



Experimental Evaluation of a Vapor Compression Cycle Integrated with A Phase Change Material Storage Tank for Peak Load Shaving

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Abstract

In this study, the combination of a vapor compression cycle with a phase change material (PCM) storage tank has been assessed experimentally during the hottest day based on Tehran city climatic conditions. The temperature conditions for outdoor (condenser, compressor, *etc.*) and indoor (evaporator) air conditioning (AC) units are provided with the help of two separate test chambers and a controller system. The desired system has been surveyed based on two scenarios. In each scenario, the system is evaluated for the conventional AC system (with no PCM involved) and the AC plus PCM unit (conventional AC + PCM storage tank). Based on scenario 1 operating strategy, the results show that adding the PCM tank diminishes the total COP and total accessible cooling load during 24 hours. Whereas the AC plus PCM system's performance improves during on-peak hours (12:00 – 19:00) compared to the conventional AC system (with no PCM involved). Based on scenario 2 operating strategy, adding the PCM storage tank to the conventional AC unit increases total electric energy consumption over 24 hours. While it leads to reducing electric energy consumption during on-peak hours by about 84.5%.

Keywords: Phase change material; Vapor compression system; Peak-load shaving; Storage tank; Refrigeration.

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1. Introduction

Nowadays, increasing the world's population and enhancing living standards have led to rising energy consumption.^[1] According to the international energy agency report, commercial and residential buildings are responsible for about 30.0% of energy use in the world. They also account for 55.0% of the world's electricity consumption, while 8.5% of them belong to space cooling.^[2] There are currently 2 billion air conditioner units in operation worldwide, which is estimated to reach 3.3 billion by 2030 due to the rising average earth temperature.^[3] So, providing this amount of energy, especially on hot days of the year and during on-peak electrical hours, is one of the significant challenges ahead.^[4] The proposed problem would lead to a blackout due to the inability of the power plants to supply electricity, while in summer, the

power plants' efficiency also decreases. One way to tackle the proposed issue is to shave the electrical peak during on-peak hours and shift it to the off-peak electrical hours.^[5] To achieve this goal, a cooling thermal energy storage can be connected to the refrigeration system to store cooling energy during off-peak hours. Then uses the stored cooling energy during on-peak hours.^[6] This would be beneficial for both consumers and the government. Due to the high electricity tariff during on-peak times and its low price during off-peak times, the consumers pay less for electrical bills because their cooling system consumes less energy during on-peak hours. Furthermore, this leads to saving in government expenditures cause they no longer need to construct new power plants to provide electricity demands during on-peak hours for preventing blackouts.^[7] In this regard, the electricity price of a building in Thailand, which was modeled by Chichana *et al.*,^[8] was diminished by up to 55% per month when used an ice storage tank. In another study, Yau and lee^[9] claimed that using an ice slurry could diminish the total electricity cost by about 24%. However, the system's total energy consumption

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increased up to 20.0%.

Generally, thermal energy storage (TES) systems can be divided into three categories based on their operation: sensible, latent, and thermochemical.^[10] The sensible TES systems are the simplest and cheapest among the proposed TES types. But their volume and size are huger in comparison with other types of TES due to their low energy density. Since the latent TES units use solid-to-liquid or liquid-to-gas phase change material to store energy, their tank's volume is smaller than sensible ones and has a higher energy density compared to theirs.^[11] The significant weakness of these types of TES is their low thermal conductivity. The highest energy density among proposed TES units belongs to thermochemical energy storage (TCES) units. Though, they are yet in the laboratory stage and have not been commercialized.^[12] Salunkhe and Krishna^[13] evaluated phase change material (PCM) with different specifications for low-temperature (25 – 80 °C) applications. They introduced several PCMs for solar water and space heating. In this regard, Stropnik *et al.*^[14] indicated that adding 15% of encapsulated PCM to the water storage tank improved the heat supply twice as long as the water storage tank. Moreover, they showed using 40% PCM in a storage tank led to decreasing the storage tank volume from 2.1 m³ to 1.4 m³ based on equal operating conditions. Lin *et al.*^[15] optimized and evaluated a PCM TES for a building in Australia. It was found that PCM tubes inner diameter, PCM tubes distance-to-diameter ratio, the type of PCMs, the number of the PCM tubes, and the inlet water temperature significantly affected the charging performance of the TES unit. It was reported that the energy storage density improved from 13.58 to 26.47 kWh/m³ compared to basic design.

Employing PCMs as the medium of the latent TES has received enormous interest over the years.^[16] Throughout the past 15 years, study on PCMs utilization was mostly allocated to building applications. They have also been used to enhance the performance of refrigeration cooling units. Owing to this, the possible locations of a shell and tube PCM heat exchanger in the refrigeration system were examined by Wang *et al.*^[17] They located the PCM heat exchanger after the compressor, after the condenser, and after the evaporator, which led to a decrease in condenser pressure, an increment in evaporator capacity, and a diminishing in superheat degree of the compressor inlet stream, respectively. Also, The COP was raised by 6.0% and 8% for the first and second states, respectively, compared to the system without the PCM storage tank. No improvement was observed in COP for the third case.^[18] Moreover, the numerical optimization of the proposed systems showed that the greatest enhancement in COP happened in the second case, with 8.0%.^[19] In another similar

work, the influence of using a PCM storage tank after the condenser of a vapor compression refrigeration system was experimentally conducted by Korth *et al.*^[20] This led to enhancing the sub-cooling temperature of the condenser. Also, the cooling capacity of the proposed system, which used paraffin as the PCM with a melting temperature of 18 °C, was improved by about 18%. Riahi *et al.*^[21] investigated the performance of a refrigeration system dynamically by employing a PCM storage tank before the condenser. It was indicated that the desired system could diminish the electrical consumption and increase the accessible cooling load during on-peak load hours. Furthermore, it was claimed that although the total COP reduced, the COP during on-peak times improved, which led to a reduction in electrical peak load. Moreover, the influences of various PCMs with different melting temperatures were investigated in the proposed system in which SP224A attained the highest peak load shaving with 76.3%.^[22]

Moreover, the PCM storage tanks are hugely used as a second evaporator in the refrigeration system to increase cooling system capacity during on-peak electrical load hours. In this regard, Yang *et al.*^[23] evaluated the performance of a refrigeration system in which the PCMs were employed in a warehouse's walls and ceilings. The PCMs charged during compressor ON periods and cooled the room (discharged) during compressor OFF periods. It led to reducing the electrical bill price by shifting the electrical load to off-peak hours. The payback period of the proposed system was determined by about 2.6 years, according to China's economic conditions. Torregrosa-Jaime *et al.*^[24] experimentally evaluated the performance of a PCM tank connected to an 8-kW chiller in which the paraffin was selected as the PCM. It was indicated the COP increased during charging mode when the refrigerant temperature decreased. Mostafa *et al.*^[25] examined the performance of an air conditioning unit of a building in which the PCMs were employed in its ventilation air duct system. The COP of the proposed system was calculated by about 3.1 based on the numerical analysis. Rahdar *et al.*^[26] compared three various operating conditions of using an air conditioning chiller in a building, which were without TES, integrated with an ice TES, and integrated with a PCM TES. It was claimed that the annual energy consumption of the desired systems for the second and third cases were diminished by 4.6% and 7.6%, respectively, compared to the first case. Moreover, the economic analysis indicated that the second case had the best results with the 3.2 years payback period. In another work, Erdemir and Altuntop^[27] evaluated the influence of the sizing strategies of the PCM TES for the hypermarket in Turkey. It was shown

that the 10.0% partial storage mode had the shortest payback period with 1.5 years. However, the full storage mode had the highest cost saving with a payback period of 3.1 years. Gholamibozanjani and Farid^[28] experimentally investigated the performance of a PCM storage unit for the two huts in the winter and summer seasons. It was illustrated that using PCM for space cooling led to energy savings of about 30.0% according to New Zealand's climatic conditions.

Based on the literature review and the summary of the previous studies mentioned in Table 1, most of the mentioned articles have focused solely on the effect of discharging the PCM to shift the electricity peak load of refrigeration systems. While in this work, the influence of the full charge and discharge of a PCM storage tank over 24 hours on the performance of a vapor compression refrigeration system has been evaluated experimentally. Also, the ambient and building temperature conditions have been imitated by two separate test chambers. Moreover, the desired system has been assessed based on two operating strategies. The aim of this survey is to evaluate the role of combining a PCM TES with the conventional vapor compression system on its performance under specific situations. The temperature conditions of the outdoor and indoor units of the vapor compression refrigeration system are provided through two test chambers. In this study, a PCM TES, which uses water as its medium, has been connected to the conventional vapor compression system with slight changes in its pipelines. The stored energy in the PCM TES transfers to the indoor unit section with the help of a water pump. To the best of the authors' knowledge, no works have ever investigated the performance of the

compression cooling system integrated with PCM TES like this. So, this experimental study is novel and has been done for the first time.

2. Experimental setup

The whole setup comprises a conventional 12000 BTU air conditioning unit, electrical heaters, two air fans, a conventional 30000 BTU air conditioning unit, a PCM thermal storage tank, a programmable logic controller (PLC), a circulating water pump, a water heat exchanger, and two test chambers. The aim of the test chambers is to provide a realistic imitation of real indoor (building) and outdoor (ambient) temperature conditions for the 12000 BTU AC indoor and outdoor units, respectively. The electrical heaters and a 30000 BTU AC unit have been used to achieve the proposed purpose. Moreover, a control system has been used to adjust the desired temperature with high accuracy.

2.1 Outdoor test chambers

Two separate test chambers have been constructed to simulate the ambient air (outdoor) and indoor (building) temperatures for the outdoor and indoor units of the AC system. The dimensions of each of these test chambers are 4 m³ (2×2×1). The outdoor test chamber temperature is adjusted by the six electrical heaters, a 30000 BTU AC unit, and an air fan. Its controller system, which is equipped with four thermometers, adjusts the setpoint temperature of the outdoor test chamber.

Three of the thermometers are implemented in the various spots inside the outdoor test chamber, and one of them is located in the lab environment. According to the lab, outdoor

Table 1. The summary of previous studies.

Ref	Type of Cooling System	Type of Storage System	Experimental Work	Time of Evaluation	Effect of Charging & Discharging Process
[8]	AC unit	Ice Storage	No	1 Day	No
[9]	Chiller	Ice Storage	No	1 Year	No
[15]	HVAC unit	Ice Storage	No	9 Hours	No
[17]	AC unit	Ice Storage	Yes	4000 Second	No
[18]	AC unit	Ice Storage	No	4000 Second	No
[19]	AC unit	Ice Storage	No	4000 Second	No
[20]	AC unit	PCM Storage	No	6 Hours	No
[21]	AC unit	PCM Storage	No	1 Day	Yes
[22]	AC unit	PCM Storage	No	1 Day	Yes
[23]	Vapor Compression Refrigeration unit	Ice Storage	No	1 Day	No
[24]	Chiller	PCM Storage	Yes	20 Hours	No
[25]	AC unit	PCM Storage	No	1 Day	No
[26]	AC unit	Ice Storage	No	1 Year	No
[27]	Chiller	Ice Storage	No	24 Hours	No
[28]	AC unit	Active PCM Storage Unit	Yes	1 Year	No

test chamber, and setpoint temperatures, the controller switches ON/OFF the electrical heaters and the conventional 30000 BTU AC unit to provide a realistic imitation of the air temperature inside the outdoor test chamber (simulated ambient temperature) according to the given temperature data of the desired city. According to Fig. 1, the air is sucked into the outdoor unit test chamber by an adjustable air fan, which its rotation speed is equal to the AC condenser's speed fan. When the setpoint temperature of the outdoor test chamber, according to the ambient temperature of the desired city understudy, has to be higher than the lab temperature, the sucked air will be heated up by the electrical heaters through a channel and then enters the outdoor test chamber. When the setpoint temperature of the outdoor test chamber, according to the ambient temperature of the desired city understudy, has to be lower than the lab temperature, the sucked air will first be cooled by the 30000 BTU AC unit and then is reached the desired temperature by the electrical heaters. Accordingly, the PLC turns ON/OFF the electrical heaters and 30000 BTU AC unit based on the received temperatures by the thermometers. The experimental setup of the outdoor test chamber with equipment used in it is indicated in Fig. 1. It should be noted

that, since the only way for air stream to enter the outdoor test chamber is through the adjustable air fan, the amount of air stream which is sucked by the adjustable air fan must be the same as the amount of air sucked in by the condenser's fan of the AC unit at normal operating condition. Otherwise, a low or high amount of the adjustable fan load will affect the performance of the AC unit condenser. So, an airflow meter has been used to adjust the outdoor test chamber fan speed. Also, the amount of compressor and pump electric powers consumptions of the AC unit is measured through a wattmeter, which is located in the controller system. Then, these data are recorded by the supervisory control and data acquisition (SCADA), which is an industrial software that connects the controller system to the computer.

2.2 Indoor test chamber

The indoor test chamber comprises two heat exchangers, electrical heaters, and an air fan. The aim of the indoor test chamber is to simulate the temperature condition inside the building. The electrical heaters play the role of the heat gain of the building in the summer (required cooling load of the building). Two heat exchangers have been used to provide



Fig. 1 The experimental setup of the outdoor test chamber with its equipment.

the building cooling loads demand (the amount of heat energy that would need to be removed from the indoor test chamber to maintain the temperature in an acceptable range, which is between 23 - 25 degrees). One of them is an evaporator of the 12000 BTU AC unit with refrigerant R410A (Composition of R32/R125) in this study. The other one uses circulating cold water, which comes from the PCM TES by a circulating water pump. The heat load of the electrical heaters is adjusted by the controller system. The electrical heaters are switched ON/OFF in a way that the indoor test chamber temperature maintains an acceptable range (23 - 25 degrees). Controlled indoor test chamber temperature variations for a specific scenario are shown in Fig. 3. As can be seen, the room temperature is well maintained at around 24 degrees. The thermostat of the indoor unit of the AC system (refrigerant evaporator) is responsible for adjusting the desired temperature. The experimental setup of the indoor test chamber with equipment used in it is indicated in Fig. 2. It should be noted that the power consumption of electrical heaters, which must be equal to the cooling load production of the AC unit in steady-state conditions, is measured through a wattmeter placed in the controller system. Then, these data are recorded by SCADA, which is an industrial software that connects the controller system to the computer.

2.3. PCM TES

The inner volume of the PCM TES is about 300 liters and covered with elastomeric insulation. Copper and aluminum pipes with lengths of 60 m and diameters of 10 mm and 12.5 mm, respectively, are placed inside the PCM TES in six rows. The experimental setup of these pipes is illustrated in Fig. 4. In cold energy charging mode, the refrigerant enters the

cooper pipe and cools the water used as PCM. In the cold energy discharging mode of the PCM, the circulating water enters the aluminum pipe and is cooled by the PCM. Then it goes to the indoor water heat exchanger by a circulating water pump. Water has been used as the PCM medium in this study. Its properties are listed in Table 2.

Table 2. Properties of the PCM medium at 0 degrees.^[29]

Parameters	Value
Type of PCM	Water
Density ($\frac{kg}{m^3}$)	1000
Melting Temperature ($^{\circ}C$)	0
Latent Heat of Fusion ($\frac{kJ}{kg}$)	333.7
Specific Heat ($\frac{kJ}{kg \cdot K}$)	4.22

2.4 System description

The schematic of the proposed system is illustrated in Fig. 5. The system operates in two modes, which are conventional AC mode (with no PCM involvement), and the AC plus PCM mode (combination of the conventional AC unit and PCM storage tank).

The AC plus PCM mode comprises processes of cold energy charging (storing cold energy in the PCM TES by solidifying) and discharging (releasing cold energy from PCM TES by melting). In this study, the time of cold energy charging (storing cold energy in PCM TES by freezing it) has been considered between 00:00 to 8:00. For this purpose, the refrigerant (R410A) exits from the expansion valve (point 2) and enters solenoid valve 2 (point 6) to charge the PCM TES (storing cold energy by means of solidification). Then the outlet refrigerant goes to the compressor (point 7) until the normal process of the vapor compression cycle is completed.

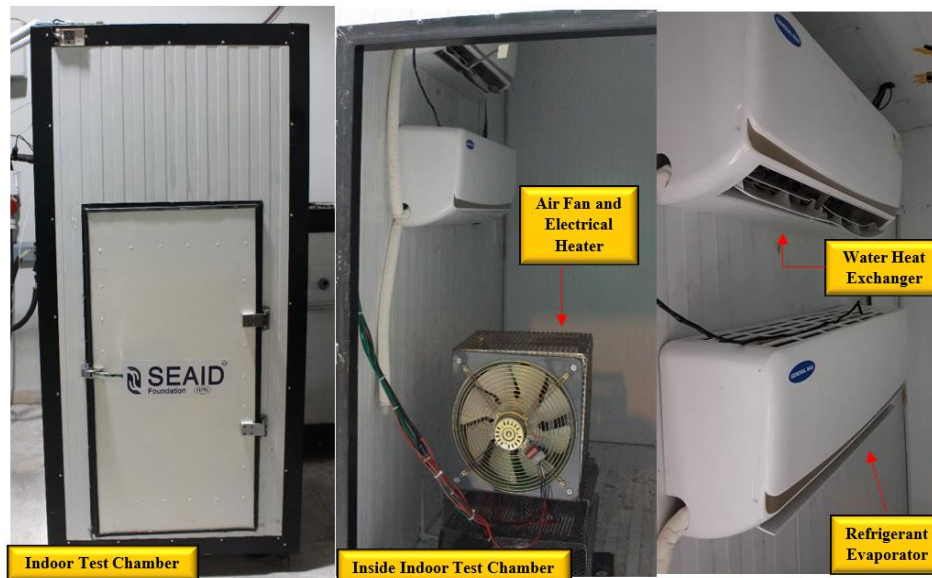


Fig. 2 The experimental setup of the indoor test chamber with its equipment.

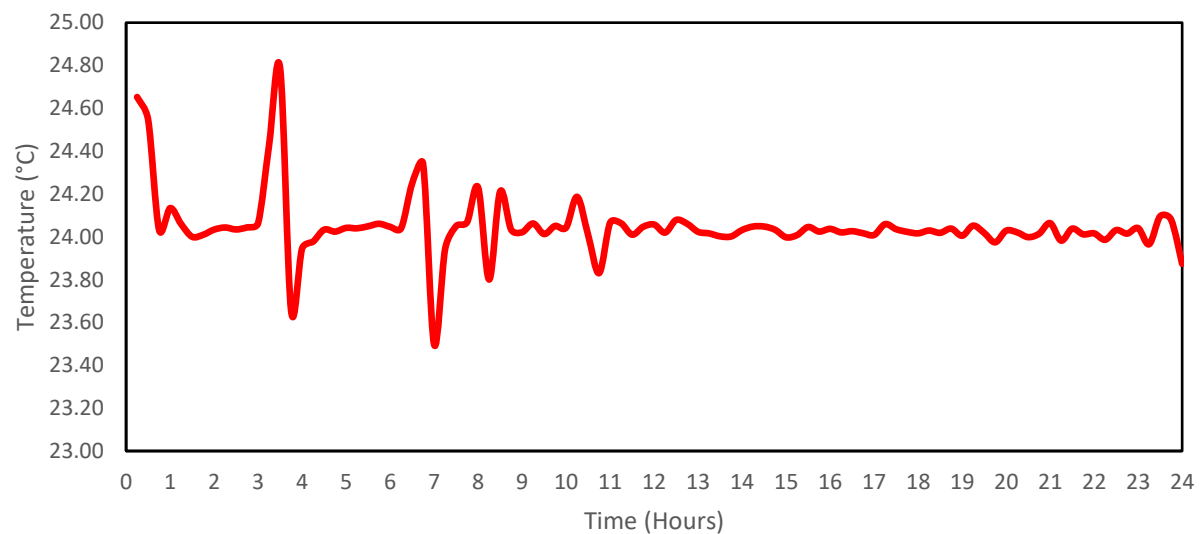


Fig. 3 The temperature range of the indoor test chamber (building) for a specific test over 24 hours.



Fig. 4 The experimental setup of the PCM TES.

It should be noted that if the building requires the cooling load for counterbalancing the electrical heaters inside the indoor test chamber during this time, only the circulating water pump will provide the cooling load from the PCM TES. In other words, while the cold refrigerant of the vapor compression system stores its cooling energy in the PCM TES, the circulating water simultaneously extracts this cooling energy from the PCM TES and transfers it to the room. The schematic of the cold energy charging process is indicated in Fig. 5b. At this time, all of the cooling load production, also named as the accessible cooling load of the AC compressor, is stored in the PCM TES. The cooling load demand of the indoor test chamber (building) is supplied from PCM TES by the circulating water pump during this time due to the types of the

scenario operating conditions. Consequently, the building cooling load demand is provided by heat exchanger 1.

During cold energy discharging time (extracting cold energy from the PCM TES by melting it), 12:00 – 19:00, the compressor of the AC unit is switched off the whole time. During the proposed time, the building cooling load demands (counterbalancing the electrical heaters inside the indoor test chamber to maintain constant room temperature) are only provided by the PCM TES through the circulating water pump. There are two heat exchangers for providing building cooling demands. One of them uses a refrigerant evaporator (heat exchanger 2), which is a part of the vapor compression cycle, and the other one uses circulating cold water, which is integrated to the PCM TES by the circulating water pump. The schematic of the cold energy discharging process is depicted in Fig. 5c. The cooling load demand of the indoor test chamber (building) during this time is provided from the PCM TES by heat exchanger 1. In other words, during cold energy discharging mode (12:00 – 19:00), all of the cooling load production by the vapor compression system during the cold energy charging process (00:00 – 8:00) is re-used and transferred to the indoor test chamber (building) from the PCM TES by the heat exchanger 1 to provide the building cooling load demand.

In the conventional mode with no PCM involvement, the water pump is switched off the whole time, and the vapor compression system alone (conventional AC) provides all the cooling load demand by the refrigerant evaporator (heat exchanger 2). In this mode, the refrigerant exits from the expansion valve and enters the solenoid valve 1 (point 3). Then it goes to heat exchanger 2 to absorb the heat load produced by the electrical heaters inside the indoor test

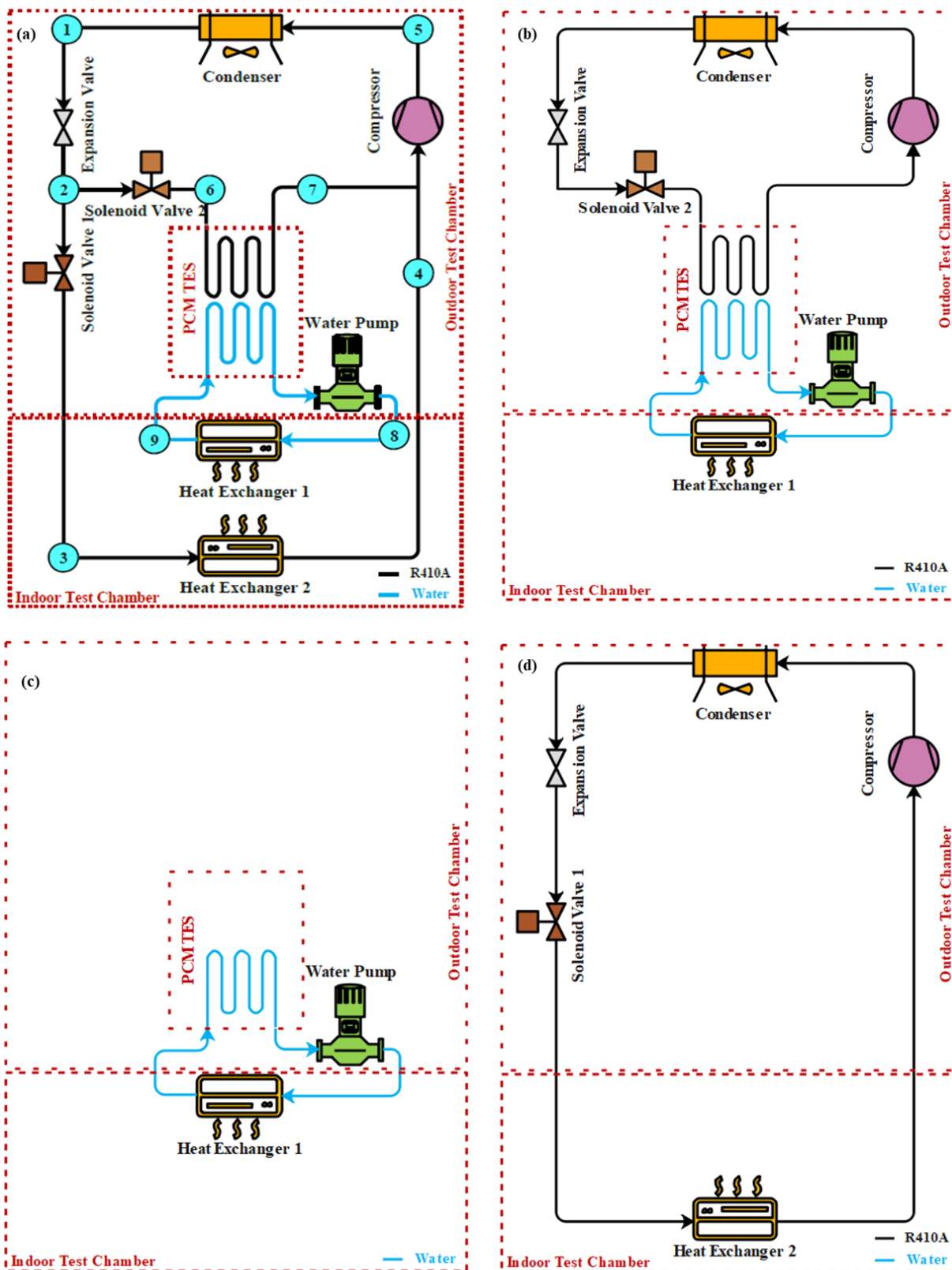


Fig. 5 The schematic of the a) conventional AC plus PCM TES, b) cold energy charging process, c) cold energy discharging process, d) conventional AC unit.

chamber (building). After that, it enters the compressor to complete the normal process of the conventional vapor compression cycle. The schematic of the conventional mode process is illustrated in Fig. 5d. Moreover, the power

consumption of the electrical heaters inside the indoor test chamber, which is measured by the wattmeter, plays the role of the cooling load demand of the building. In other words, the amount of the power consumption of the electrical heaters

inside the indoor test chamber is equal to cooling load production, named as the building accessible cooling load by the proposed system in each mode.

The specifications of the main equipment which are used in the desired experimental evaluation are listed in Table 3.

Table 3. The specifications of the main equipment used in this study.

Equipment	Description
AC Cooling Unit	12000 BTU rated cooling capacity Maximum input power = 1700 W Refrigerant Type = R410A Manufacture = General Max
Electrical Heater	5 electrical heaters with 2 kW power each one
Expansion Valve	MOP = 15 °C Design Type = Thermostatic Manufacture = Honeywell Temperature Range = -50 to 15 °C
Air Fan	Voltage = 380 V Power = 750 W 2800 RPM (Max) Manufacture = Moto Gen
Inverter	Power = 1.5 kW Model = LS iG5 A
Temperature Sensors	Model = PT 100 Error = ± 0.2 °C Range = -200 to 850 °C
Pressure Gauges	Error = 2.5% Range = 0 to 40 bar Type = Analog
Wattmeter	Type = Digital Error = 0.5%

2.5. Outdoor test chamber (ambient) temperature condition

To simulate the realistic imitation of ambient temperature in the outdoor test chamber, the weather data of Tehran city on its hottest day of the year have been given to the controller. The weather data information has been extracted from Meteororm software and then has been read by the TRNSYS software. The only parameter, which has been controlled in the outdoor test chamber is temperature, and the other climatic conditions, such as humidity, are constant during the test and have not been controlled.

Tehran city temperature changes over the 24 hours are indicated in Fig. 6. It is notable that the changes in the outdoor test chamber (ambient) during the day directly affect the performance of the vapor compression system condenser. Consequently, changes in condenser conditions lead to changing the whole system's performance. Also, the temperature variations in the indoor test chamber (building) and outdoor test chamber (ambient) have been measured by the thermometers and have been recorded by the SCADA software on a computer.

2.6. Performance indicators

To evaluate the performance of the proposed system, Equation (1), Equation (2), Equation (3), and Equation (4) have been used.

$$COP = \frac{Q_{Heaters}}{W_{comp} + W_{Pump}} \tag{1}$$

$$Q_{Heaters} = Q_{Building} = Q_{Hex,1} + Q_{Hex,2} \tag{2}$$

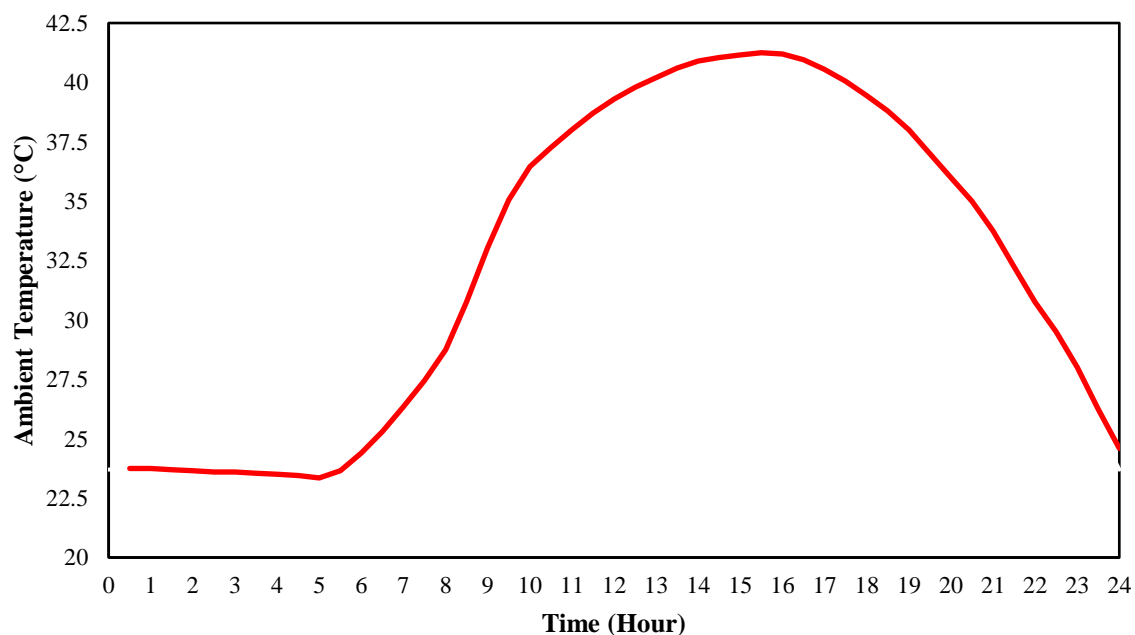


Fig. 6 The temperature changes of Tehran city at the hottest day of the year.

$$Peak\ load = Max\ power\ consumption - AVG\ power\ consumption\ of\ conventional\ cooling\ system \quad (3)$$

$$Peak\ load\ shaving = \left(\frac{Peak\ load\ of\ conventional\ system - Peak\ load\ of\ PCM\ integrated\ system}{Peak\ load\ of\ conventional\ system} \right) \times 100 \quad (4)$$

where COP, $Q_{Heaters}$, W_{comp} , and W_{Pump} are the system coefficient of performance, the electric heaters' energy consumption inside the indoor test chamber (counterbalancing cooling load production), vapor compressor energy consumption, and circulating water pump energy consumption, respectively. $Q_{Hex,1}$ and $Q_{Hex,2}$ also denote the cooling loads, which have been provided by heat exchanger 1 and heat exchanger 2, respectively. Since the indoor test chamber has been designed to imitate the building temperature conditions by using electrical heaters as consumers, the heat exchanger cooling load productions are equal to building (or electrical heaters) loads. Moreover, the differential between the system's maximum daily power consumption and the system's average daily power consumption for both conventional and AC plus PCM configurations have been calculated to evaluate the amount of peak load shaving based on Equation (3) and Equation (4). It should be noted the values of electrical heaters inside the test chamber, vapor compressor, and circulating water pump energy consumptions have been measured by the wattmeters and have been recorded by the SCADA software in a computer.

2.7 Experimental procedure

The performance of the proposed system has been conducted based on two scenarios. The operating function of each scenario is described below.

2.7.1 Scenario 1

In scenario 1, the AC unit operates non-stop during the 24 hours based on its maximum capacity to produce cooling loads. The aims of scenario 1 are to determine the maximum accessible cooling load during 24 hours and estimate the maximum accessible cooling load or maximum allowable building cooling load demand during on-peak hours (12:00 – 19:00). In other words, the changes of maximum accessible cooling load or maximum allowable building cooling load demand during 24 hours by adding PCM TES to the conventional AC unit so that the room temperature remains within the specified comfort zone have been examined in the proposed scenario.

In the proposed scenario, the cold energy charging process of the PCM storage tank only occurs between 00:00 to 8:00. During this time, all of the cooling load production by the vapor compression system is stored in the PCM TES. During the proposed time, the AC plus PCM unit cannot transfer cooling load energy to the building.

As mentioned before, the cold energy discharging process of the melting PCM only happens between 12:00 to 19:00 (Fig. 5c). During this time, the AC compressor is switched off, and the stored cooling energy of the PCM TES is used at this time to absorb the heat from the indoor test chamber. So, the power consumption of the AC plus PCM unit is significantly reduced during cold energy discharge mode from 12:00 to 19:00. However, the amount of AC plus PCM building accessible cooling load demand is less than the conventional AC unit during this time. During this time, the system's performance has been calculated from Equation (5) and Equation (6). During the proposed time, only heat exchanger 1 provides the consumers' heating load demand (Building load).

$$COP = \frac{Q_{Heaters}}{W_{Pump}} \quad (5)$$

$$Q_{Heaters} = Q_{Building} = Q_{Hex,1} \quad (6)$$

During the other times of the day, which are 8:00 to 12:00 and 19:00 to 24:00, the vapor compression system works as the conventional AC mode with no PCM TES involvement at its maximum cooling load capacity (Fig. 5d). The system's performance during this time has been calculated from Equation (7) and Equation (8). During the proposed time, only heat exchanger 2 provides the consumers' heating load demand (Building load).

$$COP = \frac{Q_{Heaters}}{W_{comp}} \quad (7)$$

$$Q_{Heaters} = Q_{Building} = Q_{Hex,2} \quad (8)$$

where $Q_{Building}$ denotes heaters' energy consumption inside the indoor test chamber. It should be noted that the operating function of the system based on scenario 1 has also been done for the conventional AC system (with no PCM TES involved) to evaluate the influence of integrating a PCM TES to the conventional AC unit. The vapor compression system alone is operated non-stop during 24 hours at its maximum capability. The system's performance for the conventional AC mode during 24 hours has been calculated from Equation (7) and Equation (8).

Also, in order for this comparison to be made precisely, the power consumption of the electrical heaters inside the indoor test chamber, which is equal to cooling load production, have been adjusted in a way to maintain the temperature inside the building within a comfort zone of 23 - 25 degrees for all modes and scenarios.

2.7.2 Scenario 2

In scenario 2, a building cooling load demand profile has been

scheduled for the indoor test chamber by turning ON and OFF the electric heaters. The aim of scenario 2 is to evaluate the compressor's energy consumption based on the fulfillable building cooling load demand profile over 24 hours. In other words, the changes in energy consumption of the AC unit's compressor during 24 hours by adding the PCM TES to the conventional AC unit have been examined in the proposed scenario.

In the proposed scenario, the cold energy charging process of the PCM only occurs between 00:00 to 8:00 (Fig. 5b). During this time, all of the cooling load production by the vapor compression system is stored in the PCM TES. Meanwhile, the required cooling load for the indoor test chamber (building cooling load demand) is only provided by the circulating water pump from the PCM TES. In other words, some portion of the cooling load being stored in the PCM TES is re-used during the cold energy charging process to supply the cooling load demand of the test chamber (building cooling load demand). The system's performance during this time has been calculated from Equation (5) and Equation (6).

It should be noted that the operating function of the system based on scenario 2 has also been done for the vapor compression system alone (with no PCM TES involved) to evaluate the influence of adding a PCM TES to an AC unit. The conventional AC system is also operated based on the fulfillable cooling load demand profile for the indoor test chamber. Also, the temperature inside the building is always maintained in an acceptable range (23 - 25 degrees). The system's performance for the conventional AC unit during 24 hours has been determined from Equation (7) and Equation (8).

The daily fulfillable building cooling load demands profile based on scenario 2 operating conditions is shown in Fig. 7

based on Tehran city climatic conditions. The fulfillable building cooling load demand of Tehran city has been determined according to the off-peak and on-peak hours. So, the building requires more cooling load demand during on-peak hours, as shown in Fig. 7. Also, the daily fulfillable building cooling load demand profile has been determined through the process of trial and error in a way that all of the stored cold energy in the PCM storage tank is consumed during the day.

3. Results and discussion

It should be noted that the measurement equipment, which are wattmeters, pressure indicators, and thermometers, have errors of up to 2.5%. So, their error impacts on the results are insignificant. The T – S diagrams of the conventional AC unit and AC plus PCM unit during the charging process are depicted in Fig. 8. As can be seen, Fig. 8a shows the charging process when the AC plus PCM unit is about to freeze the PCM storage tank. Fig. 8b indicates the charging process when the AC plus PCM unit is about to charge the PCM storage tank. According to Fig. 8a, when the PCM storage tank is about to freeze, the evaporator temperature and pressure decrease. So, the compressor power consumption increases in AC plus PCM mode compared to conventional AC mode. According to Fig. 8b, when the PCM storage tank is about to charge, the evaporator outlet temperature rises. Consequently, the amount of the evaporator outlet stream superheat value increases. So, the refrigerant stream enters the compressor at a higher temperature compared to the conventional AC one. Therefore, the AC plus PCM compressor consumes more power during the charging process compared to the conventional AC unit.

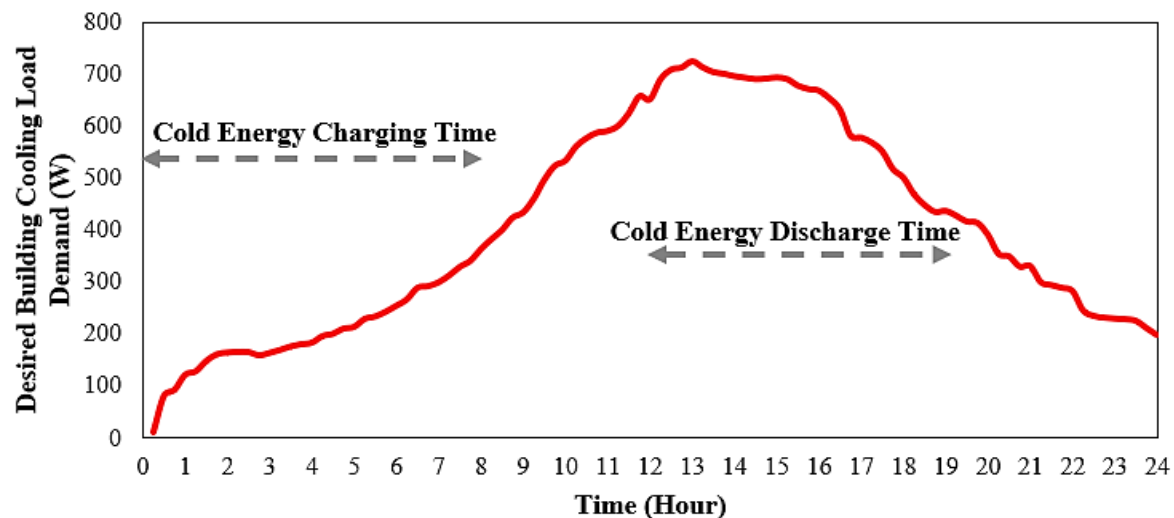


Fig. 7 The daily fulfillable building cooling load demands profile of scenario 2 operating condition based on Tehran city weather conditions.

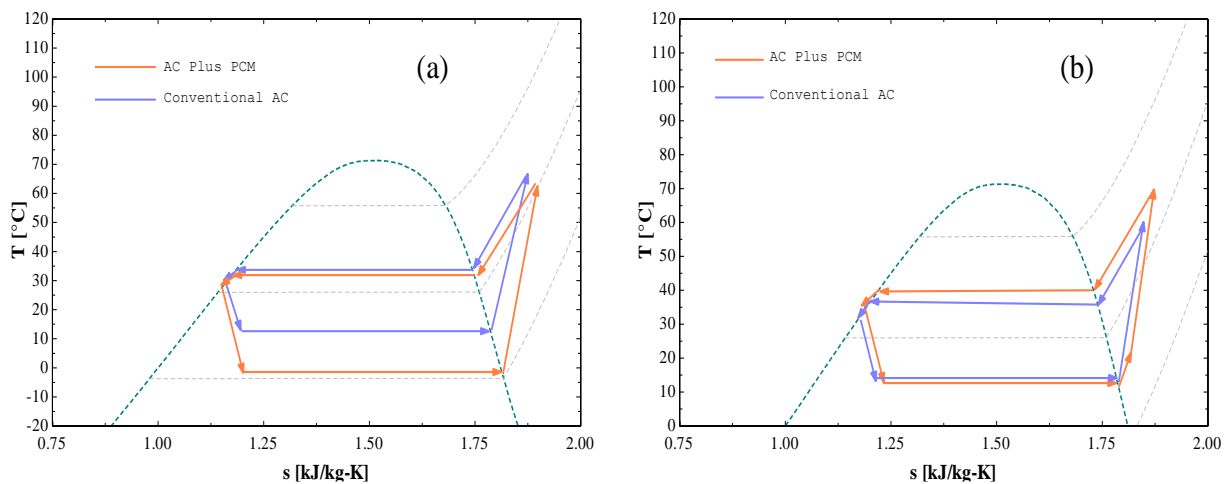


Fig. 8 The T-S diagrams of the charging process in PCM and conventional modes for a) storage tank temperature about 0 °C b) storage tank temperature about 21 °C.

3.1 Scenario 1 results

The changes in accessible cooling load and power consumptions of the AC unit plus PCM and the conventional AC system with no PCM TES involvement based on scenario 1 operating conditions are shown in Fig. 9 over 24 hours based on Tehran city climatic conditions. As can be seen from 00:00 – 8:00, the indoor accessible cooling load is equal to the whole cooling load production of the conventional AC system since no PCM TES is involved. While during the cold charging process, the AC plus PCM unit is stored all of the accessible cooling load production in the PCM tank, and accessible cooling load is not received by the indoor test chamber. Then the stored accessible cooling load in the PCM TES is re-used during on-peak hours from 12:00 – 19:00 when the AC plus compressor is switched off. This leads to a significant reduction in the amount of electric energy consumption of the AC plus PCM system during the cold energy discharging

process. However, the amount of its accessible cooling load production is less than the conventional AC during the proposed time. The conventional AC unit's maximum electric power load during this cold energy discharging time based on Tehran city climatic conditions is about 1186 watts which is about 755% higher than that of the conventional AC plus PCM unit.

As it can be seen in Fig. 9, during cold energy discharging time from 12:00 – 19:00, the AC plus PCM accessible indoor cooling load reaches its maximum at the beginning and then decreases due to the reduced cooling energy drainage from the PCM TES as a result of the melting process and increase in thermal resistance. As we get closer to the end of cold energy discharging time (19:00), the cooling load extraction from the PCM significantly reduces. The amount of stored cooling energy is highly dependent on the system's performance during cold energy charging hours from 00:00 – 8:00.

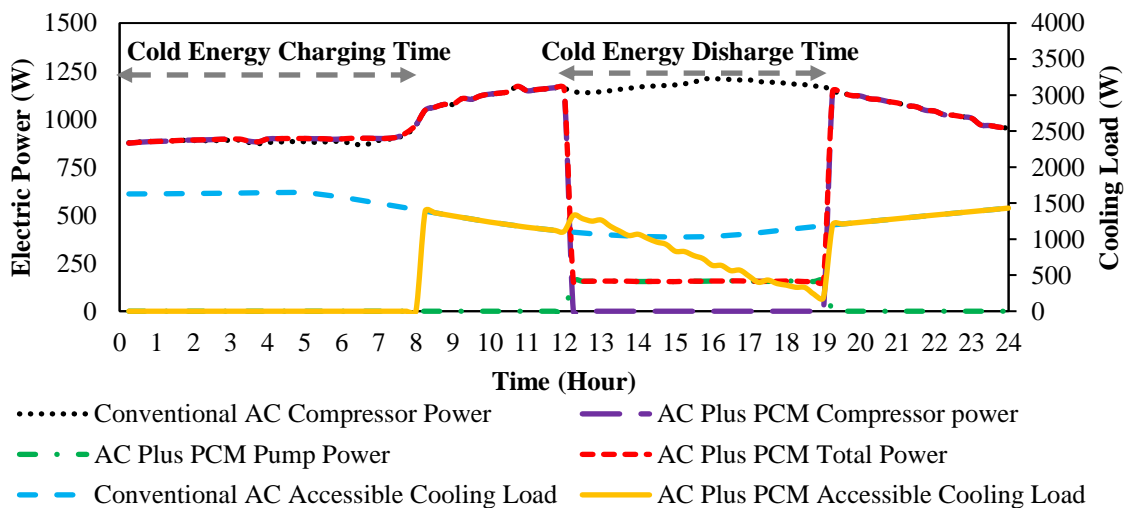


Fig. 9 The changes in cooling load production and power consumption of the AC unit with PCM and with no PCM involvement based on scenario 1 over 24 hours.

The influence of the ambient temperature (outdoor test chamber temperature) on the performance of the conventional AC unit is indicated in Fig. 9. It can be seen that the accessible cooling load reaches its maximum from 00:00 – 8:00 based on Tehran city climatic conditions due to its lower ambient temperature (outdoor test chamber) during the proposed time compared to other times of the day. In contrast, it reaches its minimum during on-peak hours from 12:00 – 19:00 due to the higher ambient temperatures (outdoor test chamber) during the proposed time compared to other times of the day. Tehran city's maximum accessible cooling load power from 00:00 – 8:00 is about 1650 watts. While during on-peak hours, it reduces to 1029 watts. It can be seen that ambient temperature plays a significant role in the amount of conventional AC unit accessible cooling load.

The ambient temperature also affects the compressor power consumption, as shown in Fig. 9. It can be seen that the conventional AC unit's compressor power consumption reaches its minimum from 00:00 – 8:00 based on Tehran city climatic conditions due to the lower ambient temperature compared to other times of the day. In contrast, it reaches its maximum during on-peak hours from 12:00 – 19:00 due to the higher ambient temperature compared to other times of the day. Tehran city's compressor power reaches 865 watts from 00:00 – 8:00. In comparison, it increases up to 1210 watts during on-peak hours from 12:00 – 19:00. So, adding the PCM TES to the conventional AC unit can sharply reduce the amount of electric power consumption during the charging process.

Accordingly, the changes in ambient temperature affect the AC system's condenser pressure and temperature. In this regard, condenser temperature and pressure increase as the ambient temperature increases. Hence, the AC unit's compressor must consume more power to boost the refrigerant pressure from the evaporator pressure up to the condenser pressure. Also, the amount of cooling load production is affected according to the proposed changes.

The results of the daily performance of the conventional AC system with no PCM TES involvement and the AC plus PCM based on scenario 1 operating conditions are summarized in Table 4. Also, the changes in the performance of the AC plus PCM compared to the conventional AC one are stated in Table 5. It should be noted that the negative sign in Table 5 indicates a decrease in the desired parameters after adding the PCM TES to the conventional AC unit. The positive sign indicates an increase in the desired parameters after adding the PCM TES to the conventional AC unit.

It can be seen that adding PCM TES to the conventional AC unit leads to a reduction in daily total accessible cooling energy based on Tehran city climatic conditions, which has

Table 4. The daily results of the conventional AC system (with no PCM TES involved) and AC plus PCM unit based on scenario 1 operating conditions.

Mode	Conventional AC	AC Plus PCM
Daily Total Accessible Cooling Energy (kWh)	31.8	16.8
Daily Total Compressor Energy Consumption (kWh)	25.1	16.9
Daily Total Pump Energy Consumption (kWh)	0.00	1.1
Daily Total Electric Energy Consumption (kWh)	25.1	18.0
Daily Average COP	1.3	0.9
COP at On-peak Hours (12 – 19)	0.9	4.9
Accessible Cooling Energy at On-peak Hours (12 – 19) (kWh)	7.5	5.3
Electric Energy Consumption at On-peak Hours (12 - 19) (kWh)	8.2	1.1

been obtained by integrating accessible cooling load over time. It happens due to the heat transfer loss during the cold energy charging and discharging processes. Moreover, the AC plus PCM unit's evaporator temperature (PCM TES temperature) is less than the conventional AC unit's evaporator temperature (heat exchanger 2) due to the PCM melting temperature (0 °C) during the cold energy charging process from 00:00 – 8:00. So, it decreases the AC plus PCM unit's evaporator pressure, which reduces the daily total accessible cooling energy. Furthermore, the AC plus PCM unit doesn't transfer any cooling load to the indoor test chamber (building) during the cold energy charging process (00:00 – 8:00). So, during the cold energy charging process, the accessible cooling energy production by the AC plus PCM is equal to zero. In contrast, the conventional AC unit operates at its maximum capacity to provide accessible cooling energy during the proposed time to take heat from the indoor test chamber (building). Also, the AC plus PCM unit's compressor is switched off during the cold discharging process, which leads to decreasing the amount of accessible cooling energy production by the AC plus PCM system. As can be seen in Table 5, adding the PCM TES to the conventional AC unit leads to 47.2% reduction in daily total accessible cooling energy based on scenario 1 operating conditions.

From the electric energy point of view, adding the PCM TES to the conventional AC system reduces daily total electric energy consumption (time-integral of electric power). Since the AC plus PCM unit's compressor is switched off during the cold energy discharging process (12:00 – 19:00) and only a circulating water pump works during the proposed time, its daily total electric energy consumption is less than the

conventional AC one. According to Table 5, the AC plus PCM unit's daily total electric energy consumption has been reduced by 28.2% compared to the conventional AC one. This value is about 86.8% during on-peak hours (12:00 – 19:00). Consequently, adding the PCM TES to the conventional AC unit leads to shaving the electric peak load by about 24.1%. Although adding the PCM TES to the conventional AC unit leads to decreasing the daily average COP by about 26.42% compared to the conventional AC one, it improves the COP during the cold energy discharging process (on-peak hours) by about 430.4%. It can be seen that adding PCM TES to the conventional AC unit based on scenario 1 operating conditions leads to a significant reduction in daily total accessible cooling energy. In contrast, it reduces daily total electric energy consumption, especially during on-peak hours. Moreover, the COP of the system is sharply improved during on-peak hours.

Table 5. The reduction and increase of the AC plus PCM unit parameters compared to the conventional AC system based on scenario 1 operating conditions.

Parameters	Variations
COP at On-Peak Hours (%)	430.4
Accessible Cooling Energy at On-Peak Hours (%)	-29.8
Electric Energy Consumption at On-peak Hours (%)	-86.8
Daily Averaged COP (%)	-26.4
Daily Total Accessible Cooling energy (%)	-47.2
Daily Total Electric Energy Consumption (%)	-28.2
Electric Peak Load Shaving (%)	24.1

The COP changes for conventional AC and AC plus PCM units during the 24 hours based on the scenario 1 operating conditions are shown in Fig. 10. As can be seen, the

conventional AC COP decreases during on-peak hours and increases during the night. The AC plus PCM COP equals zero during the charging process. Because all of the cooling load production by the AC plus PCM unit is stored in the PCM storage tank during the charging process. So, the cooling load is not sent to the building (AC plus PCM accessible cooling load = 0) during the proposed time. The COP significantly increases during on-peak hours due to switching off the AC unit compressor. The AC plus PCM COP is decreased by reducing the amount of stored cooling energy. However, its value is higher than the conventional AC unit during the whole on-peak hours (12:00 – 19:00).

3.2 Scenario 2 results

The changes in fulfillable building cooling load demand and power consumptions of the AC unit plus PCM and the conventional AC system with no PCM TES involvement based on scenario 2 operating conditions are shown in Fig. 9 over 24 hours based on Tehran city climatic conditions. According to Table 6, Tehran city, with a daily average ambient temperature of 35.1 °C, has a daily total fulfillable building cooling energy demand of 9.6 kWh.

As shown in Fig. 11, the total electric energy consumption of the AC plus PCM during cold energy charging hours (00:00 – 8:00) is higher than the conventional AC one. During the proposed time, the conventional AC unit only needs to provide the fulfillable building cooling load demand profile. In comparison, the AC plus PCM charges the PCM TES in addition to supplying the fulfillable building cooling load demand profile. So, the AC plus PCM compressor works at its maximum capacity during cold energy charging hours, which

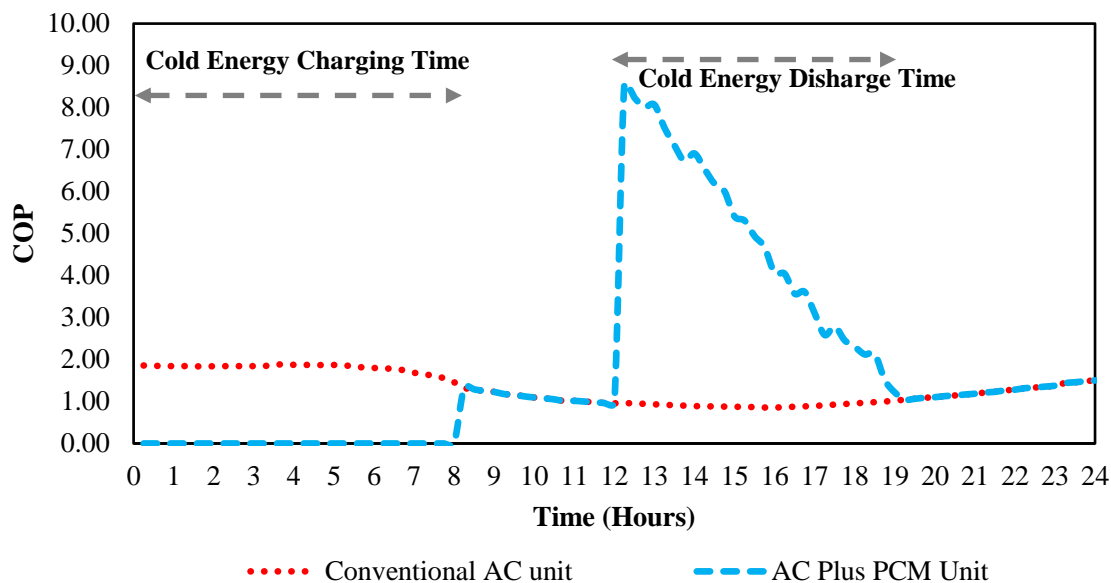


Fig. 10 The COP variations of the AC plus PCM and conventional AC units during 24 hours based on scenario 1 operating conditions.

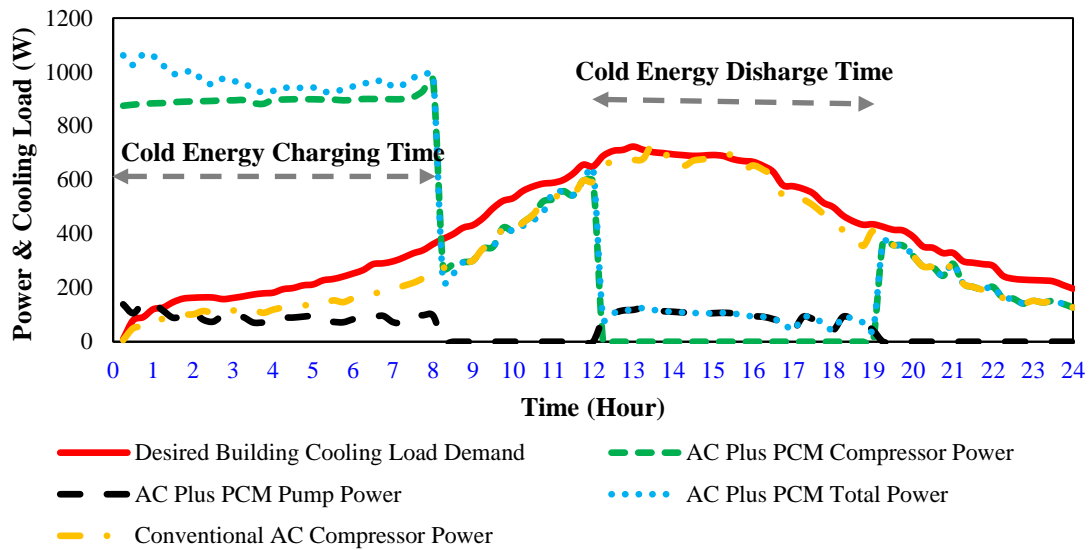


Fig. 11 The changes in power and cooling load of the refrigeration system in PCM and without PCM modes based on case 2 scenario.

leads to increasing electric energy consumption during the proposed time. It should be noted that the fulfillable building cooling load demand profile during the cold energy charging hours has been provided from PCM TES by the circulating water pump. In other words, the AC plus PCM operates at cold energy charge and discharge modes simultaneously during the proposed time. As a result, the total electric consumption of the AC plus PCM during cold energy charging hours is the summation of the compressor and circulating water pump electric energies consumptions.

During the cold energy discharge hours (12:00 – 19:00), the AC plus PCM unit’s compressor is switched off, and the building cooling load demand is provided from the PCM TES alone by the circulating water pump. In other words, during the proposed hours, the cold energy stored in the PCM TES is transferred to the indoor test chamber (heat exchanger 1) by a circulating water pump. It reduces electric energy consumption compared to the conventional AC one during the cold energy discharge hours. According to [Table 6](#), the AC

plus PCM system can reduce the electric energy consumption by up to 84.5% compared to the conventional AC unit during the on-peak hours. However, the AC plus PCM system based on scenario 2 operating strategy leads to increasing total electric energy consumption compared to the conventional AC one over 24 hours. In this regard, Tehran’s daily total electric energy consumption rises by about 39.0% compared to the conventional AC unit.

The COP changes for conventional AC and AC plus PCM units during the 24 hours based on the scenario 2 operating

Table 6. The performance of the AC plus PCM based on scenario 2 operating condition.

Parameters	Value
Reduction in Electric Energy Consumption Compared to the Conventional AC at On-peak hours (%)	84.5
Daily fulfillable Building Cooling Energy Demand (kWh)	9.6
Increase in Daily Total Electric Energy Consumption Compared to the Conventional AC (%)	39.0

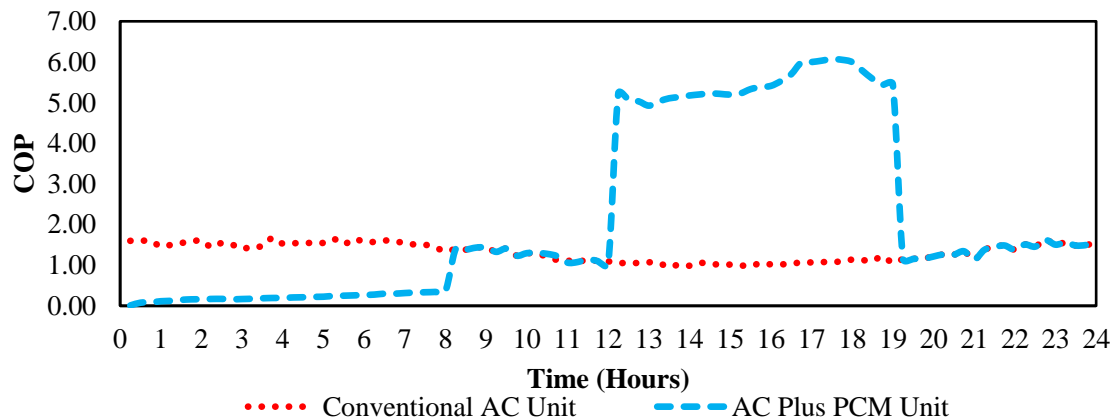


Fig. 12 The COP variations of the AC plus PCM and conventional AC units during 24 hours based on scenario 2 operating conditions.

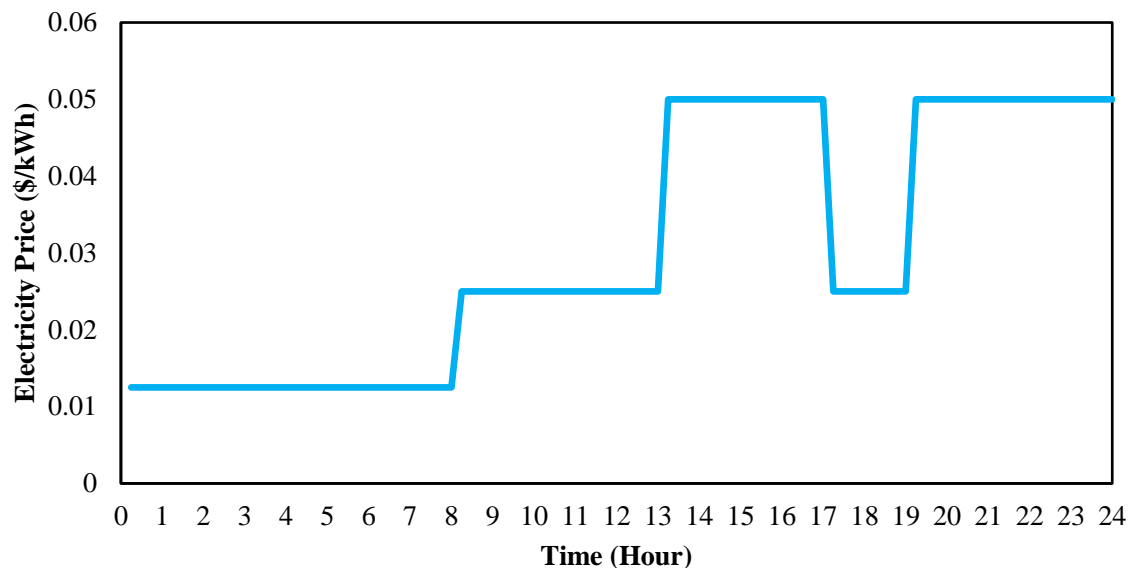


Fig. 13 Electricity prices for different hours during the summer days in Iran.

conditions are shown in Fig. 12. As can be seen, the conventional AC COP decreases during on-peak hours and increases during the night. The AC plus PCM COP is lower than the conventional one during the charging process. Because all of the cooling load production by the AC plus PCM unit is stored in the PCM storage tank during the charging process, and some portion of it is used by the water pump in the case of required cooling load demand. The COP significantly increases during on-peak hours due to switching off the AC unit compressor. During this time, only the water pump is working. The AC plus PCM COP is higher than the conventional AC unit during the whole on-peak hours (12:00 – 19:00).

3.3 Economic results based on scenario 2 operating conditions

The changes in electricity price, which are given by the Iranian power distribution company, is illustrated in Fig. 13. As can be seen, during the on-peak hours, the tariff price is at its maximum value, while during the night is at its minimum value. Although the AC plus PCM unit consumes more electric energy compared to the conventional one, its electricity price is reduced by about 20.7%. It happens due to the high electricity price value during on-peak hours in which the AC plus PCM unit compressor is switched off. Moreover, the electricity price value during the night is minimum in which the AC plus PCM unit stores cooling energy to re-use it during on-peak hours.

4. Conclusion

In this study, the performance of an AC unit has been

conducted experimentally based on two scenarios. In each scenario, two states have been compared, which are the conventional AC system (with no PCM involved) and the AC plus PCM system. The analysis has been performed according to Tehran city ambient temperatures (outdoor test chamber temperature) over 24 hours. Moreover, the precise realistic imitation of temperature conditions for outdoor (condenser, compressor, *etc.*) and indoor (evaporator) units of the vapor compression system is provided by the two separated test chambers with the help of the controller. Based on scenario 1 operating strategy, adding the PCM TES to the conventional AC system leads to decreasing daily total COP and daily total accessible cooling energy by about 26.4% and 47.2%, respectively. On the other hand, it boosts COP during on-peak hours (12:00 – 19:00) by about 430.4%. Moreover, based on scenario 2 operating strategy, adding the PCM TES to the conventional AC unit increases total electric consumption over 24 hours by about 39.0%. However, it reduces by about 84.5% during cold energy discharge hours. Although the AC plus PCM unit consumes more electric energy compared to the conventional one, its electricity price is reduced by about 20.7% based on scenario 2 operating conditions.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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