.5. HVAC system

The heating and cooling set points (22-30°C) were taken according to the local practice [40]. For energy analysis, heating and cooling energy consumptions were obtained by using Ideal Loads Air System module of EnergyPlus [21] and the schedule for HVAC utilized for residential building (00:00-8:00 and 16:00-24:00 hours) was according to the guidelines given by Saffari et al. [41]. Since it is a comparative study, hence, the selection of the Ideal Loads Air System was based on estimating total energy demand and energy savings of building under different operating conditions.

3.6. Validation

EnergyPlus PCM algorithm was validated analytically, comparative testing and empirically by Tabares-Velasco et al. [32]. Many researchers have been validated the EnergyPlus PCM model against experimental and field data [13, 21, 42-45]. In this research, the model was validated against the data presented in Alam et al. research [21]. For demonstration purpose the comparison of the average temperature fluctuation reduction (ATFR) values for Canberra city with PCM 20 have been given below in the Figure 3.12**.**

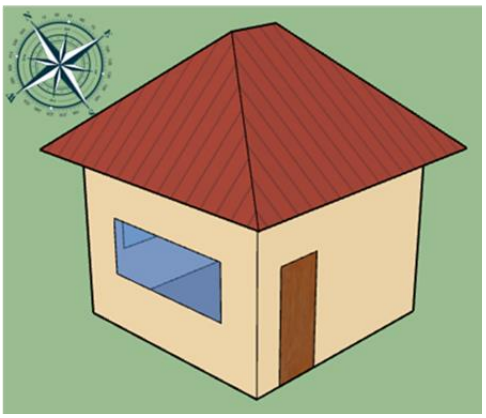


Figure 3.11 Single room model

Average temperature fluctuation reduction was found by calculations (3.3,3.4) :

$$ATFR = \bar{a} + \bar{b} \tag{3.3}$$

$\bar{a}$ –mean daytime temperature decrease

$\bar{b}$ –mean nighttime temperature increase

$$a = t_{noPCM} - t_{PCM}\,; \qquad b = t_{PCM} - t_{noPCM} \tag{3.4}$$

t_{noPCM}- temperature without PCM, t_{PCM} – temperature with PCM.

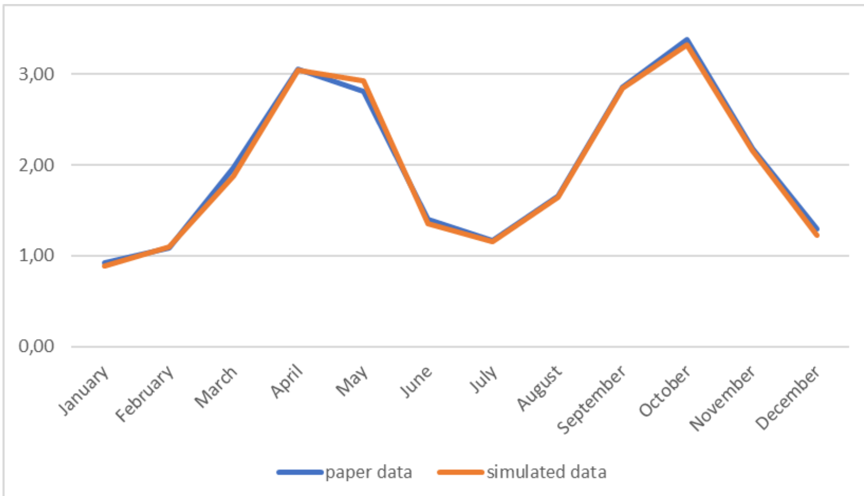


Figure 3.12 Validation results

The difference between the obtained values (ATFR and ECR) and those available in literature [21] were found to be less than 5%. Hence, the developed model can be used to evaluate the performance of PCM incorporated building.

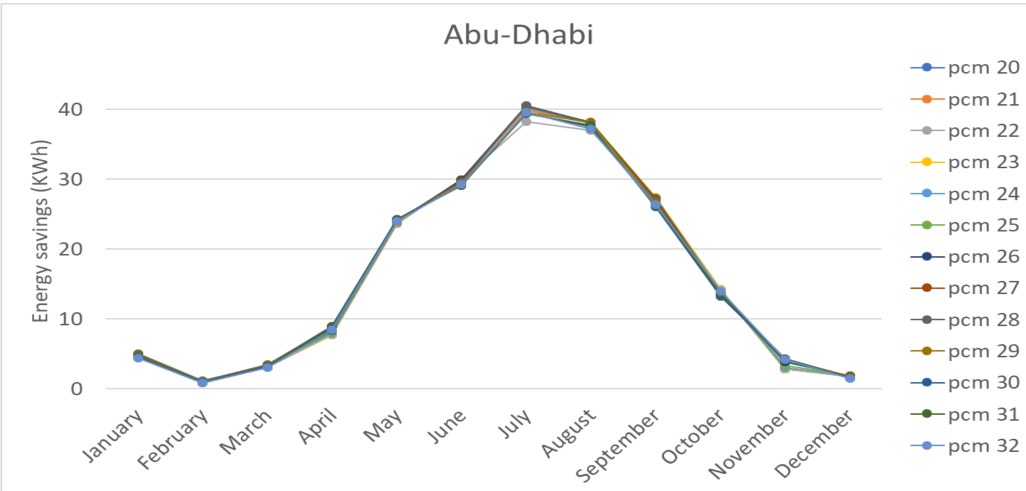
Chapter 4 – Results and discussion

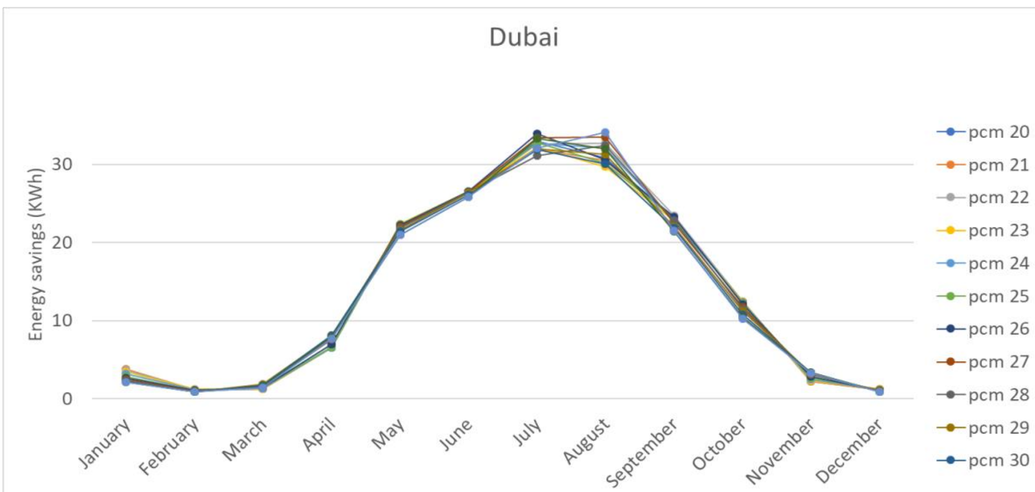
The results of the study have been discussed here. First of all, the effect of PCM on monthly energy savings in eight cities has been analyzed. Afterwards, temperature profiles for months with the highest and lowest energy savings have been plotted in order to see the reason on different energy savings during the year. Then the optimum PCM for each city have been considered and in order to see the reason of such wide range of optimum PCM in whole BWh climate zone, energy consumption of the cities have been observed. After analyzing the optimum PCM for each city, thickness and location comparison have been done. At final step, the influence of meteorological parameters like temperature, wind speed, solar radiance, relative humidity has been evaluated.

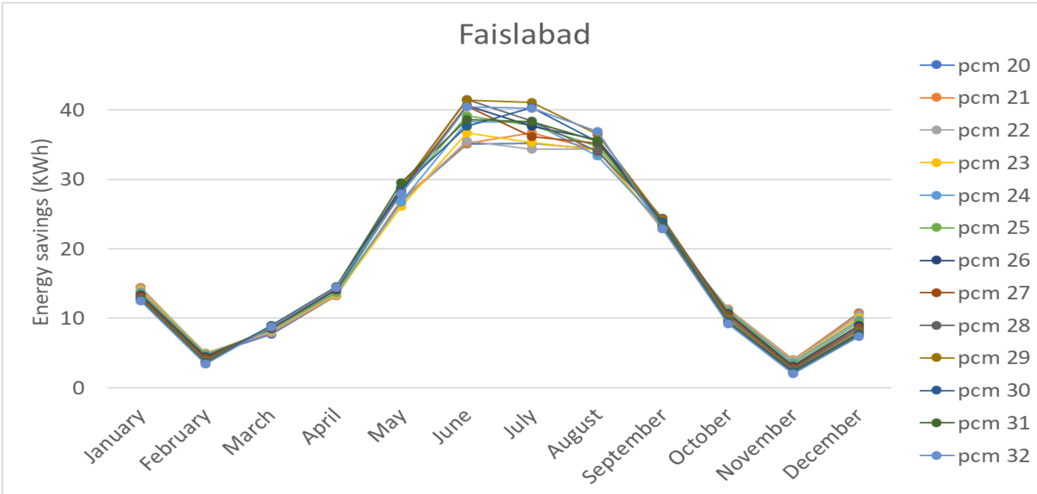
4.1 Effect of PCMs on Monthly Energy savings

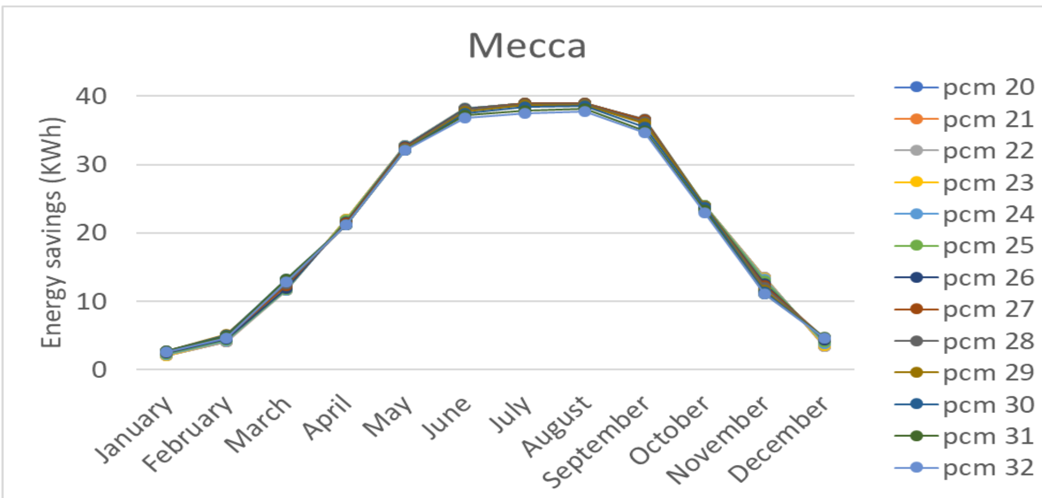
In this section, the energy saving potential of PCM integrated two-story residential house was evaluated by using PCMs ranging from PCM20 to PCM32. The HVAC is controlled based on indoor temperature response and works to hold the temperature within thermal comfort range. Hence, the PCMs with melting point within or close to thermal comfort range are predicted to show better performance. By incorporating the guidelines suggested by [40], the allowable thermal comfort range was set from 22-30ºC and hence the PCMs with melting temperature within or close to this range may possibly show better performance.

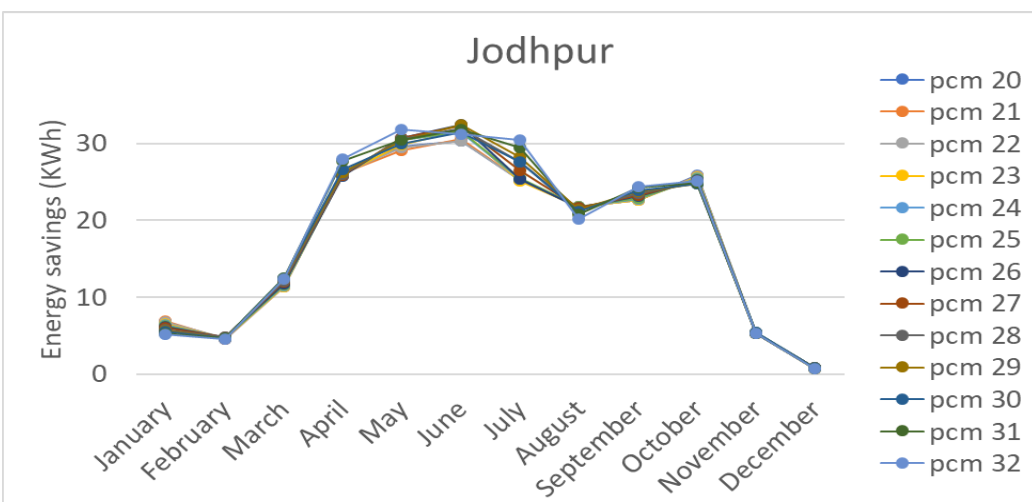
The results of energy efficiency of PCM integrated two-story residential house in terms of monthly energy savings for eight cities are shown in Figure 4.1. For Abu-Dhabi, the energy savings were lower from January to March. In April, the energy savings started to increase and reached peak value of around 41kWh in July. Thereafter, the energy savings started to decrease and averaged around 1.73kWh in December. Similar trend of energy savings was observed in Dubai, Faisalabad, Mecca, Jodhpur and Nouakchott. The maximum energy savings in Dubai, Faisalabad, Mecca, Jodhpur and Nouakchott were in August, June, July, June and September and were equal to 34.11, 41.5, 38.98, 32.4 and 18.3 kWh. As far as Cairo and Biskra are concerned, their pattern of energy savings was similar. In January, the energy savings in these cities were on the higher side. The energy savings started to decrease and showed lower values in April. Thereafter, energy savings started to increase and reached peak values in July (Cairo 18kWh and Biskra 29.6kWh) followed by the decrease in energy savings values and reaching lowest values in October. Finally, the energy savings increased once again and in December averaged around 9.58kWh and 20.97kWh for Cairo and Biskra respectively. Soares et al. [26] used multi-dimensional optimization technique to evaluate the performance of PCM in single-zone living room and found that in temperate climate (C), the energy demand in summer is due to cooling. Overall, the phase change materials are able to decrease the amount of energy required for heating and cooling of buildings.






Faislabad
Energy savings (KWh)
0
10
20
30
40
January
February
March
April
May
June
July
August
September
October
November
December
pcm 20
pcm 21
pcm 22
pcm 23
pcm 24
pcm 25
pcm 26
pcm 27
pcm 28
pcm 29
pcm 30
pcm 31
pcm 32


Mecca
Energy savings (KWh)
0
10
20
30
40
January
February
March
April
May
June
July
August
September
October
November
December
pcm 20
pcm 21
pcm 22
pcm 23
pcm 24
pcm 25
pcm 26
pcm 27
pcm 28
pcm 29
pcm 30
pcm 31
pcm 32


Jodhpur
Energy savings (KWh)
0
10
20
30
January
February
March
April
May
June
July
August
September
October
November
December
pcm 20
pcm 21
pcm 22
pcm 23
pcm 24
pcm 25
pcm 26
pcm 27
pcm 28
pcm 29
pcm 30
pcm 31
pcm 32

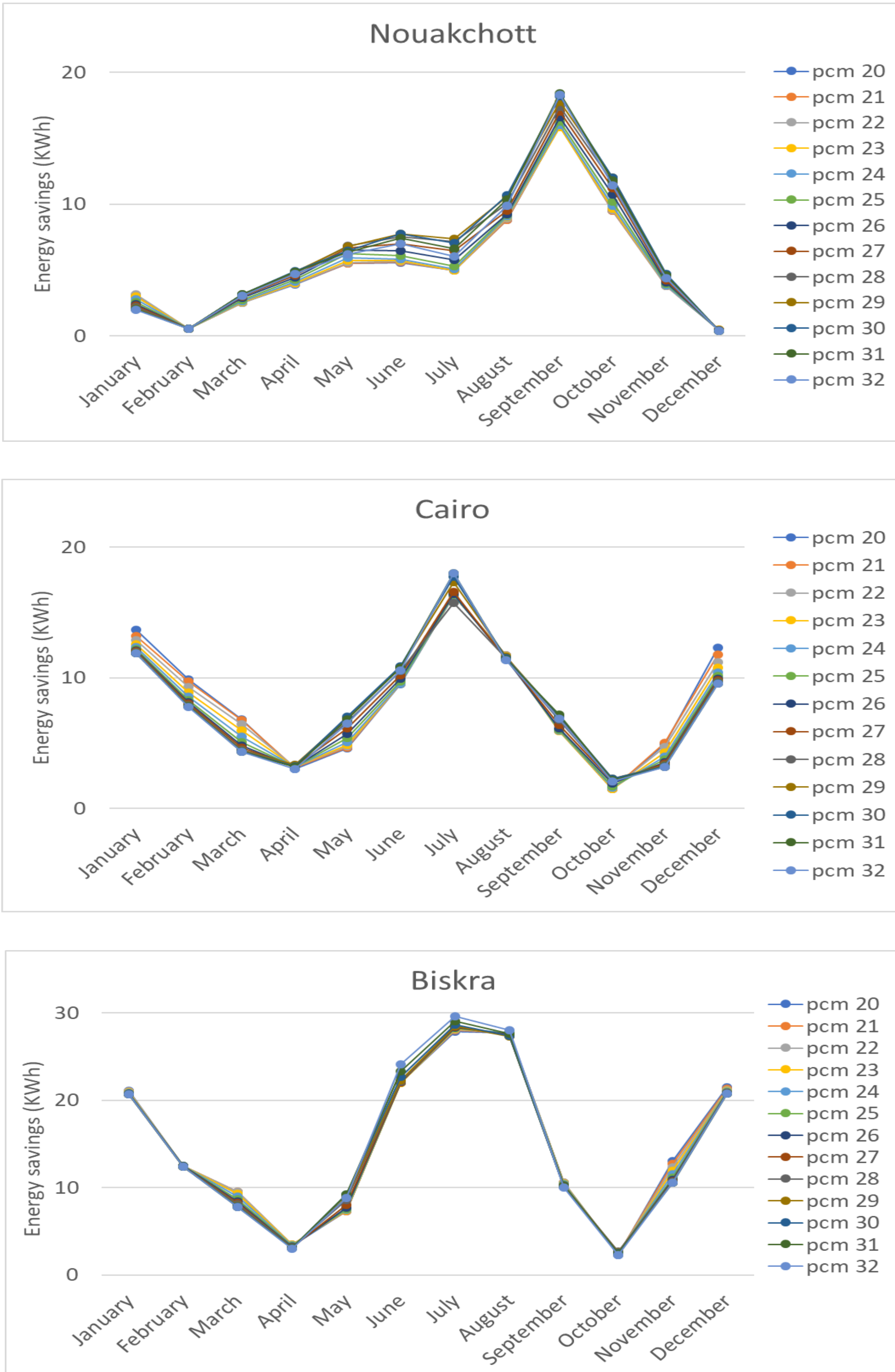
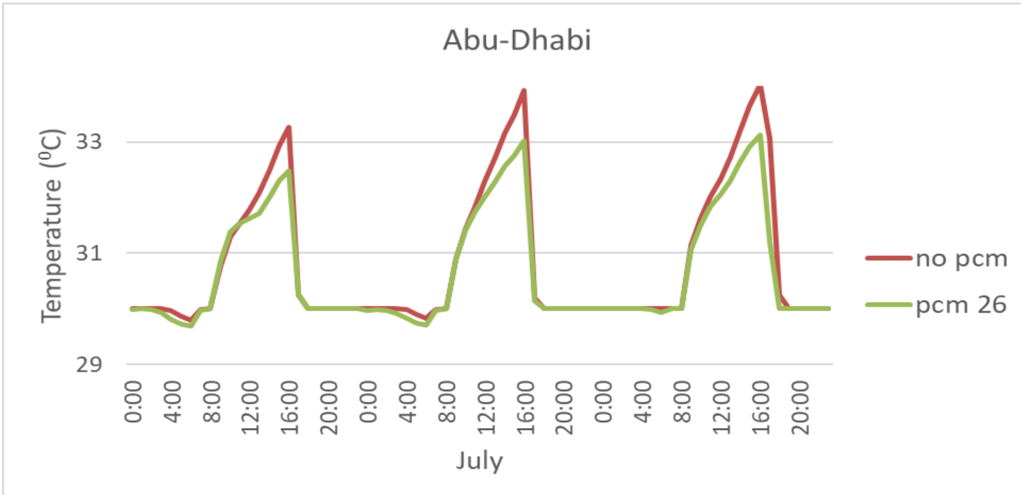


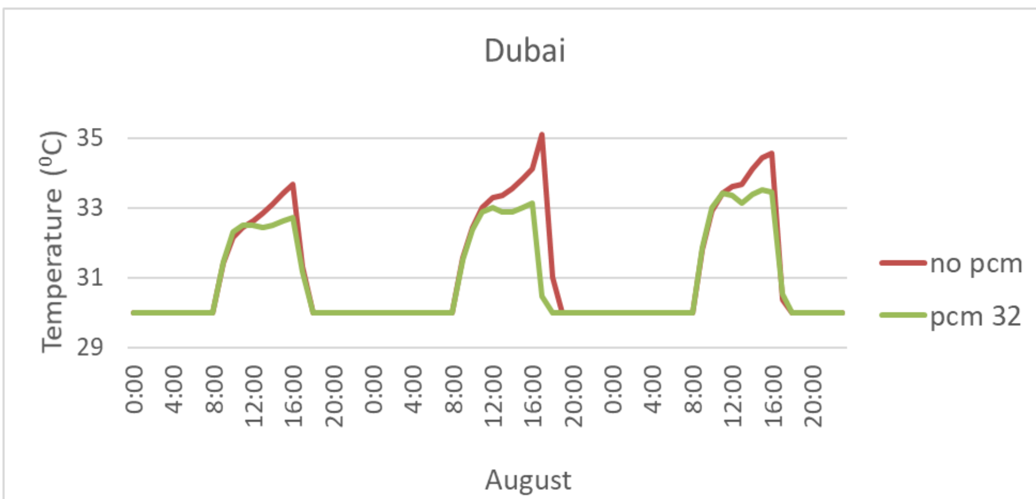
Figure 4.1. Monthly energy savings results for all cities.

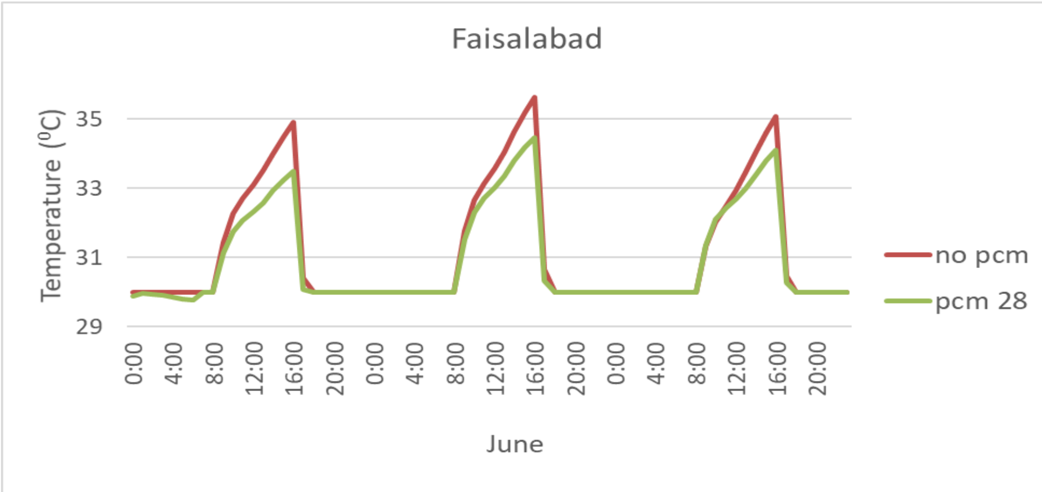
4.2 Effect of Optimum PCM on Thermal performance (HVAC switched on)

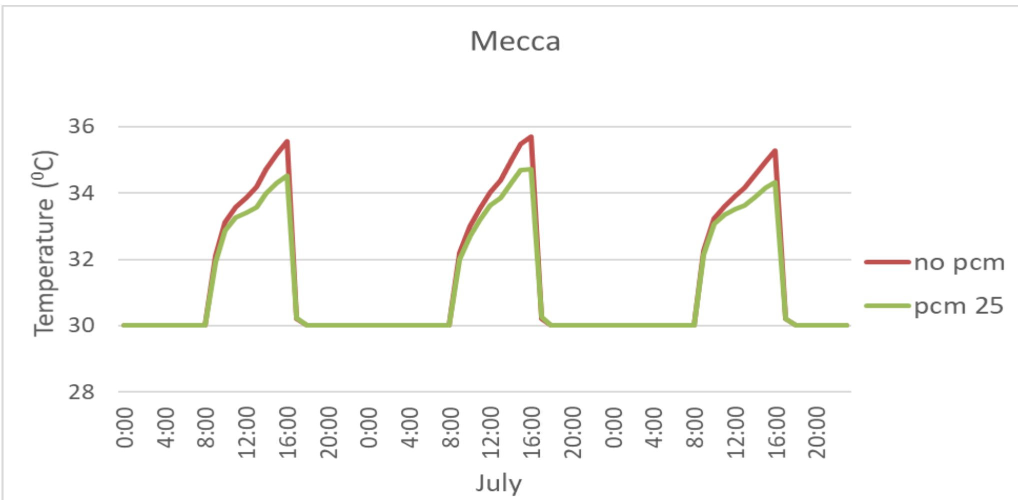
Temperature profiles were plotted in order to explain clearly the relationship between temperature and energy savings. For this purpose, the months, which showed highest and lowest values of energy saving were selected. For each city, two temperature profiles with optimum PCM and without PCM were plotted. The optimum PCM for Abu-Dhabi, Dubai, Faisalabad, Mecca, Jodhpur, Nouakchott, Cairo and Biskra in the months where energy savings were higher, were found to be PCM26, PCM32, PCM25, PCM28, PCM31, PCM32, PCM26 and PCM21 respectively. The results of temperature profile for the months where the energy savings were higher are plotted in Figure 4.2. It can be seen that for all cities, the higher energy savings were in the summer months. The maximum temperature for the residential house without PCM located in Abu-Dhabi, Dubai, Faisalabad, Mecca, Jodhpur, Nouakchott, Cairo and Biskra were found to be 33.06^{o}C, 35.11^{o}C, 34.9^{o}C, 35.56^{o}C, 35.26^{o}C, 31.52^{o}C, 33.31^{o}C and 36.29^{o}C respectively while the maximum temperature in the residential house integrated with optimum PCMs in these cities reached 31.2^{o}C, 30.47^{o}C, 33.5^{o}C, 34.53^{o}C, 34.14^{o}C, 29.44^{o}C, 32.36^{o}C and 35.23^{o}C respectively. This shows that the maximum indoor temperature in these cities dropped by up to 4.64^{o}C. Hence, the part of the cooling load has been taken by the PCM. It was mentioned earlier that the occupancy schedule of HVAC system was from 00:00 to 8:00 and from 16:00 to 24:00 hours. Hence, the above maximum temperature peaks are reached from 08:00 to 16:00 hours. Thus, more energy is consumed for the residential house without PCM to bring the maximum temperature back to thermal comfort range during the selected HVAC schedule (00:00 to 8:00 and from 16:00 to 24:00 hours).

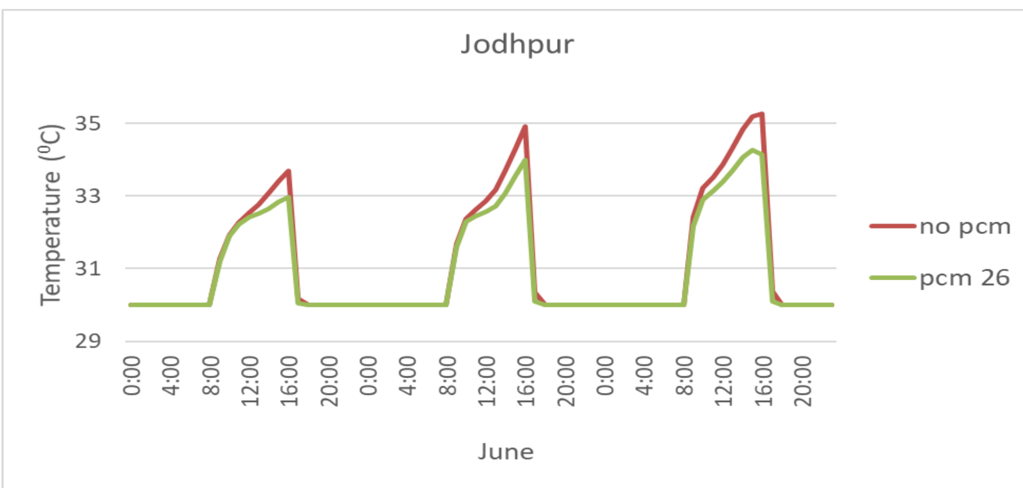
In order to know the reason why the energy savings were lower in certain months, the temperature profiles for residential house integrated with (optimum PCM) and without PCM were plotted. The optimum PCM for Abu-Dhabi, Dubai, Faisalabad, Mecca, Jodhpur, Nouakchott, Cairo and Biskra in the months where energy savings were lower, were found to be PCM24, PCM23, PCM21, PCM29, PCM27, PCM23, PCM29 and PCM28 respectively. The results of temperature profiles during the months are plotted in Figure 4.3. It can clearly be seen that for all cities the indoor temperature was in the thermal comfort range, which in turn, resulted in lower energy savings. Although, the indoor air temperature was in thermal comfort range, still PCM was able to reduce the temperature fluctuation ranging from 0.75 to 1.95^{o}C. For example, in Dubai, the difference between maximum and minimum temperature during the day with and without PCM were 2.04^{o}C and 4.29^{o}C respectively. This shows that despite the lower energy savings, PCM could control the temperature fluctuation; thereby it helps to maintain temperature more stable during the day. Various researchers have shown that PCM are efficient in reducing the maximum indoor temperature as well as indoor temperature fluctuation [13, 46-48].






Faisalabad
Temperature (⁰C)
35
33
31
29
0:00
4:00
8:00
12:00
16:00
20:00
June
no pcm
pcm 28


Mecca
Temperature (⁰C)
36
34
32
30
28
July
no pcm
pcm 25


Jodhpur
Temperature (⁰C)
35
33
31
29
June
no pcm
pcm 26

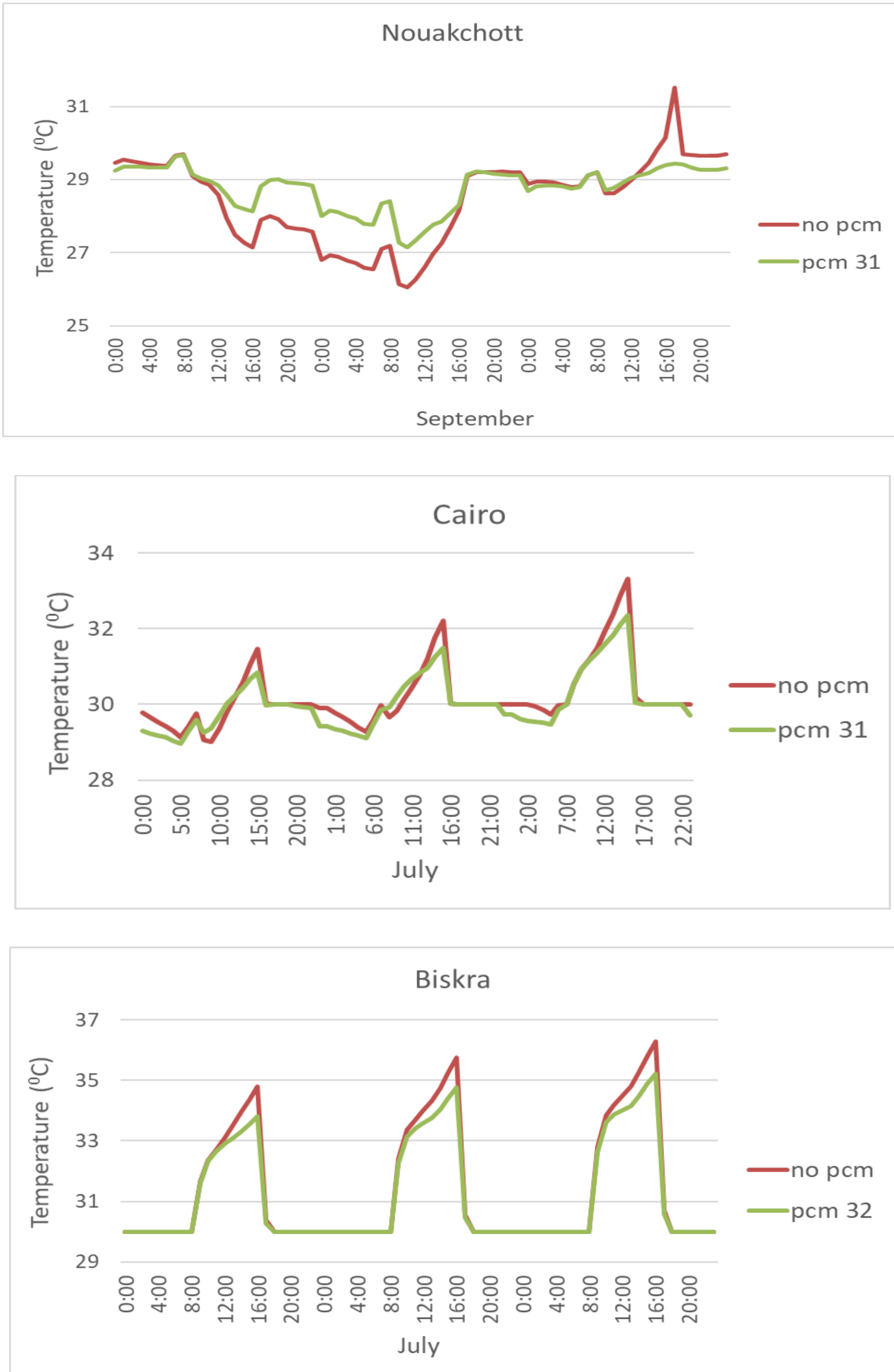
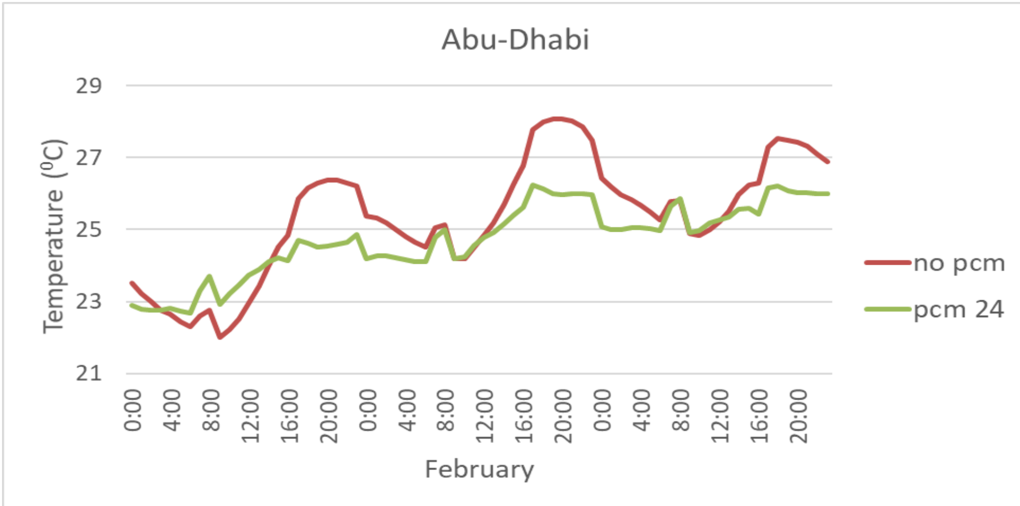
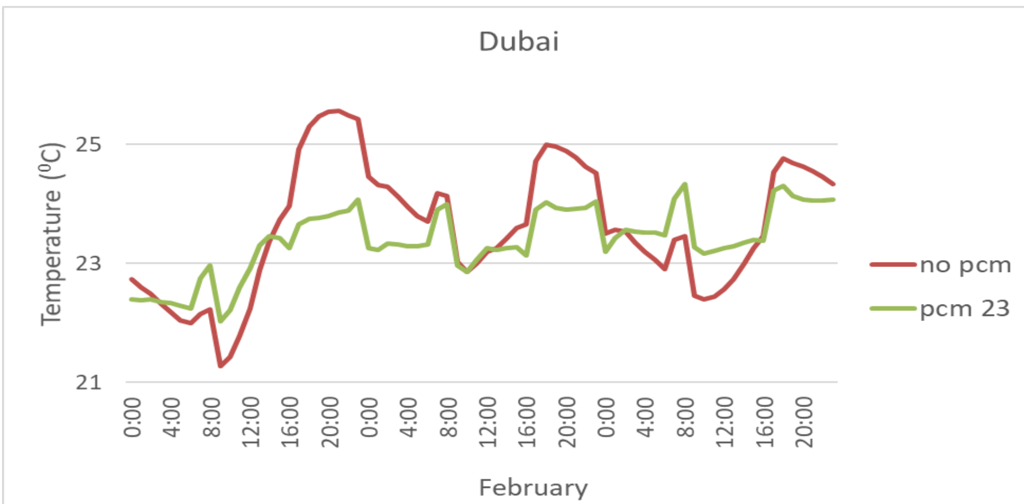
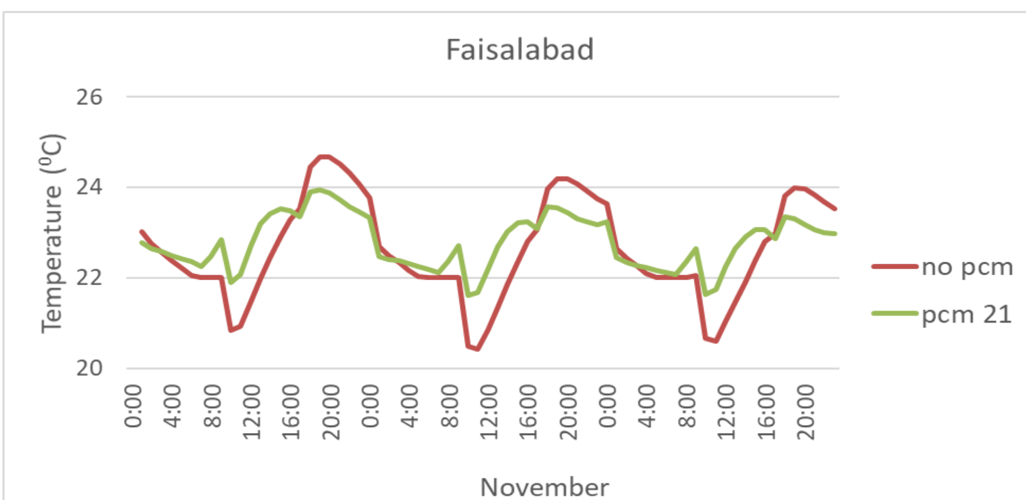
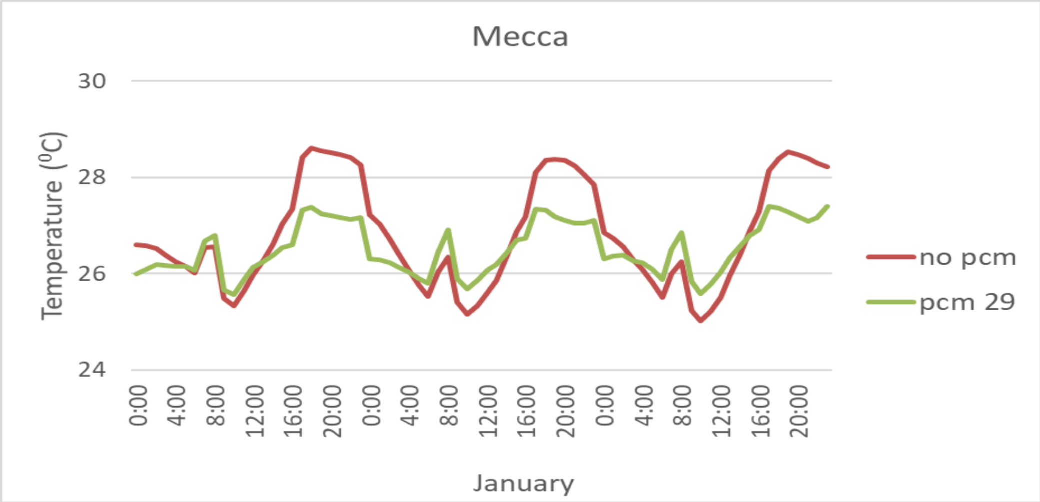


Figure 4.2 Temperature profiles for all cities in months with highest energy savings

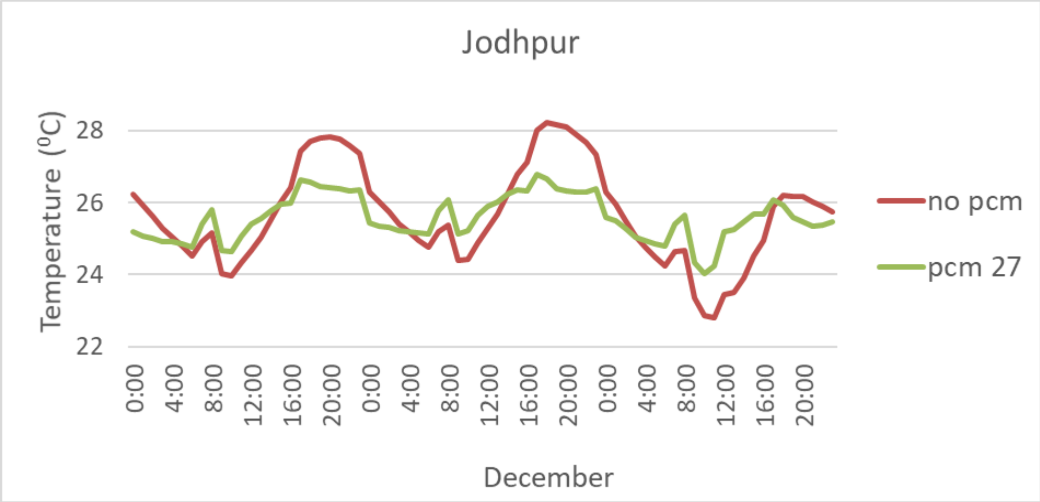

Abu-Dhabi
29
27
25
23
21
Temperature (⁰C)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
February
no pcm
pcm 24


Dubai
25
23
21
Temperature (⁰C)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
February
no pcm
pcm 23

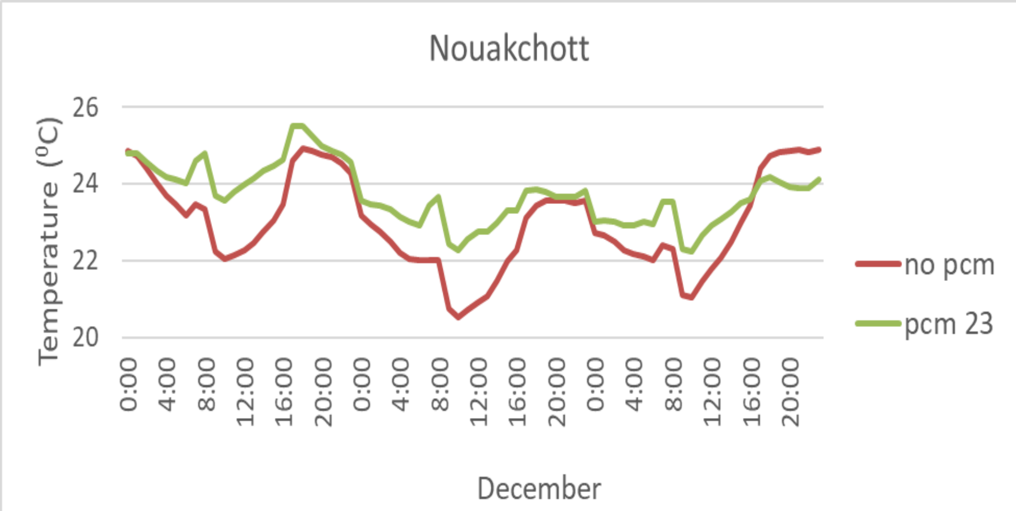

Faisalabad
26
24
22
20
Temperature (⁰C)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
November
no pcm
pcm 21



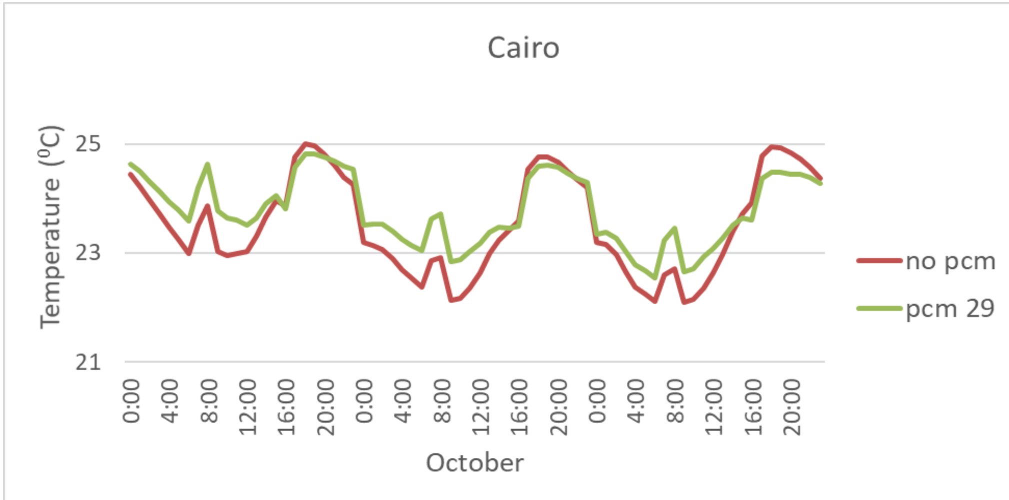
Mecca
30
28
26
24
Temperature (ºC)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
January
no pcm
pcm 29



Jodhpur
28
26
24
22
Temperature (ºC)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
December
no pcm
pcm 27



Nouakchott
26
24
22
20
Temperature (ºC)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
8:00
12:00
16:00
20:00
December
no pcm
pcm 23



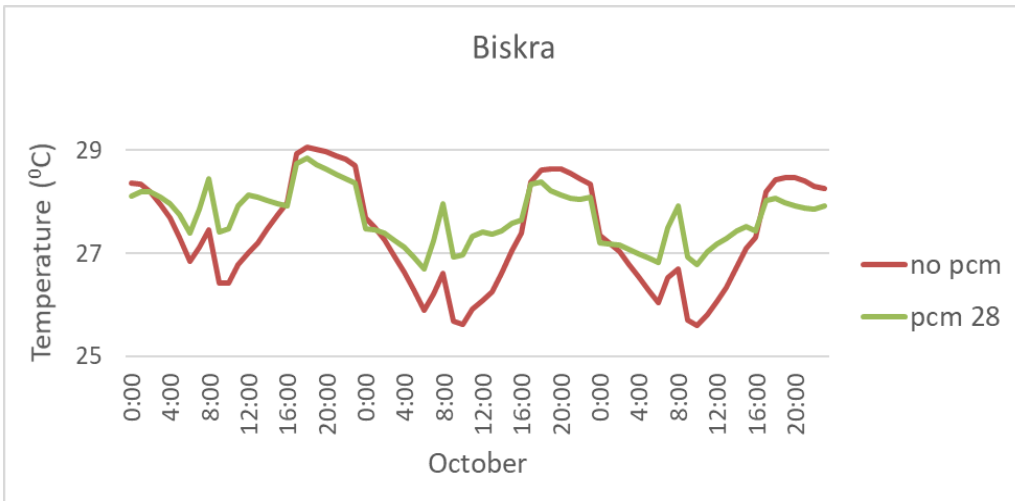
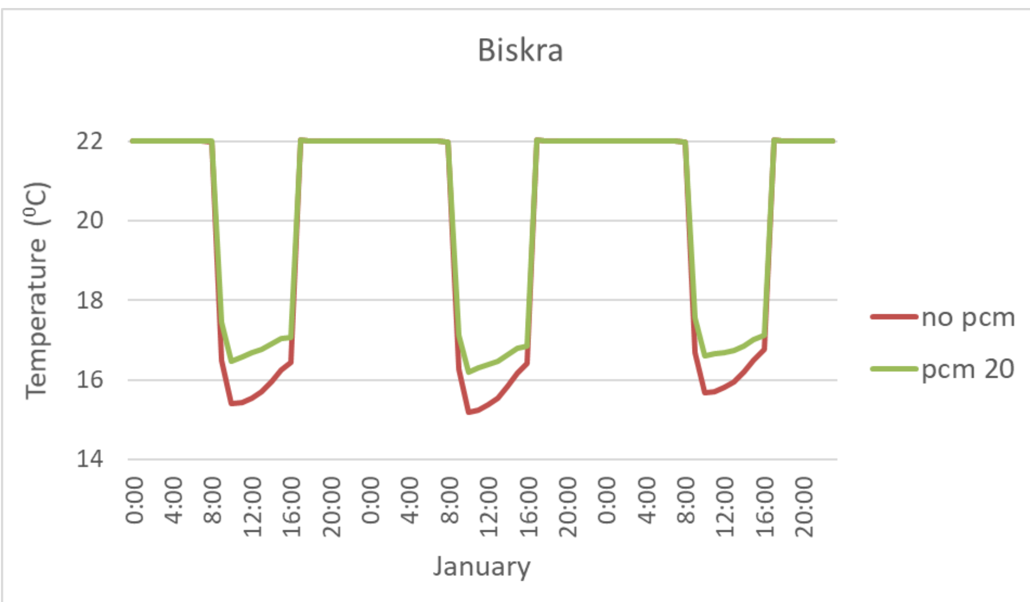


Figure 4.3. Temperature profiles for all cities in months with lowest energy savings

Based on above results, it can be deduced that PCM decreases the temperature peaks and reduces temperature fluctuations during the day and hence it conserves energy and makes comfortable conditions inside the building.

It was mentioned in the last section that for Cairo and Biskra, the energy savings in January were higher when compared with other cities. To find the reason, the temperature profiles for these cities with and without PCM were plotted as shown in Figure 4.4. For Cairo and Biskra, the temperature in residential house without PCM dropped up to 17.15^{o}C and 15.18^{o}C while the temperature in residential house with PCM dropped up to 18.03^{o}C and 16.18^{o}C respectively. This shows that in comparison to house with PCM, more heating energy is required for the house without PCM to bring it back to thermal comfort zone. The higher values of minimum temperature suggest that during the cooling process, the residential house integrated with PCM is releasing more heat than the house without PCM. This feature is beneficial for application in building where PCM walls can be applied for absorbing and releasing the heat during day and night when there are no heat sources inside [49, 50].



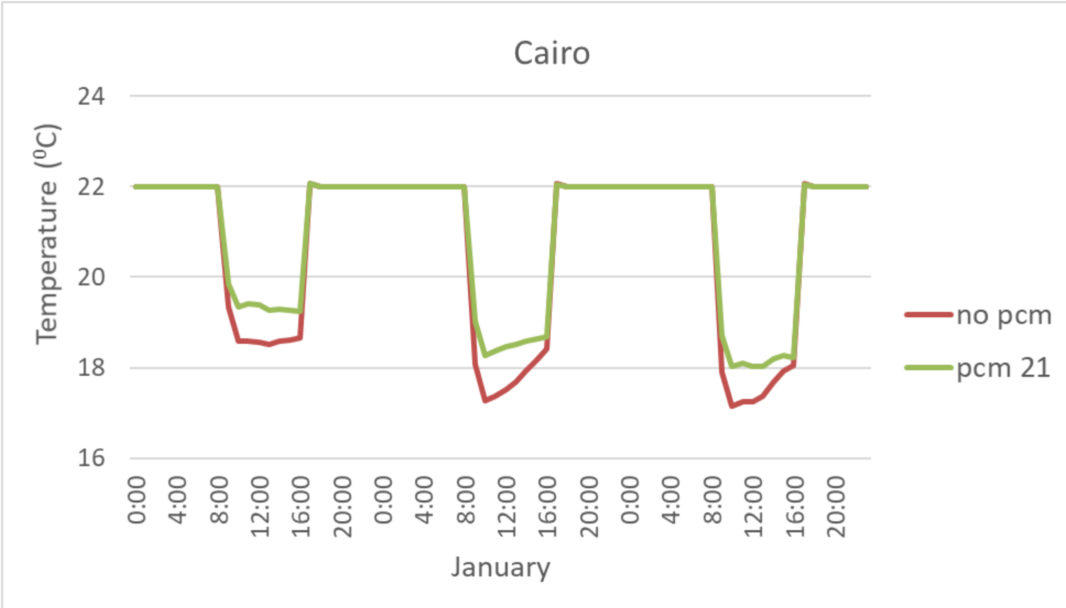


Figure 4.4 Temperature profiles for January in Cairo and Biskra

4.3 Selection of Optimum PCM

As a result of energy analysis, it can clearly be seen that PCMs perform variously in each month and it is difficult to select one PCM which shows best energy saving results. Hence, in order to find the optimum PCM, the energy saving potential of PCM integrated two-storey residential house for the whole year was evaluated. For Abu-Dhabi, Dubai, Faisalabad and Mecca, the optimum PCMs were found to be PCM27, PCM27, PCM29 and PCM27, and were in the thermal comfort range (22^{o}C-30^{o}C) while for Nouakchott and Jodhpur, the optimum PCMs were found to be PCM31 and PCM32 which are close to upper limit of thermal comfort range. Saffari et al. [30] performed the energy analysis of mid-rise apartment located in Abu-Dhabi, Jaisalmer and Phoenix. For the selected cities with the thermal comfort range set from 20^{o}C to 26^{o}C, the optimum PCM was found to be PCM26. This shows that selection of optimum PCM is also contingent upon the selection of thermal comfort range. In the same literature, the authors concluded that, in general, PCM with higher melting points perform better in cooling dominant climate. Solgi et al. [51] performed energy analysis of a room (8 x 6 x 2.7 m^3) located in Bandar Abbas with heating and cooling points set according to the Building code of Iran (20^{o}C-25^{o}C). For the selected city, the PCM showing highest energy savings was found to be PCM27 and was close to the cooling set point. As far as Cairo and Biskra are concerned, the optimum PCM for these cities was located near the lower limit of thermal comfort range. In order to find the reason, the results of heating and cooling energy consumed by residential house located in these cities were plotted (Figure 4.5). It can be seen that heating energy required by these cities represent substantial portion of total energy consumed. The heating requirement in Cairo and Biskra was around 62% and 51% of the total energy consumed. The results are in line with the findings of Saffari et al. [30] where they found that for heating dominant climate, the optimum PCM are close to heating set point. Hence, It can be concluded that although the eight cities are located in one climate zone, but the optimum PCM are different for most of the cities.

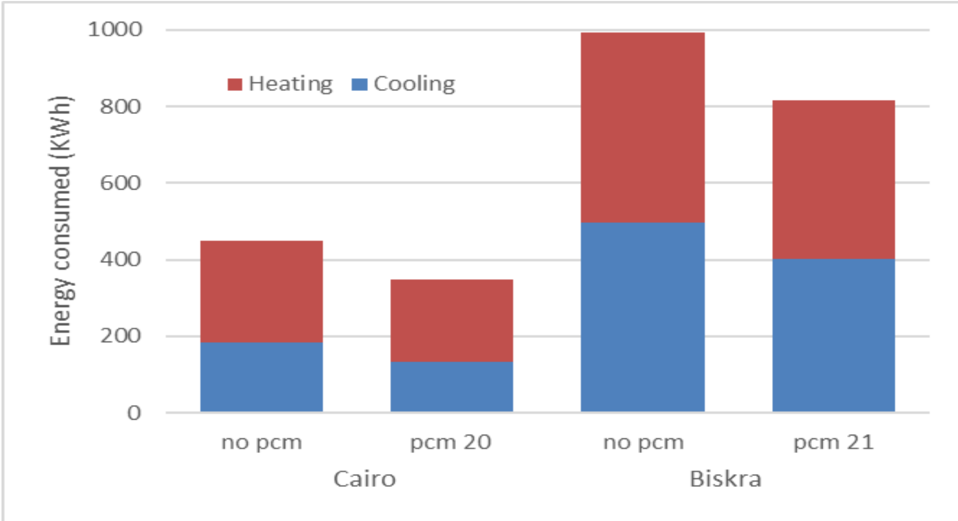


Figure 4.5 Annual energy required for heating and cooling of residential house located in Cairo and Biskra

4.4 Annual energy consumption and Energy savings

For demonstration purpose, the results of annual energy consumed for heating and cooling by a two-story residential house located in Mecca, Abu-Dhabi, Jodhpur and Dubai are plotted (Figure 4.6). Figure 4.6 shows that more energy is required for cooling rather than for heating and even there is no heating in Mecca. This is due to the hot desert climate, which throughout the year are generally hot, sunny and dry. Moreover, according to Figure 4.3, in winter, the temperature inside the building remain within thermal comfort range and hence less energy is required for heating. For the three cities considered in Arid climate condition, Saffari et al. [30] found that PCM was effective in reducing high cooling demand. In another research conducted by Marin et al. [27], it was concluded that PCM has significant potential in Dry climate (B). It can also be seen that for Mecca, Abu-Dhabi, Jodhpur and Dubai, the residential house without PCM consume 1389.43 kWh, 979.78 kWh, 1104.09 kWh and 927.02 kWh for heating and cooling while for these cities, the residential house integrated with optimum PCM, required approximately 20% less energy. Consequently, PCM incorporation into building walls is an effective method for improving the energy efficiency of buildings.

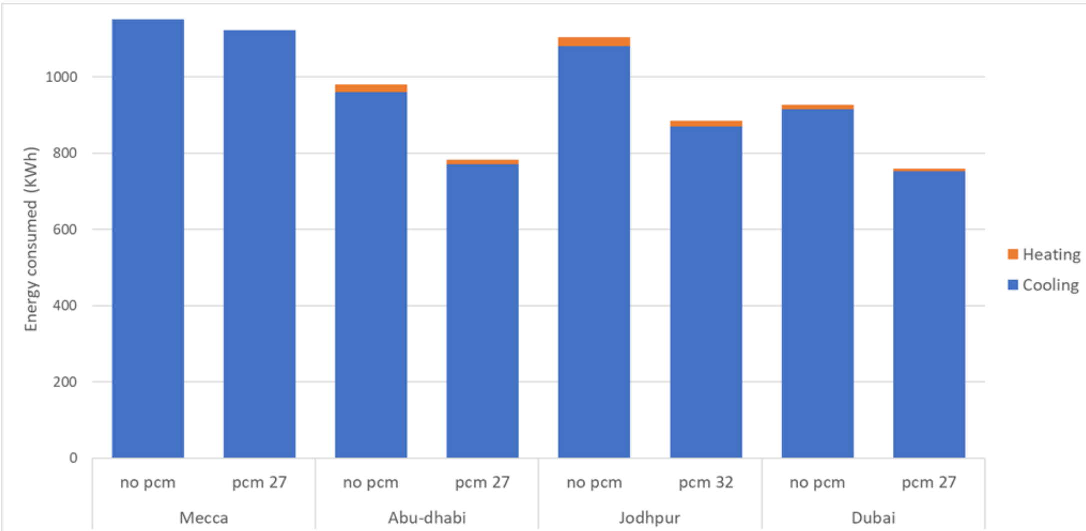


Figure 4.6. Annual energy required for heating and cooling of residential house located in Mecca, Abu-Dhabi, Jodhpur and Dubai

The results of total annual energy saving along with energy consumption reduction (ECR) calculated by using the Equation 4.1 for all cities are shown in Table 4.1.

$$ECR = \frac{EC\ (no\ PCM) - EC\ (PCM)}{EC\ (no\ PCM)} x100\% \quad (4.1)$$

Where ECR- energy consumption, EC -energy consumption.

Table 4.1 Annual Energy savings and Energy consumption reduction for all cities

City	Optimum PCM	ES (kWh)	ECR (%)
Cairo	PCM 20	100.17	22.29
Biskra	PCM 21	178.59	17.97
Dubai	PCM 27	166.62	17.97
Abu-Dhabi	PCM 27	196.83	20.09
Mecca	PCM 27	266.67	19.19
Faisalabad	PCM 29	232.56	20.43
Nouakchott	PCM 31	76.40	34.26
Jodhpur	PCM 32	219.27	19.86

The energy savings varied from 76.40 to 266.67 kWh while ECR ranged from 17.97 to 34.26%. For the three cities (Abu Dhabi, Jaisalmer and Phoenix) located in BWh climate classification and with thermal comfort range 20^{o}C-26^{o}C, Saffari et al. [30] found that ECR values varied from 1.4 to 2.7%. Solgi et al. [51] considered the energy saving potential of a room located in Bandar Abbas with thermal comfort range 20^{o}C-25^{o}C. The authors found that total energy consumption reduced by 10.9%. For a single room located in Abu Dhabi with thermal comfort range 18^{o}C-25^{o}C, Marin et al. [27] found that energy saving was on the lower side and was less than 60 kWh. Although, thermal comfort range selected in this research (22^{o}C-30^{o}C) is representing the local climate zone and is higher than mentioned in above literature, still the ECR values found are on the higher side. As far as the lower energy savings in Nouakchott and Cairo are concerned, it can be explained by the fact that in these cities, the temperature inside the residential house for some duration in summer months remained in thermal comfort range (Figure 4.2). Although, ECR for Nouakchott was on the higher side, however, as pointed out by Saffari et al. [30], higher percentage of savings does not necessary translate into higher energy savings. Hence, the results should be interpreted carefully.

4.5 Assessment of different Thickness

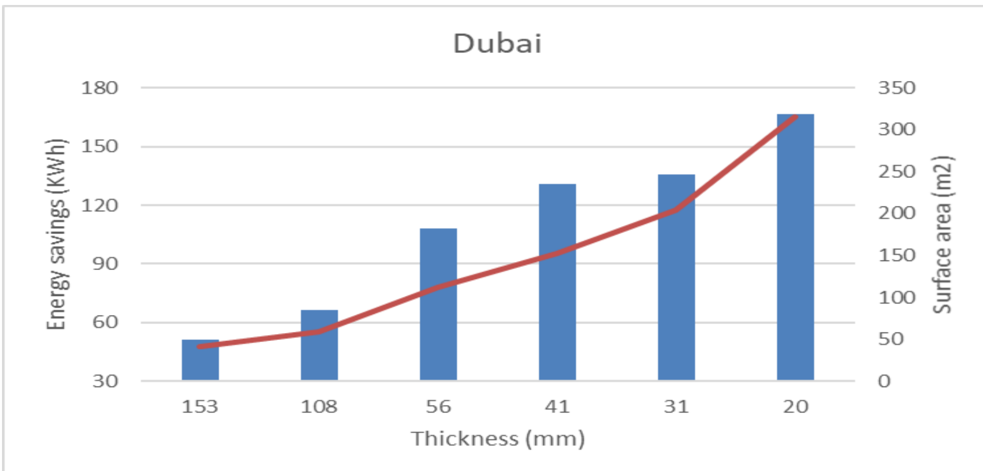
The impact of thickness of PCM layer was evaluated by using optimum PCM for each city. For this purpose, relative differences between energy savings and ECR values with thickness varying from 10 mm to 50 mm were considered. For demonstration purpose, only the results of four cities (Jodhpur, Abu-Dhabi, Mecca and Biskra) are shown (Table 4.2). It can be seen that energy savings increased with the increase in the thickness of PCM layer. It is due to the increasing quantities of heat that is absorbed by the PCM layer. The results are in line with Lei et al.'s research [23] where for Singapore, the authors evaluated the effect of increase in thickness of PCM layer on energy savings and found that energy savings increased with the increase in the thickness of PCM layer. By looking at the relative increase in energy saving and ECR values, the PCM with thickness of 20 mm is the most optimum option. It is pertinent to mention here that for all other cities, the efficiency of 20mm thick PCM layer was found to be optimum.

Table 4.2 Energy savings as a function of PCM thickness

City	Thickness (mm)	ES, KWh	Relative difference, KWh	ECR,%	Relative difference,%
Jodhpur	10 mm	115.68	-	10.48	-
	20 mm	219.27	103.59	19.86	9.38
	30 mm	287.27	68.00	26.02	6.16
	40 mm	338.67	51.40	30.67	4.65
	50 mm	359.55	20.88	32.57	1.9
Abu-Dhabi	10 mm	115.69	-	11.81	-
	20 mm	196.83	81.14	20.09	8.28
	30 mm	262.39	65.56	26.78	6.69
	40 mm	311.30	48.91	31.77	4.99
	50 mm	351.07	39.77	35.83	4.06
Mecca	10 mm	152,78	-	11,00	-
	20 mm	266,67	113,89	19,19	8,20
	30 mm	354,9	88,23	25,54	6,35
	40 mm	433,05	78,15	31,17	5,62
	50 mm	491,39	58,34	35,37	4,20
Biskra	10 mm	103,89	-	10,45	-
	20 mm	178,59	74,7	17,97	7,52
	30 mm	240,33	61,74	24,18	6,21
	40 mm	284,22	43,89	28,60	4,42
	50 mm	332,8	48,58	33,48	4,89

4.6 Assessment of Surface Area on Energy Savings

The effect of surface area on annual energy savings were considered in this section. For demonstration purpose, only the results of two cities (Dubai and Mecca) are presented. In order to make a comparison, the volume of PCM layer remain the same. The results are presented in Figure 4.7. It can be seen that energy saving increased with the increase in the surface area and decreased with the increase in the thickness of PCM layer. It is believed to be because of the fact that increase in surface area causes efficient heat transfer rate between PCM and the residential house [21]. Furthermore, thinner layers are more efficient during melting-freezing cycle [23]. The results are also in line with the findings of Alam et al. [21]. According to the above discussion, it can be concluded that the most efficient case of implementing PCM will be 20mm layer in the walls and roof of residential house.



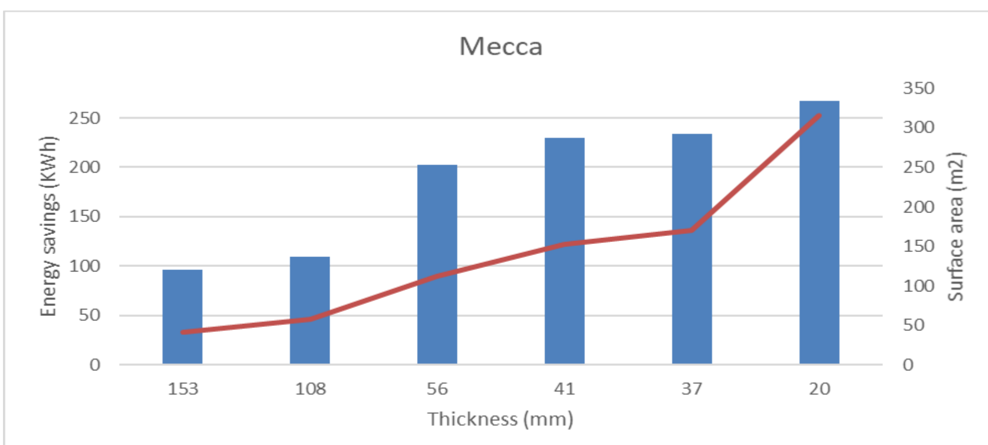


Figure 4.7. Relationship between energy savings in Dubai and Mecca for different PCM surface area with constant volume

4.7 Impact of wind speed, temperature, solar radiation and relative humidity on energy savings

Koppen-Geiger climate classification remains one of the most widely used climate classification systems [52]. However, it does not take into account several factors such as relative humidity, daily temperature, wind speed, sunshine duration, precipitation intensity, altitude, amount of cloud cover [30, 51]. Therefore, in this section, the influence of several meteorological parameters like wind speed, temperature, solar radiation and relative humidity on the energy saving potential of PCM integrated buildings has been evaluated. For this purpose, one-year data of mean monthly values of energy saving, wind speed (V), temperature (T), solar radiation (R) and relative humidity (H) has been taken (Table 4.3). Mean monthly values of energy savings are taken as dependent variable while wind speed, temperature, solar radiation and relative humidity are taken as independent variables.

Table 4.3 Mean monthly meteorological values for Abu-Dhabi, Dubai, Jodhpur and Mecca

Month	ES (KWh)	V (m/s^2)	T (^oC)	R (w/m^2)	H (%)
Abu-Dhabi					
January	4,85	3,04	18,01	167,97	64
February	1,03	3,45	19,93	185,3	58
March	3,38	3,89	22,24	161,17	51
April	8,61	3,81	26,53	173,38	43
May	24,03	4,21	30,81	226,05	39
June	29,76	4,15	32,81	223,72	46
July	40,45	3,61	34,45	202,88	46
August	38,03	3,7	34,8	209,05	44

September	27,21	3,71	32,55	201,34	51
October	13,55	3,49	28,58	203,19	54
November	4,19	2,99	24,36	177,43	58
December	1,74	3,65	20,1	160,53	64
Dubai					
January	2,47	2,95	19,24	75,36	63
February	1	3,66	20,75	71,44	62
March	1,63	3,48	23,12	82,11	59
April	7,6	3,36	26,49	91,95	51
May	22,08	3,3	31,36	113,46	46
June	26,48	3,95	32,97	116,88	53
July	33,42	3,85	35,08	112,12	52
August	33,49	3,89	35,31	109,83	51
September	22,52	3,64	32,49	101,45	57
October	11,77	3,16	29,53	100,6	58
November	3,1	2,98	25,53	87,42	59
December	1,06	2,84	21,13	73,15	63
Jodhpur					
January	5,18	0,94	17,31	81	81
February	4,54	1,13	20,17	77	77
March	12,32	1,06	25,65	70	70
April	28,04	1,16	30,98	51	51
May	31,87	1,84	34,85	48	48
June	31,25	2,18	34,87	60	60
July	30,49	1,77	31,62	79	79
August	20,14	1,15	29,09	83	83
September	24,12	1,19	29,78	82	82
October	25,09	0,49	29,27	72	72
November	5,31	0,58	23,21	69	69
December	0,71	0,96	19,36	78	78
Mecca					
January	2,56	1,53	24,25	81,7	56
February	4,74	1,75	24,91	82,24	52
March	12,26	2,07	27,49	103,63	45
April	21,39	1,89	31,01	103,55	38
May	32,54	1,92	34,46	109,78	33
June	38,09	1,44	35,74	122,53	28
July	38,95	1,48	35,89	119,49	31
August	38,94	1,85	35,68	111,01	37

September	36,48	1,3	35,1	104,77	40
October	23,92	1,33	31,69	104,39	47
November	12,26	1,19	28,98	86,91	52
December	4,54	1,58	25,1	75,6	56

For demonstration purpose, Abu-Dhabi, Dubai, Jodhpur and Mecca cities were selected. From bivariate correlation analysis, the correlation coefficients were determined (Equation 4.2) and are enlisted in Table 5.

$$R(x,y) = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (4.2)$$

Where, n – Sample size; x and y – independent and dependent variables; $\bar{x}$ and $\bar{y}$ - means of two variables.

Table 4.4 Correlation coefficients for selected cities

Cities	V(m/s)	T(^{0}C)	R (w/m^2)	H (%)
Abu-Dhabi	0.43	0.94	0.91	-0.74
Dubai	0.73	0.95	0.79	-0.68
Jodhpur	0.62	0.96	-0.17	-0.49
Mecca	-0.08	0.99	0.91	-0.91

According to Table 4.4, for all cities, strong correlation exists between energy savings and temperature. For Abu-Dhabi, Dubai, Jodhpur and Mecca, the correlation coefficients between energy saving and temperature were found to be 0.94, 0.95, 0.96 and 0.99 respectively. However, in some cases, the correlation between energy saving and dependent variable is weak. For example, the correlation coefficient between energy savings and solar radiation is 0.17 for

Jodhpur. It could be explained by the rainy season especially during July and August. During these months, the average precipitation was around 125 mm and cloud cover was 50%, which consequently reduced the solar radiation to 62.25 W/m^2. This shows that precipitation and cloud cover are also influencing the energy savings. Table 5 also shows that, in general, the increase in wind speed, temperature and solar radiation resulted in the increase in the energy savings while the increase in relative humidity resulted in the decrease in energy saving values.

Overall, factors such as wind speed, temperature, solar radiation and relative humidity influence energy saving potential of PCM integrated in building. However, more in depth research is required in this area to evaluate the impact of metrological parameters such as relative humidity, daily temperature, wind speed, sunshine duration, precipitation intensity, altitude, amount of cloud cover.

Chapter 5 – Conclusion and Recommendations

The main conclusions are as follows.

- For all eight cities, the monthly energy savings in two-story residential building integrated with PCM were higher during summer months. The maximum energy savings during summer months were up to 41.5 kWh. During these months, the maximum temperature in PCM integrated buildings located in these cities reduced by up to 4.64^{o}C consequently PCM decreased the energy consumption.
- The indoor temperature from November to February for all cities (except Cairo and Biskra) was in thermal comfort range, which in turn, resulted in lower energy savings. However, still PCM integrated residential building was able to decrease the temperature fluctuation by up to 1.95^{o}C and hence it makes comfortable living conditions inside the building.
- For Abu-Dhabi, Dubai, Faisalabad, Mecca, Nouakchott and Jodhpur, the optimum PCM were found to be PCM27, PCM27, PCM29, PCM27, PCM31 and PCM32 and were close to the cooling set points. This shows that for the selected dry climate region (BWh), in general, PCM with higher melting points perform better. However, for Cairo

and Biskra, the optimum PCM (PCM20 and PCM21) were located near the heating set point due to the reason that heating requirement in these cities is higher than the cooling requirement.

- The energy savings varied from 76.40 to 266.67 kWh while ECR ranged from 17.97 to 34.26%. Consequently, PCM incorporation into building walls is an effective method for improving the energy efficiency of buildings.
- For all cities, the optimum thickness of PCM layer incorporated in walls and roof of residential house was found to be 20 mm. For constant volume, it was found that the energy savings increased with the increase in the surface area and decreased with the increase in the thickness of PCM layer.
- For selected cities, in general, the increase in wind speed, temperature and solar radiation resulted in the increase in the energy savings while the increase in relative humidity resulted in the decrease in energy saving values. It is suggested that the impact of metrological parameters such as relative humidity, daily temperature, wind speed, sunshine duration, precipitation intensity, altitude, amount of cloud cover should be carried out deeply.

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