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Energy Saving in Building with Latent Heat Storage

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Abstract

This article presents an experimental analysis of peak load shifting for air conditioning system using PCM (phase change material) in a room. The melting range of the used PCM is from 20 to 25°C. The amount of the PCM is determined according to the cooling load of the room during the peak time. The hourly cooling load is calculated. A low-power fan is used to drive air over the PCM capsules, which are arranged in a chamber above the room. Auxiliary cooling unit is used to freeze the PCM when the night temperature is higher than 18°C. The temperatures of the PCM are measured by 9 thermocouples inserted inside a capsule. The variant degrees of temperature of the air at the inlet, at the middle, and at the outlet of the air-passing chamber as well as at the room are measured during day and night. In addition to that, the climate conditions are measured. As a result, during the peak load shifting time, which is within 2 hours, the decrease of the room temperature is between 7-10 °C by using PCM ceiling system. Consequently, it can be concluded that the PCM system is effective for the peak load shifting.

Keywords: *peak load shifting - PCM thermal storage- air-conditioning*

1. Introduction

As the demand for air conditioning increased greatly during the last decade, there has been a large demand of electric power. In addition, the limited reserves of fossil fuels have led to a surge of interest in efficient energy application. Electrical energy consumption varies significantly during the day and night according to the demand by industrial, commercial and residential activities. In hot climate countries, the major part of the load variation is due to air conditioning. Better power management and significant economic benefit can be achieved if some of the peak load could be shifted to the off- peak load period. This target can be achieved by thermal energy storage for cooling in residential and commercial building establishments. Phase change materials (PCMs) have been considered for thermal storage in buildings since 1980 [1]. There are several promising developments are taking place in the field of application of PCMs for heating and cooling of building. Experimental study of two real size concrete cubicles concluded that the energy storage in the walls by encapsulating PCMs and the comparison with conventional concrete without PCMs led to an improved thermal inertia as well as lower inner temperatures [1]. Pasupathy and Velraj studied the thermal performance of an inorganic eutectic PCM based thermal storage system for thermal management in a residential building by theoretical and experimental investigation [2]. Performance of a hybrid heating-system, combined with PCM thermal storage was investigated numerically [3]. The results indicated that the thermal storage of PCM plates improved the indoor thermal comfort level and saved about 47% of normal-and-peak-hour energy and 12% of total energy consumption in winter in Beijing.

The wallboards are cheap and widely used in a variety of applications, making them very suitable for PCM encapsulation. To improve the wallboard efficiency, a vacuum insulation panel (VIP) was associated to the PCM panel [4].

An empirical model for a real-scale prototype of a PCM-air heat exchanger was built from experimental results, aimed at simulating the thermal behavior in the tested heat exchanger in different cases [5]. The use of the granular PCM can lead to improvement of the indoor thermal environment in comparison with that in conventional systems due to thermal radiation from the floor surface area, which can be maintained around the phase change temperature [6].

Studies of the free-cooling potential for different climatic locations were investigated [7]. It was found that the optimum PCM had a melting temperature that was approximately equal to the average ambient air temperature in the hottest month, and that the free-cooling potential was proportional to the average daily amplitude of the ambient air's temperature swings. For all the analyzed climatic conditions, the PCM with a wider phase change temperature range (12 K) was found to be the most efficient. In experiments, a PCM wallboard room was constructed by attaching PCM wallboards, developed by

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incorporating about 26% PCM by weight into gypsum wallboards, to the surface of an ordinary wall [8]. Compared with an ordinary room, it was found that the PCM wallboard room could greatly reduce the energy cost of HVAC systems and transfer electric power peak load to valley. Experimental analysis of cooling buildings using nighttime cold accumulation in paraffin with a melting point of 22 ºC as the PCM was investigated [9].

The effects of a peak shaving control of air conditioning systems using PCM for ceiling boards in an office building were examined [10]. Potential peak air conditioning load shifting strategies was addressed using encapsulated phase change materials [11]. The materials being considered in this study were designed to be installed within the ceiling or wall insulation to assist in delaying the peak air conditioning demand times until later in the evening.

A mathematical model of the PCM air heat exchanger was presented [12]. The mathematical model was verified with measurement on a prototype heat exchanger. Arkar and Medveda [13] did a study of free cooling of a low-energy building using latent-heat thermal energy storage device integrated into a mechanical ventilation system. Theoretical and experimental investigations were done to study the thermal performance of an inorganic eutectic PCM based thermal storage system for thermal management in a residential building [14]. Numerical simulations were conducted for a multi-zone, highly glazed and naturally ventilated passive solar building. PCM-impregnated gypsum plasterboard was used as an internal room lining. The results showed that solar energy stored in the PCM–gypsum panels can reduce the heating energy demand by up to 90% [15].

In this study experimental analysis of peak load shifting for air conditioning system using coconut fatty acid as PCM in a room under climate of Cairo is investigated. In order to achieve the optimum design for the selected location the average ambient conditions for all the months are studied. Coconut fatty acid is selected due to its favorable melting and freezing temperature range as well as its low price.

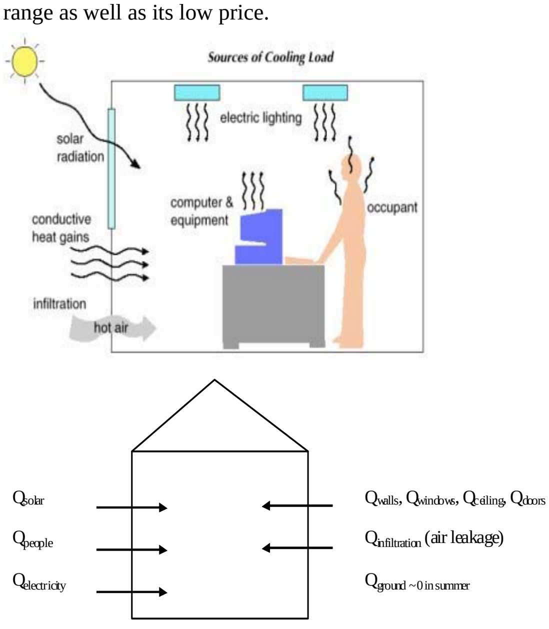


Fig. 1 The major sources of heat gain into a building [16]

2. Experimental work

2.1. Thermal design for PCM mass calculations

The PCM storage capacity is designed to be used in the test room with its thermal loads during the peak time. To reach appropriate thermal comfort the room temperature should be in the range between 21 and 28 °C. Consequently, to overcome the day/night time lag problem the thermal storage capacity of the PCM has to accommodate the heat gains within the space during the peak time. The net heat load into a building is called the cooling load. The total building cooling load consists of heat transferred through the building envelope (walls, roof, floor, windows, doors etc.) and heat generated by occupants, equipment, and lights. The major sources of heat gain into a building are shown in Fig. 1 [16]. Note that ground losses/gains are typically small and are here assumed negligible. The load due to heat transfer through the envelope is called as external load, while all other loads are called as internal loads.
Based on energy balance, the net cooling load is calculated as follows:

$$Q_{load} = (Q_{solar} + Q_{people} + Q_{electricity} + Q_{walls} + Q_{windows} + Q_{ceiling} + Q_{doors} + Q_{infiltration})_{in} \quad (1)$$

The hourly cooling load is calculated by using HAP software version 4.04. The peak load is shown in Fig. 2. The quantity of PCM is calculated according to the calculation of cooling load during the peak period. The used PCM is coconut oil its property is shown in table 1. The quantity of PCM is calculated as follows:

$$m_{PCM} = Q_{load} * \text{time} / (C_{Pl} * (T_l - T_m) + h_{fg} + C_{Ps} * (T_m - T_s)) \quad (2)$$

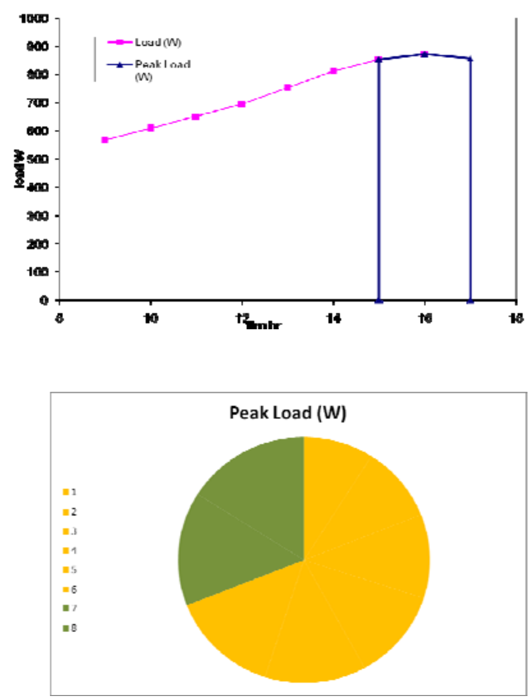


Fig. 2 Calculated peak load

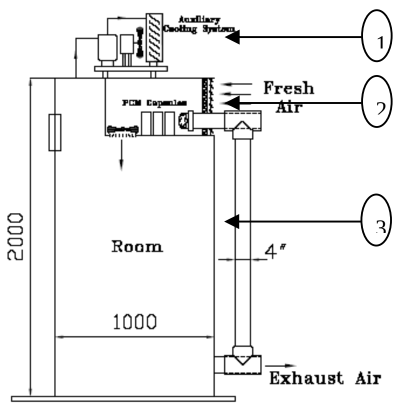
Table 1 Thermophysical property of coconut oil

Material	Melting point /range °C	Heat of fusion kJ/kg	Density kg/m^3	Specific heat kJ/kg K
Coconut oil	22-24	103.25	91.6	=0.62+ 0.1006*T

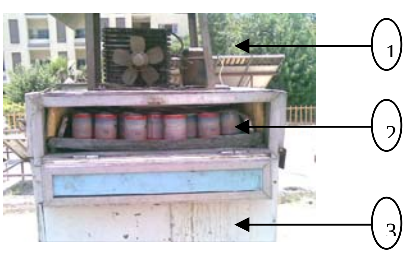
2.2. Outline of the system

The result from the thermal design process is used to produce prototype module for latent heat thermal storage for the laboratory test room. As shown in Fig. 3 the experimental apparatus consists of the following:

i) Auxiliary refrigeration circuit.
ii) PCM chamber of capsules.
iii) Room space.



a- Schematic of the prototype

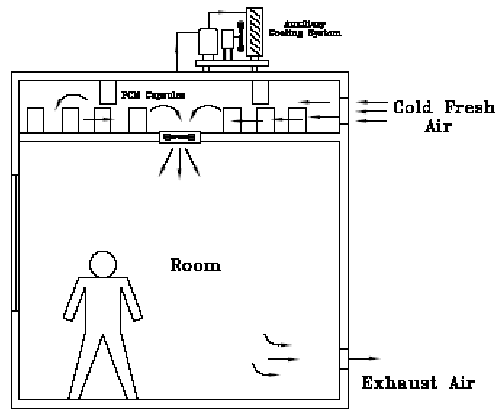


b- Photo of the prototype

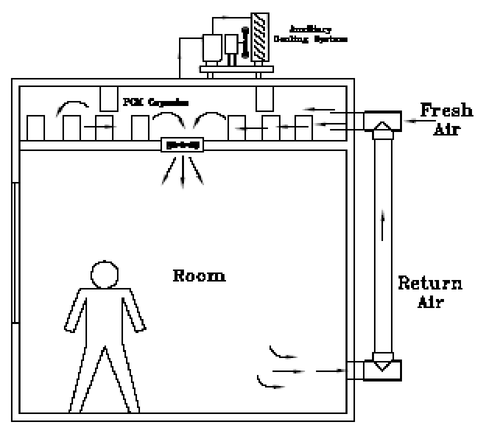
1. Auxiliary cooling system
2. PCM chamber of capsules
3. Room space

Fig. 3 Experimental apparatus

The structure is a ceiling chamber contains PCM capsules above a room space. The dimension of the room is 1 m in length, 1 m in width, and 2 m in height. The wall construction is a sandwich panel. The thickness of each wall is 52 mm. A fan opening is provided on the ceiling of the room. The ceiling chamber height is 30 cm. Figure 4 shows the outline of the system. During night, the capsules are cooled by bathing the ambient air through the ceiling chamber. After that, it bathes through the room and then exhausts from an opening at the bottom of the room. During the daytime air enters from ceiling opening flows through the room space then returns to the ceiling chamber to be recycled with fresh air to the room. If the temperature of the ambient air is higher than 18°C, a temporary cooling unit is used for cooling the capsules during the night. The cooling time (discharge time) by using the storage unit is two hours during the period from 12pm to 16pm. In this study, the thermal storage time (charge time) can be done before 9 am.



a- PCM capsules cooled at night by fresh air (charge)



b. Room cooled by PCM (discharge)

Fig. 4 Outline of the system

2.3. Measurements

The data of solar radiation on horizontal surface and ambient air temperature are measured by using weather station located in the field of experiments in Cairo. The Data Logger is DL2e of DELTA-T DEVICES (Solar radiation sensor measuring range from -0.100000 to 1.499429kW/m^2) (Ambient air temperature sensor measuring range -19.150000 to 60.000000ºC). The PCM-capsule's dimensions are 125 mm in height and 100 mm in diameter. The capsule contains 9 thermocouples of 0.3 mm diameter chromium-aluminum that are set up in the longitudinal and radial direction to measure the temperature of the PCM as shown in Fig. 5. They were calibrated within the accuracy of ±1.5% based on Extech Model MT310. The internal 6 thermocouples are inserted at the center of the capsule and at 25 mm radius to measure the temperature gradient of the PCM during the charging and the discharging processes. On the surface of the capsule, three of thermocouples are soldered to measure the temperature of the capsule's surface. Air temperature inside the storage chamber is measured by using three thermocouples that are inserted at the inlet, at the middle, and at the outlet of the chamber. The average temperature of the room space is recorded using MADGE TECH 4 channel thermocouple temperature recorder (No4344) (Temperature measuring range from -20 to 60ºC).

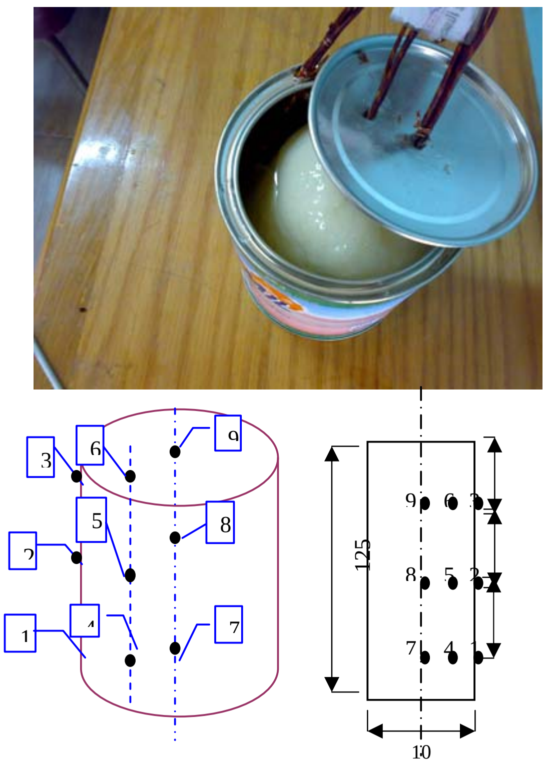


Fig. 5 The PCM Capsule and thermocouple's positions

3. Results and Discussion

3.1. Weather condition

Figure 6 shows the data of the average ambient air temperature for each month at the field of the experiments in 2010. The mean maximum and minimum temperatures are shown in table 2. From the table, it appears that for more than 120 days, PCM Melting at 22-24^{o}C is workable for free cooling. 6 months are marked in green back-ground and 6 months in white background. From May to October free-cooling can not be made available and electric cooling can be used for load shifting regime. PCM melting at 22-24^{o}C will easily give comfortable temperature during day time for rest of the months.

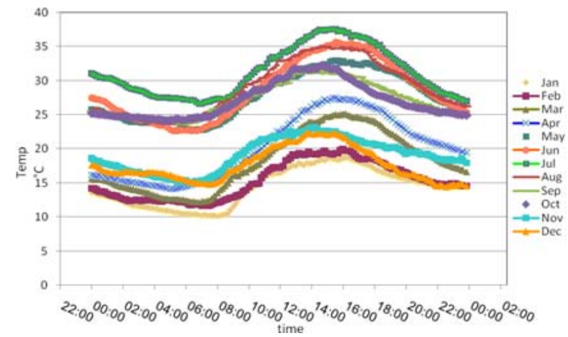


Fig. 6 Average ambient air temperature for each month at the field of the experiments in 2010

Table 2 The mean maximum and minimum temperatures

Month	Mean Temperature ^{o}C		Remarks
	Daily Min	Daily Max	
Jan	10.2	19.3	26-28^{o}C can be maintained
Feb	11.7	19.9	26-28^{o}C can be maintained
Mar	12.2	25.2	26-28^{o}C can be maintained
Apr	14.1	27.4	26-28^{o}C can be maintained
May	22.8	32.9	PCM Cooling can be used
Jun	22.6	35.6	PCM Cooling can be used
Jul	26.6	37.5	PCM Cooling can be used
Aug	23.6	34.9	PCM Cooling can be used
Sep	23.6	31.9	PCM Cooling can be used
Oct	24.1	32.3	PCM Cooling can be used
Nov	15.0	23.2	26-28^{o}C can be maintained
Dec	14.8	22.3	26-28^{o}C can be maintained

3.2. Cooling load and PCM quantity

Figure 7 shows the calculation of hourly cooling load during the 24 hours by using HAP software version 4.04. Figure 7 also shows the measured data of solar radiation on horizontal surface and the ambient air temperature on 15th of July 2010. While the solar radiation peak of horizontal plane is at noon, and the ambient air temperature peak is at (3 p.m.) the cooling load does not peak until (4 p.m.). This reveals the time it takes for heat to be conducted through the walls. Radiation heat gain from sources such as sun, lights and even people takes time to become a load. The radiant heat must first heat up the building and contents and then be conducted and released over time to the room air by convection processes. This causes a delay between the time a heat gain occurs and the time its full effects as a cooling load appear. The peak load is shown in Fig. 7. The quantity of PCM is calculated as explained before in equation (2) from Fig. 7, which is the area under the cooling load curve at the period of time from 15 pm till 17 pm. This area is approximately equal to 30% of the total cooling load. This means that 30% of the energy used for air conditioning can be saved by using free cooling of PCM. The calculated quantity of the PCM for the 30% of the cooling load of the assumed proto type is 38kg of coconut fatty acid.

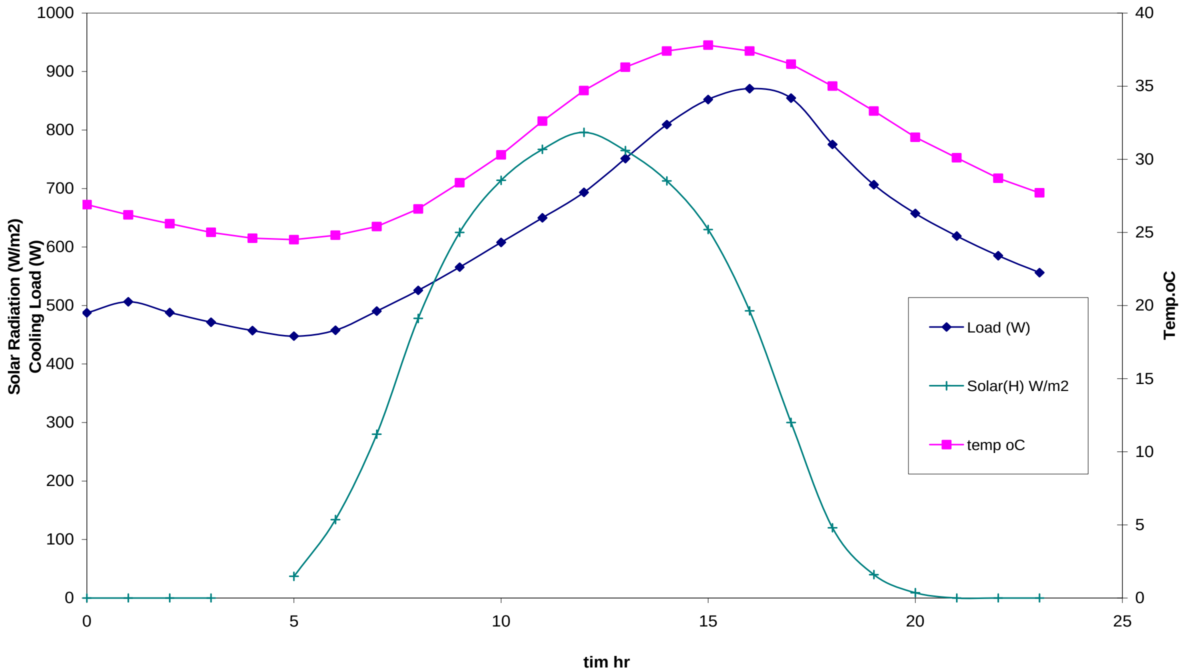


Fig. 7 Hourly cooling load, solar radiation, and the ambient air temperature

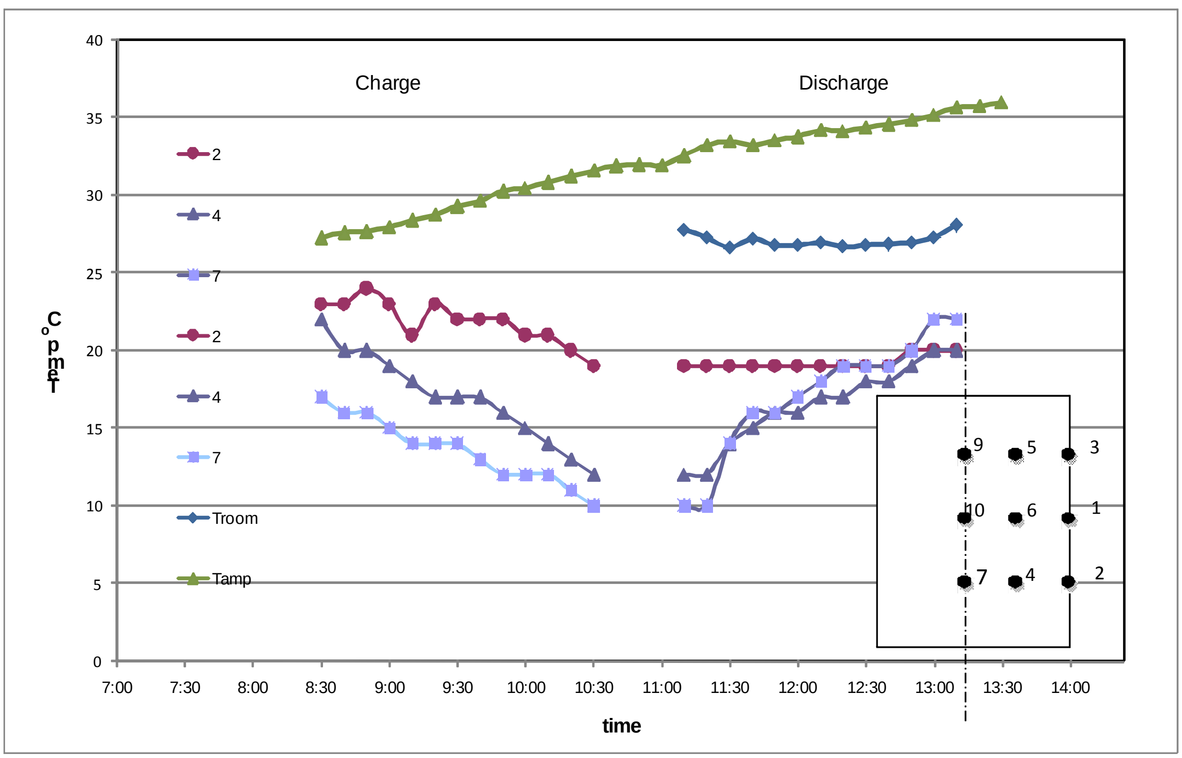


Fig. 8 Temperature profiles of the PCM (at the bottom)

3.3 Temperature profiles

The radial temperature profiles of the PCM at three different heights (30 mm, 60 mm, and 90 mm) during the charge and discharge periods are shown in Figs. 8, 9, and 10. The same figures show the variation of the ambient air temperature and the room temperature. The positions of the thermocouples are at the center of the PCM capsule and at radii of 25mm and 50mm. The temperature curves illustrate the temperature distribution in three regions during the charge and the discharge processes. The liquid region is above the upper limit of the melting range. The phase transition region is within the melting range. The solid region is below the lower limit of the melting range. At bottom of the capsule, as shown in Fig. 8, visible variation in temperature is observed during the charge and discharge processes. During the charge process, the conduction through the bottom wall of the capsule causes rapid cooling at the bottom. At the discharge process, the temperature increases rapidly until melting occurs then becomes constant.

In Fig. 9, the temperature profiles at the middle of the capsule. The temperatures are approximately constant as their values are within the melting range during the charge and discharge processes. The temperatures at the middle are due to the conduction through the PCM from the top and the bottom. Figure 10 shows the temperature profiles at the top of the capsule. During the charge process, the temperatures are approximately constant as they are cooled through the natural convection of air above the capsule. However, during the discharge process the melting occurs due to the forced convection through the moved air. The temperatures increase rapidly until the melting range then become approximately constant. After that, they increase gradually. The figures show that the room temperature is approximately equals the upper layer temperature of the PCM.

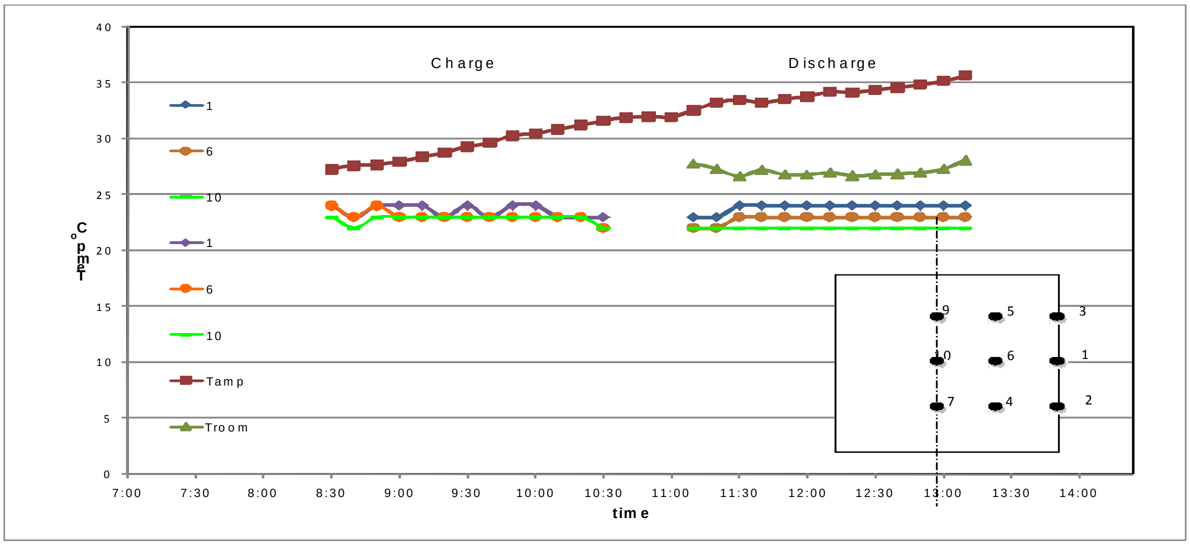


Fig. 9 Temperature profiles of the PCM (at the middle)

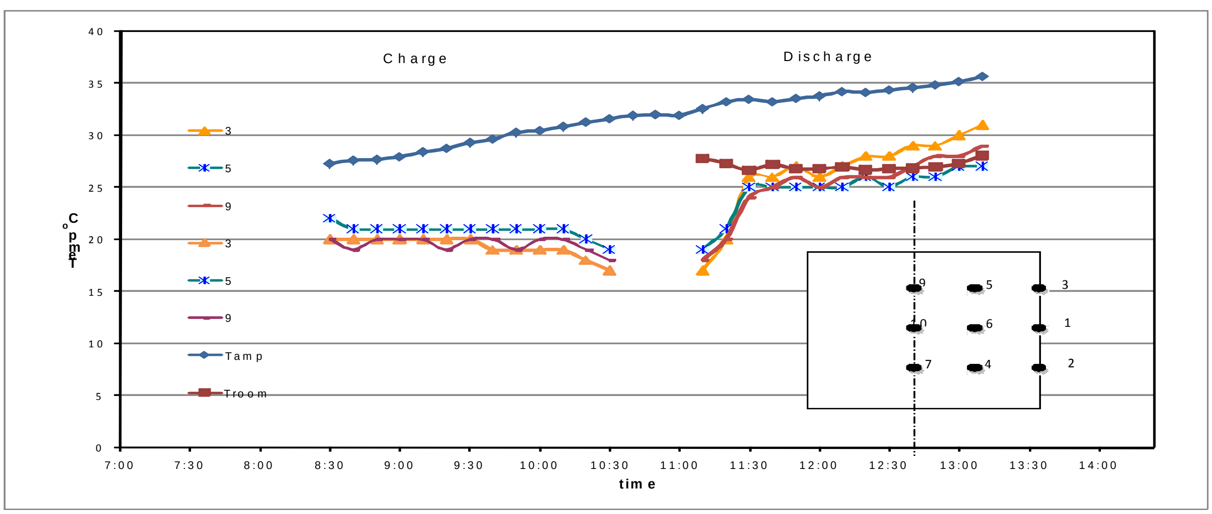


Fig. 10 Temperature profiles of the PCM (at the top)

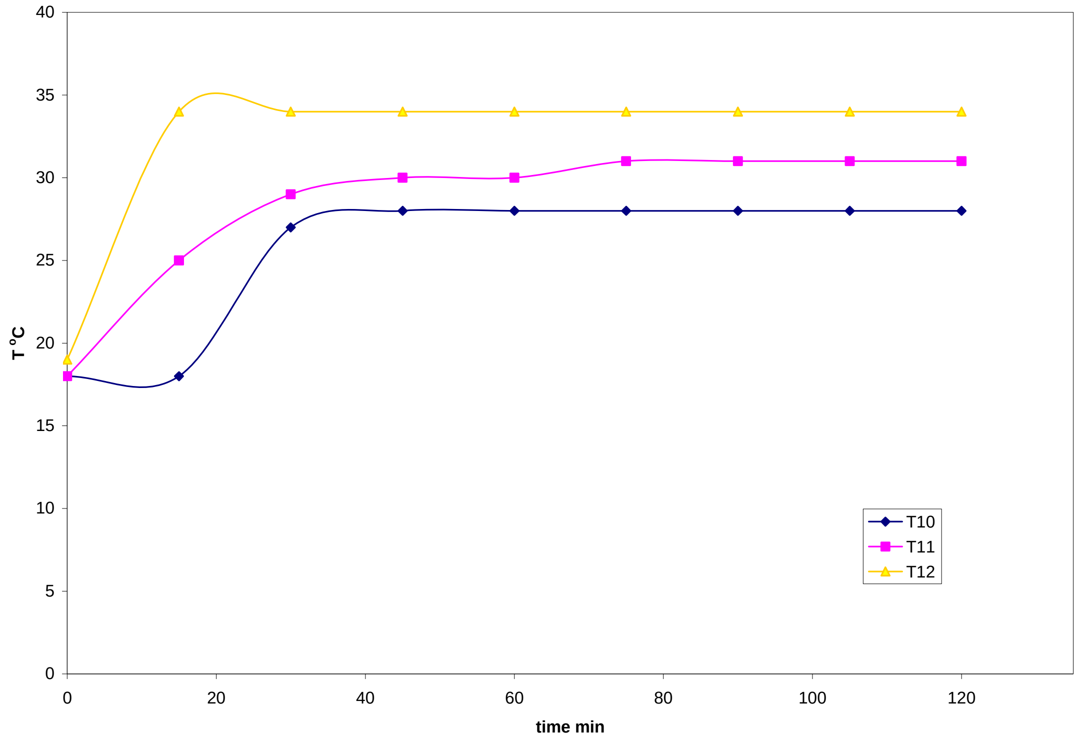


Fig. 11 Air temperature inside the duct

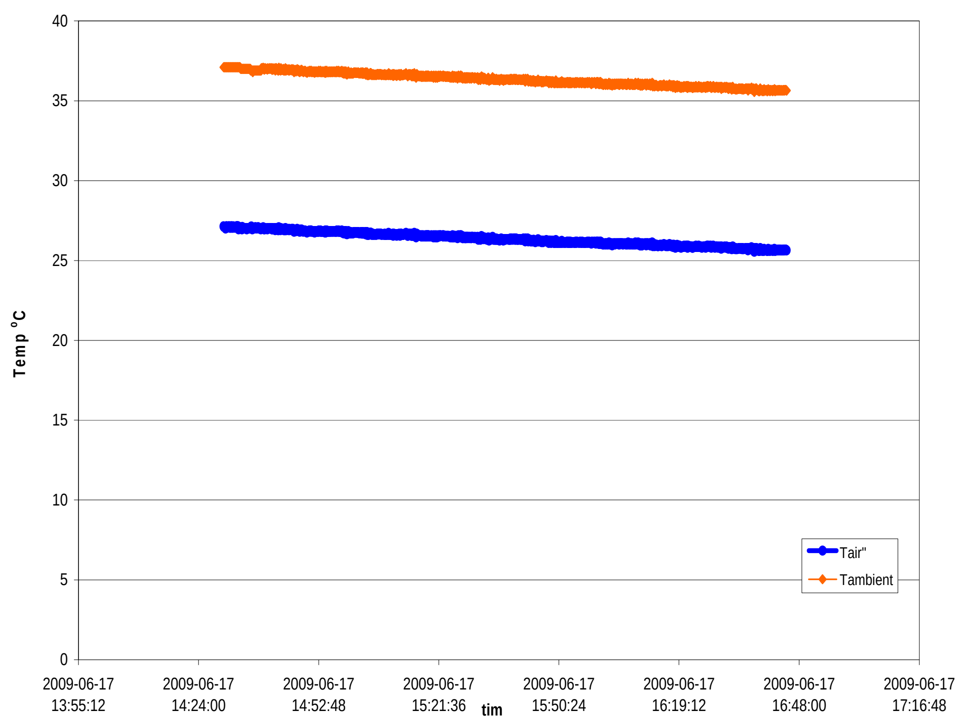


Fig. 12 Experimental results of the room air-temperature

Figure 11 shows the temperature of the air passing through the PCM capsules in the storage chamber. Thermocouples 12, 11, and 10 are at the inlet, at the middle, and at the outlet of the storage chamber respectively. The curves illustrate that the change in the air temperature is influenced directly by the change of the PCM temperature. As the sharp increase in the PCM temperature during solid, state the air temperature increases sharp. When the PCM capsules reach the phase change period the air temperature stops increasing and becomes constant tell the end of the discharge period. Temperature of thermocouple 10 is the inlet temperature of room space. Figures (12 and 13) show the average room temperature during the cooling time at two different periods. In Fig. 12, the decreasing of room temperature is proportional to the total decrease in the ambient air temperature during this period. The average room temperature is about 26 ºC. In Fig. 13 as the ambient air-temperature is approximately constant, the room temperature increases slightly then becomes constant during this period. The average room temperature is about 27 ºC. The decrease of the room temperature was about 7-10ºC by using PCM capsules in a ceiling-chamber. This means that by using free cooling of PCM capsules the room can be kept cooled at a comfort temperature by cooling with cheaper off-peak energy.

In order to understand the potential of PCM for temperature control, it is necessary to look at the case without PCM as a reference. Free cooling system can be applied during the days that have minimum temperature less than the melting point of the PCM that used. The indoor air temperatures of the room with and without PCM during a day in spring are both shown in Fig. 14 for 9 April. It can be seen that the PCM storage system obtained by recirculation of the air (see Fig. 4-b) is appropriate in this case, which can increase the lowest indoor air temperature from 16ºC to 20ºC, and maintain the temperature within the room between 20 to 26°C.

4. Calculation of Coefficient of Performance

Coefficient of Performance (COP) is the ratio of heat energy delivered or extracted to the work supplied to operate the equipment. It measures the performance efficiency of system. The 1-minute electricity consumption data of compressor and fan are used to measure the work or energy supplied to operate the equipment.

The COP of PCM storage is calculated as follows:

$$COP_{PCM} = \frac{Q_{pcm}}{power_{stor}} \tag{3}$$

where Q_{PCM} is equal to the heat absorbed by the evaporator Q_{evap}

$$Q_{pcm} = m_{PCM}*(C_{Pl}*(T_l - T_m) + h_{fg} + C_{Ps}*(T_m - T_s)) \tag{4}$$

$$power_{stor} = power_{comp}*time \tag{5}$$

The COP of the air fan is calculated as follows:

$$COP_{air} = \frac{Q_{air}}{power_{fan}} \tag{6}$$

Where

$$Q_{air} = m_{air}*Cp_{air}*\Delta T \tag{7}$$

The COP of the experimental test rig is calculated as follows

$$COP = \frac{Q_{evap} + Q_{air}}{power_{comp} + power_{fan}} \tag{8}$$

$$COP = \frac{0.8298 + 0.56}{0.2766 + 0.373} = 2.3$$

From calculations, the COP is found to be about 2.3.

5. Conclusions

In this research, the effects of the peak shaving control using PCM capsules in a ceiling-chamber for a room are examined, which is located in Cairo. The following results were obtained by examining the designed model experimentally.

1. In summer the cooling load peak is at 4 p.m. due to the time that heat takes to be conducted through the walls.
2. PCM melting at 22-24^{o}C is workable for free cooling for 6 months. For the rest 6 months the peak shaving control can be applied by a night electric cooling unit.
3. Within 2 hours of peak load shifting time, the room can be kept cooled at a comfort temperature by cooling with off-peak energy.
4. Using free cooling of PCM can save 30% of the energy used for air conditioning.
5. Using free cooling of PCM can maintain the temperature within the room between 20 to 26°C.
6. The change in the air temperature in storage chamber is proportional to the change in the PCM temperature inside the capsules.
7. The change in the air temperature in the room is proportional to the change of ambient air temperature.
8. The COP of the system is about 2.3.

From these results, it can be concluded that the PCM ceiling system is effective for the peak shaving control. Large amounts of latent heat can be stored in the PCM, which enables to make more compatible, clean, durable, and cheaper systems for air-conditioning.

Nomenclature

Cpair: specific heat of air (kJ/kgK)

Cpl: specific heat of liquid PCM (kJ/kgK)

Cps: specific heat of solid PCM (kJ/kgK)

h_{fg}: Latent heat of PCM (kJ/kg)

m_{air}: air mass flow rate (kg/s)

m_{PCM}: mass of PCM (kg)

Q_{air}: energy of air flow (kW)

$Q_{ceiling}$: ceiling cooling load (kW)

Q_{evap}: heat absorbed by the evaporator (kW)

Q_{doors}: doors cooling load (kW)

$Q_{electricity}$: electricity cooling load (kW)

$Q_{infiltration}$: infiltration cooling load (kW)

Q_{load}: net cooling load (kW)

Q_{PCM}: storage energy in the PCM (kW)

Q_{people}: people cooling load (kW)

Q_{walls}: wall cooling load (kW)

$Q_{windows}$: windows cooling load (kW)

T_l: initial temperature of liquid PCM (K)

T_m: melting temperature (K)

T_s: final temperature of solid PCM (K)

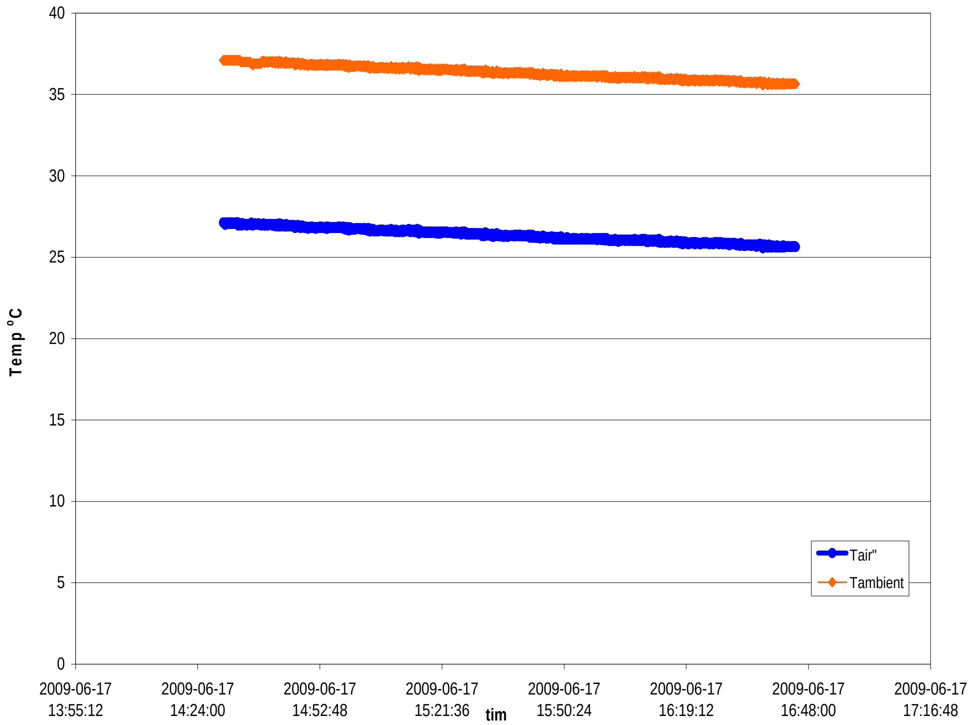


Fig. 12 Experimental results of the room air-temperature

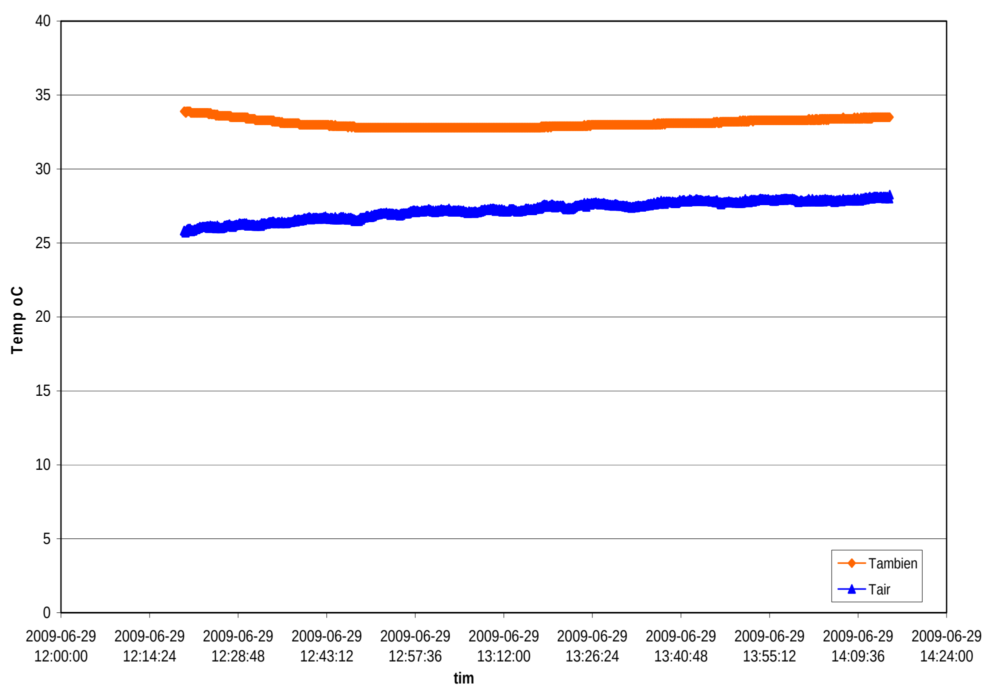


Fig. 13 Experimental results of the room air-temperature

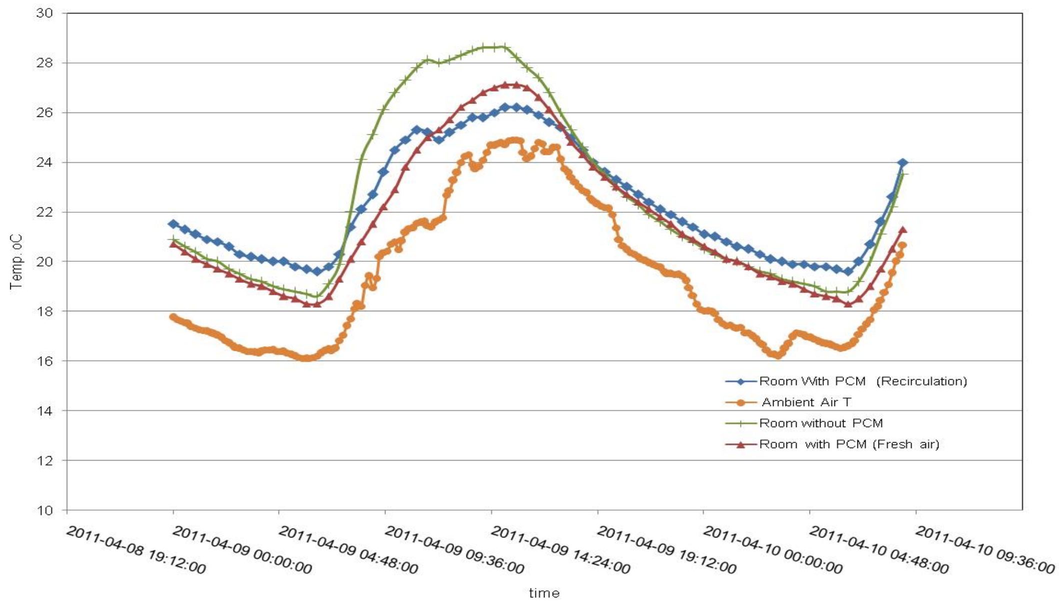


Fig. 14 The indoor air temperatures of the room with and without PCM during a day in spring

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