Energy Reduction of the Air-Conditioner by Using a Packed Ball of Phase Change Storage

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Abstract

In this study, a new concept of using phase change material (PCM) for improving cooling efficiency of an air-conditioner by installing at an evaporator and a condenser have been presented under Thai climate. Rubitherm20 (RT-20) is selected to evaluate the thermal performance by reducing the air temperature entering the air-conditioner. The model of PCM celluloid balls have been performed with the air-conditioner to verify with the testing results. For the experiment, 2 TR of R-134a air-conditioner is chosen to test a packed bed of PCM balls with thickness 40 cm. The pressure drops of the air flowing through the bed are considered with and without a set of by-pass tubes along the height of the storage bed. From the study results, it could be seen that pressure drops of the bed with and without bypass tubes were nearly the same results. Thus, PCM ball packed bed using RT-20 without bypass tubes was used to improve the cooling efficiency of air-conditioner at the evaporator and the condenser, respectively. The testing results also shown that the simulated data of the PCM temperature and the air leaving PCM bed temperature agreed quite well with the experimental results at the discrepant around 2.73% and 4.61%, respectively. The economic results found that the electrical power consumption of the modified air-conditioner decreased 3.09 kWh/d and 1.71 kWh/d in cases of installing at the evaporator and the condenser, respectively. Moreover, the saving costs of the modified systems at the evaporator and the condenser could be 8.87% and 5.76% at the payback period were 4.27 y and 6.55 y, respectively.

Keywords: Air-conditioner, Phase change material, Rubitherm20, Thermal energy storage, Thermal performance

Introduction

Phase change material (PCM) is used in office building in various literature for heating and cooling processes. In heating process, PCM is applied to warm the air entering the room and reduces the electrical power of the air heater as presented by Kedl, & Stovall, 1989. Salyer, & Sircar, 1990. and Neeper, 1989. Neeper, 2000, pp. 393-403 . In the cooling process, the main electrical energy consumption is decreased by reducing the load of the machine. Some researchers have used phase change material (PCM) which is used to charge the latent heat capacity of the PCM by freezing the material and the stored energy is released back to the occupied space to handle the heat gains during daytime. presented a cooling method by integrating PCM into ceiling board of a building. Outside cool night air could be introduced into the space and used to cool the building interior and the PCM storage. During the daytime, hot indoor air was circulated to absorb cooling load and reduced the room temperature. This technique could reduce energy for cooling between 10-87 % depended on the air flow rate. Arkar, Vidrih, Medved, 2005, pp. 8-20. designed a latent heat storage (LHTES) integrating with a mechanical ventilation system. A paraffin encapsulated of LHTES stored coldness of ambient air during the night and supplied it with time delay during the day thus free cooling was obtained. This research corresponded with Yamaha, & Misaki, 2006, pp. 861-869. which proposed an air distribution system with PCM in air ducts for peak load shaving. The PCM storage was charged from 5:00 am to 8:00 am (the charging mode) by the air flowing in the closed loop of the PCM storage tank and the air conditioner to solidify the storage medium. When the charging operation finished, the ordinary air-conditioning operation started, in which the air was bypassed the PCM storage tank and fed into the occupied room. The discharging operation was occurred from 13:00 pm to 16:00 pm. At this mode, the air after the air-conditioner at a temperature slightly higher than that of the PCM melting point would flow through the PCM tank and the room, respectively. The simulation study based on a part of one floor of an office building in Japan showed that the use of 400 kg PCM (MT 19, the melting temperature around 19 ^{o}C). From the above studies, it could be found that PCM was used with the various techniques. But those concepts of PCM did not use with the country near equator which the weather was higher than the countries in literatures.

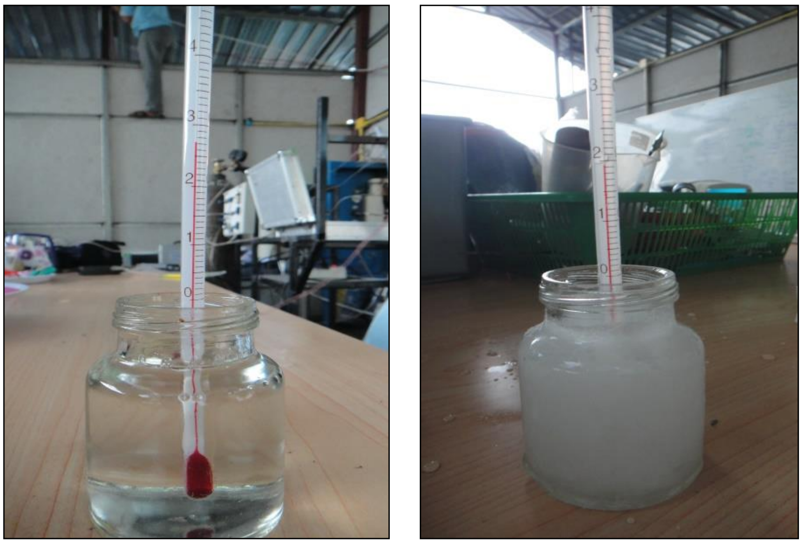
Thus in this study, a concept similar to Yamaha, & Misaki (2006, pp. 861-869) was considered with the climate of Chiang Mai, Thailand which was hotter than that of Japan and another country reported in the literatures. Moreover, a new concept for using the PCM ball with the evaporator and the condenser was presented for improving the COP of the air-conditioner. The design of the PCM bed was a pack of PCM balls similar to that of Arkar, et al., pp. 8-20 and a set of tubes as a by-pass for air flowing to reduce the pressure drop was respected combining with the PCM bed. An experimental study performed in a tested room with a cooling load around 2 TR. Therefore the main objective is to find out the energy and economic results of the PCM packed ball when it integrated with the air-conditioner at the evaporator and the condenser.

Materials and Methods

For phase change material (PCM), rubitherm20 (RT-20) was used to improve the thermal performance of the air-conditioner. The melting temperature point of RT-20 was around 20 ^{o}C which was lower than the return air temperature and it was also higher than the supply air and the ambient temperatures. The properties of the RT-20 were given in Table 1 and Figure 1 Figure 2 also shows the PCM ball in this experiment. The celluloid contained the RT-20 into the PCM ball at around 70% by volume.

Table 1 Descriptions of the RT-20 properties (“Phase”, n.d.; Khudhair, & Farid, 2007; Fieback, & Linderberg, 2005).

RT-20	Properties
Paraffin melting peak point (°C)	22
Freezing peak point (°C)	20
Heat of fusion (kJ/kg)	160-180
Density liquid (kg/l)	0.75
Volume expansion	10 %



a) RT-20 at the liquid phase. b) RT-20 at the solid phase.

Figure 1 The liquid and solid phases of RT-20 at temperature around 27 °C and 18 °C, respectively.

Figure 2 The PCM ball used in the PCM bed.

The concept similar to Yamaha, & Misaki, 2006, pp. 861-869. as shown in Figure 3 (a) was used in this study. In the charging mode, the supply air from the evaporator was used to cool and solidify the PCM storage during the off-peak period as shown in Figure 3 (b). During the daytime, the air-conditioner was used to control the air entering the room at the temperature around 16-20 ^{o}C. The return air at a temperature slightly higher than that of the PCM melting point around 22-25 ^{o}C was fed through a 40 cm PCM bed as shown in Figure 3 (c). Then the air entering the evaporator had lower temperature than the normal system which meant that the cooling load was reduced. Thus the electrical power consumption of the air-conditioner could be reduced. For using PCM with the condenser, the PCM bed was used to reduce the ambient temperature at around 35 ^{o}C to be around 30 ^{o}C as shown in Figure 3 (d). Then the air temperature entering the condenser decreased, the refrigerant temperature at condenser was decreased and the electrical power of compressor could be decreased. The COP and the electrical power of the air-conditioner had been investigated.

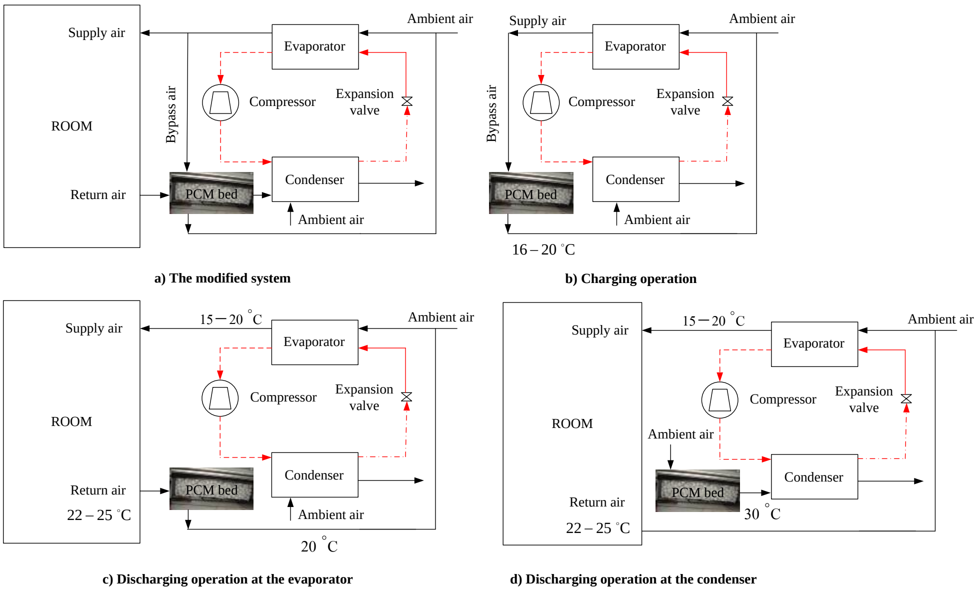


Figure 3 Schematic of the modified air-conditioner system.

An experimental setup was built and tested in a well-insulated room which composed of a R-134a air conditioner of 2 TR (24,000 BTU/h) with air-cooled condenser, a set of PCM packed bed, a type-T of thermocouple, a data acquisition unit. The main data to evaluate the thermal performance of the air-conditioner was temperature. Thus, type-T of thermocouple was calibrated at the cavitation range ± 0.5 °C. The data acquisition unit converted and transferred data from thermocouple to the personal computer. Table 2 also shows the descriptions of the air-conditioner components.

Table 2 Descriptions of air-conditioner components.

Devices	Type	Properties
Fan coil	Fin and Tube heat exchanger	Capacity 7.032 kW Tube Size (OD) 5.0 mm Fins per inch 18 (FPI) No. of Rows & Column 2R, 15C
Compressor	Hermetic (Rotary) compressor R-134a	Capacity 2.868 kW Compression ratio 6.0 Max
Condenser	Fin and Tube heat exchanger	Capacity 5.275 kW Tube Size (OD) 7.0 mm Fins per inch 18 (FPI) No. of Rows & Column 2R, 36C
Expansion valve	Orifice type Thermo static	Capacity 7.032 kW Pressure ratio 3.00

The storage medium was paraffin having the melting point of around 19-22 °C. Paraffin contained in a set of plastic balls and kept in a packed bed as shown in Figure 4 The pressure drop of the air flowing through the bed was considered. If it was too high, a set of by-pass tube along the height of the storage bed was used to reduce the pressure drop. This concept had been used successfully in a PCM bed sensible heat storage (Fieback, & Linderberg, 2005, pp. 18-20)

Figure 4 Installing the PCM bed in the return duct.

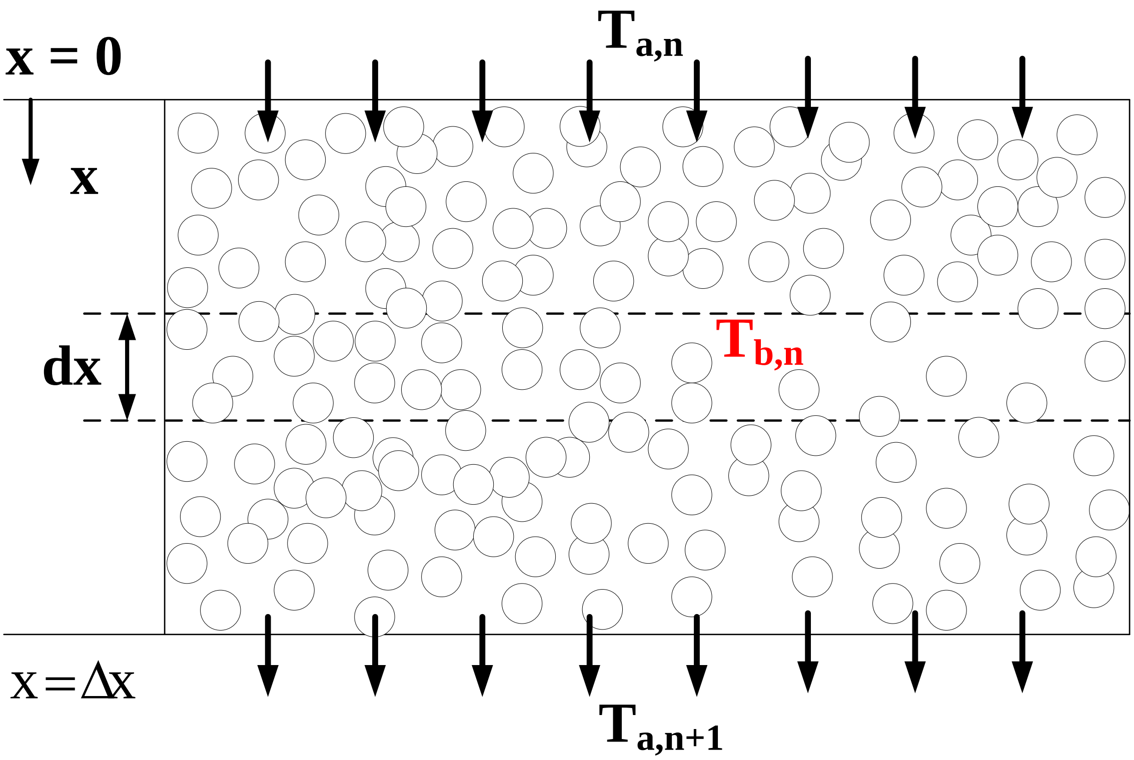


Figure 5 Energy balance in the thermal storage.

From the Figure 4, the thermal storage could be represented by the simply model in Figure 5 The air entering the thermal storage bed transfers heat to PCM which could be calculated the air temperature leaving the PCM bed by theory of energy balance and heat transfer equation as follows:

$$\dot{m}_a Cp_a dT_a = h_v (Adx)(T_{b,n} - T_a), \quad (1)$$

$$h_v = a\left(\frac{G}{D_b}\right)^b, \quad (2)$$

$$G = \frac{\dot{m}_a}{A}, \quad (3)$$

$$\frac{dT_a}{dx} = \left(\frac{h_v A}{\dot{m}_a Cp_a}\right)(T_{b,n} - T_a) \quad (4)$$

Boundary condition of the PCM is assumed as:

$$BC_1 : x = 0 \longrightarrow T_a = T_{a,n}, \quad (5)$$

$$BC_2 : x = \Delta x \longrightarrow T_a = T_{a,n+1}, \quad (6)$$

$$\frac{T_{a,n+1} - T_{b,n}}{T_a - T_{b,n}} = \exp\left(-\frac{h_v A}{\dot{m}_a Cp_a}\Delta x\right), \quad (7)$$

$$T_{a,n+1} = T_{b,n} + \left(T_{a,n} - T_{b,n}\right)\cdot \exp\left(-\frac{h_v A \Delta x}{\dot{m}_a Cp_a}\right). \quad (8)$$

Thus, the convection heat transfer coefficient could be shown by equation as:

$$\dot{m}_a Cp_a (T_{a,n} - T_{a,n+1})\Delta t = \rho_b A \Delta x (1-e)\Delta h, \quad (9)$$

$$\Delta h = \frac{\dot{m}_a Cp_a \left(T_{a,n} - T_{a,n+1}\right)\Delta t}{\rho_b A \Delta x (1-e)}. \quad (10)$$

From the performance of PCM, it is found that the temperature of PCM varies with the phase change of PCM as shown in Figure 6 Thus, the PCM bed temperature of each period could be calculated by enthalpy as follows:

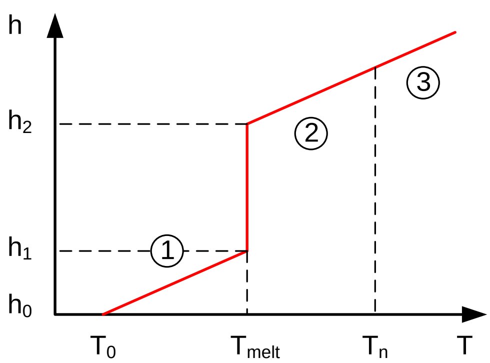


Figure 6 Enthalpy and temperature profile of PCM.

Period 1, the variant temperature of PCM at solid phase:

$$\Delta h \le Cp_{(S)}(T_{melt} - T_0), \tag{11}$$

$$T_b = T_0 + \frac{\Delta h}{Cp_{(S)}}. \tag{12}$$

Period 2, the melting point of PCM:

$$Cp_{(S)}(T_{melt} - T_0) \le \Delta h \le Cp_{(S)}(T_{melt} - T_0) + l, \tag{13}$$

$$T_b = T_{melt}. \tag{14}$$

Period 3, the variant temperature of PCM at liquid phase:

$$\Delta h \ge Cp_{(S)}(T_{melt} - T_0) + l, \tag{15}$$

$$T_b = T_0 + \left[\frac{\left(\Delta h - Cp_{(S)}(T_{melt} - T_0) - l\right)}{Cp_{(L)}}\right]. \tag{16}$$

The step for calculating the thermal storage performance of PCM ball was shown in Figure 7 In the calculation, the properties of the air entering bed and RT-20 were used to find out the PCM bed temperature and the air leaving PCM bed temperature.

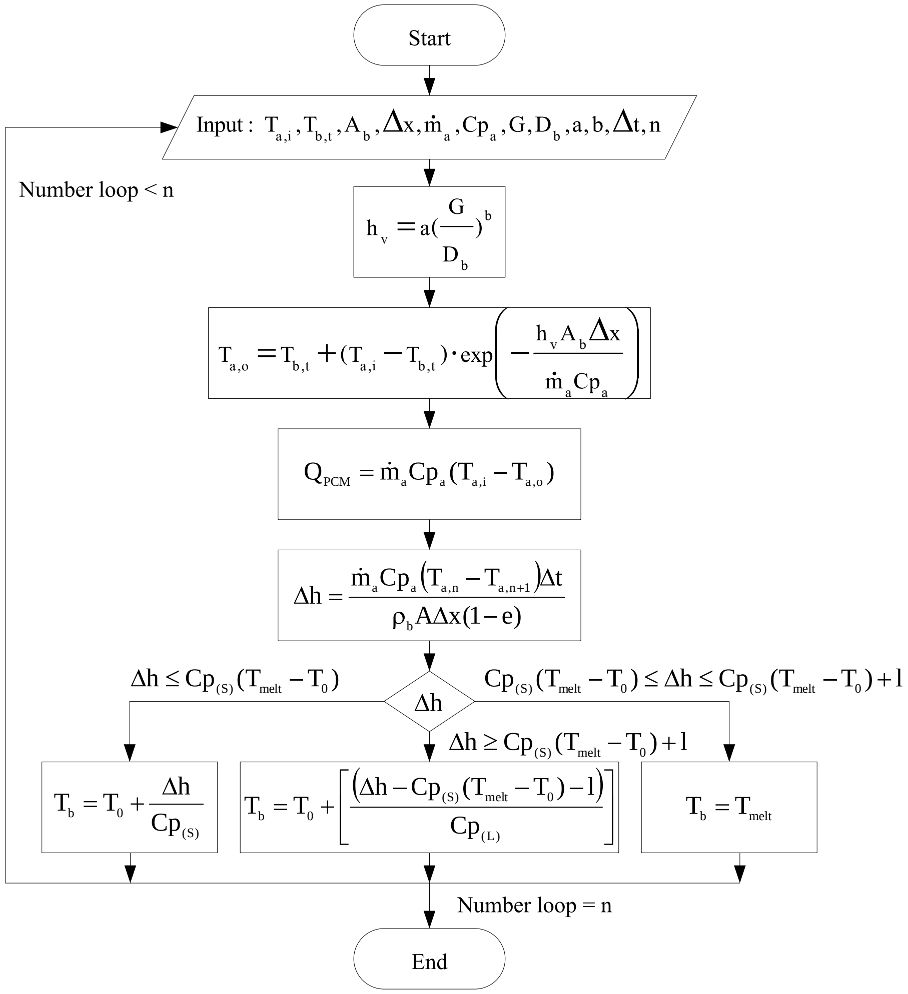


Figure 7 Flow chart of the simulation program for evaluating the PCM bed temperature and the air leaving PCM bed temperature.

Results and Discussions

The Suitable sizing of the PCM Bed

From the calculation, the PCM bed at area of 20 cm x 80 cm was varied to find out the appropriate thickness. It could be found that the suitable thickness of the PCM bed for using in the on-peak period between 9:00-12:00 am combined with 2 TR of the air-conditioner was 40 cm as shown in Table 3. Thus in this study, the sizing of PCM bed at 20 cm x 80 cm x 40 cm was used to improve the thermal performance of the PCM ball bed integrating with the air-conditioner.

Table 3 Discharge time of the PCM for varying thickness of the PCM bed.

Properties	Data				
The PCM bed thickness (cm)	20	30	40	50	60
Discharge time (min)	75	108	182	297	453

Pressure Drop

Table 4 shows the measuring data of pressure drop between the PCM bed with thicknesses of PCM bed at 40 cm bed and the diameter of bypass tube at 3/8 inch. It could be seen that pressure drops of the bed with and without bypass tubes were nearly the same. Therefore, the bed without bypass tubes was chosen in the next study. Moreover, the air velocity of without bypass tubes was rather uniform for the whole cross-section compared with the bed installed bypass tubes.

Table 4 Pressure drop between the PCM bed for varying the numbers of bypass tube.

Conditions	Pressure drop (in H_2O)
The number of bypass tube at 0 tube	0.37
The number of bypass tube at 5 tubes	0.36
The number of bypass tube at 10 tubes	0.33
The number of bypass tube at 15 tubes	0.31

Thermal Performance of the Normal Air-conditioner

In this study, the single-stage vapor compression air-conditioner having R-134a as refrigerant had been used to transfer heat of a room temperature and relieved to the environment at a higher temperature level. From the experimental results, it could be found that its energy efficiency ratio (EER_{AC}: a ratio of heat at the evaporator and the electrical power consumption) could be set up as a function of temperature difference between the surrounding ambient (T_{amb}) and the room temperature (T_r) as shown in Figure 8 The EER_{AC} decreased when the temperature difference of the heat source and heat sink increased. The result was similar to the studies of Kiatsiriroat, Chaiyat, & Sanjit, 2012, pp. 24-26. Kiatsiriroat, & Chaiyat, 2010, pp. 11-12. The EER_{AC} dropped down and an empirical correlation of these parameters could be fitted as:

$$EER_{AC} = -0.2811(T_{amb}-T_r) + 5.7915. \quad (17)$$

For the consumed electrical power, the value also depended on the temperatures of the ambient and that of the air-cooled which was correlated as:

$$W_{Comp} = 0.0829\,(T_{amb} - T_r) + 2.7851. \quad (18)$$

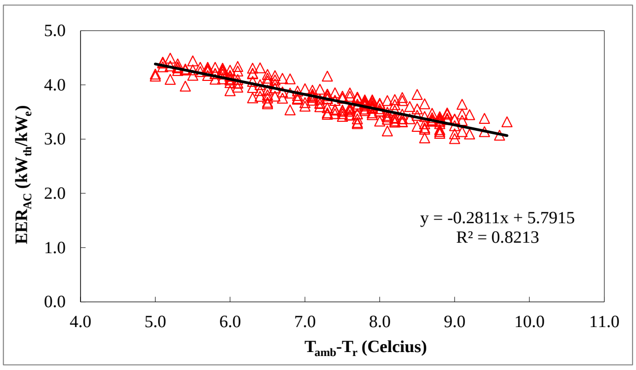


Figure 8 Thermal performance curve of the normal air-conditioner.

From the result in Figure 8, it could be noted that it the air temperature entering the condenser decreases, the electrical power consumption of the compressor decreases too and the system COP of air-conditioner could be increased which followed the Carnot efficiency concept.

Thermal Performance of the Modified Air-conditioner

Figure 9 shows the temperature profile of the air-conditioner units combined with PCM bed at the thickness of 40 cm. It could be seen that the operating cycle of the modified system could be separated into 3 modes which included charging mode, discharging mode and normal mode. In charging mode, the supply air from the evaporator at the temperature around 15 °C was used to cool and solidify the PCM bed during the off-peak period at 6:00-9:00 am around 3 hr for the PCM bed thickness of 40 cm. In discharging mode, the high temperature air was fed through the PCM bed and reduced the air temperature ($T_{a,PCM,o}$) to be around the PCM melting point ($T_{PCM,ave}$) at about 20 °C. Thus the air temperatures entering evaporator and condenser decreased. The both temperatures effected directly to reduce the cooling load at evaporator and the heating load at condenser. The electrical power consumption of the air-conditioner could be saved during the on-peak period. In normal mode, all the PCM was melted into liquid phase, then the air-conditioning was switched back to the normal air-conditioner to control the air temperatures leaving the evaporator and the condenser.

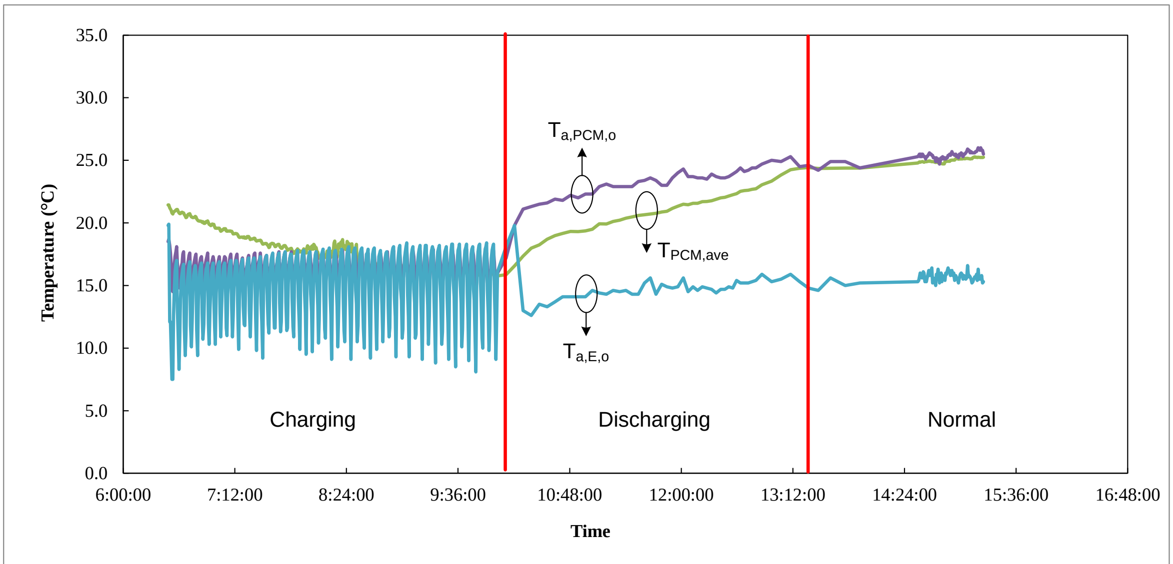


Figure 9 Temperature profile of the modified air-conditioner at thickness of the PCM bed at 40 cm.

Verification of the Simulation Results with the Experimental Data

For the study procedures, the mathematical model of PCM ball bed was developed to predict the thermal performances of the PCM storage. The objective of this procedures was to verify data with the testing data from the constructed of modified air-conditioner.

Table 5 shows the initial data of the simulation process to predict behavior of the set of 40 cm PCM unit. Figure 10 shows the temperature profile of hot air entering the PCM bed ($T_{a,PCM,i}$) which affects to the air leaving PMC bed temperature ($T_{a,PCM,o}$) of the discharging period. Moreover, Figure 10 also represents the comparison result of the measured data and the simulation result of the air leaving PMC bed temperature. It could be seen that the simulated result agreed quite well with the experimental data at the discrepant around 4.61%. And, Figure 11 shows the comparison result of the measured data and the simulation result of the PCM temperature (T_{PCM}) of the discharging period which was effected from the hot air in Figure 10 It could be found that the simulated result of the PCM temperature was similarly with the experimental data at the discrepant around 2.73%.

For the cooling capacity of PCM bed (Q_{PCM}), the comparison result of measured data and calculated data was also nearly well as shown in Fig. 12. It could be seen that Q_{PCM} gradually decreased and reached the lower level which meant that the PCM temperature and the air leaving bed temperature gradually increased similarly the results in the Figure 10 and Figure 11, respectively.

Table 5 Initial conditions of the mathematical model.

Descriptions	Data	Unit
Bed section area (A)	0.16	m^2
Bed thickness (Δx)	0.4	m
Number loop (n)	3	-
PCM ball diameter (D_b)	0.04	m
PCM density of liquid PCM ($\rho_{(L)}$) (Chaichana, Chaiyat, Khunatorn, & Kiatsiriroat, 2013, pp. 13-15)	770	kg/m^3
Heat capacity of liquid PCM ($Cp_{(L)}$) (Chaichana, Chaiyat, Khunatorn, & Kiatsiriroat, 2013, pp. 13-15)	2.3	kJ/kg·K
PCM density of solid PCM ($\rho_{(S)}$) (Chaichana, Chaiyat, Khunatorn, & Kiatsiriroat, 2013, pp. 13-15)	880	kg/m^3
Heat capacity of solid PCM ($Cp_{(S)}$) (Chaichana, Chaiyat, Khunatorn, & Kiatsiriroat, 2013, pp. 13-15)	2.4	kJ/kg·K
Heat fusion ($\Delta h = h_{melt}$) (Chaichana, Chaiyat, Khunatorn, & Kiatsiriroat, 2013, pp. 13-15)	177.7	kJ/kg
Void fraction (e) (Chaichana, Chaiyat, Khunatorn, & Kiatsiriroat, 2013, pp. 13-15)	0.4	-
Air velocity flow rate at fan coil (V_a)	1.415	m/s
Heat capacity of air (Cp_a)	1	kJ/kg·K

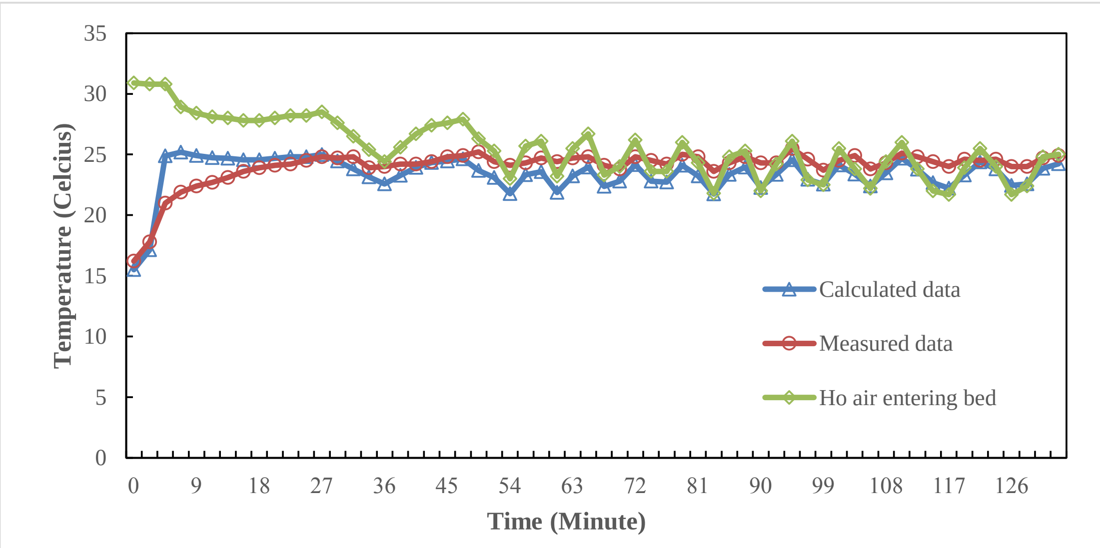


Figure 10 Comparison results of the measured data and the simulation results of the air leaving PMC bed temperature.

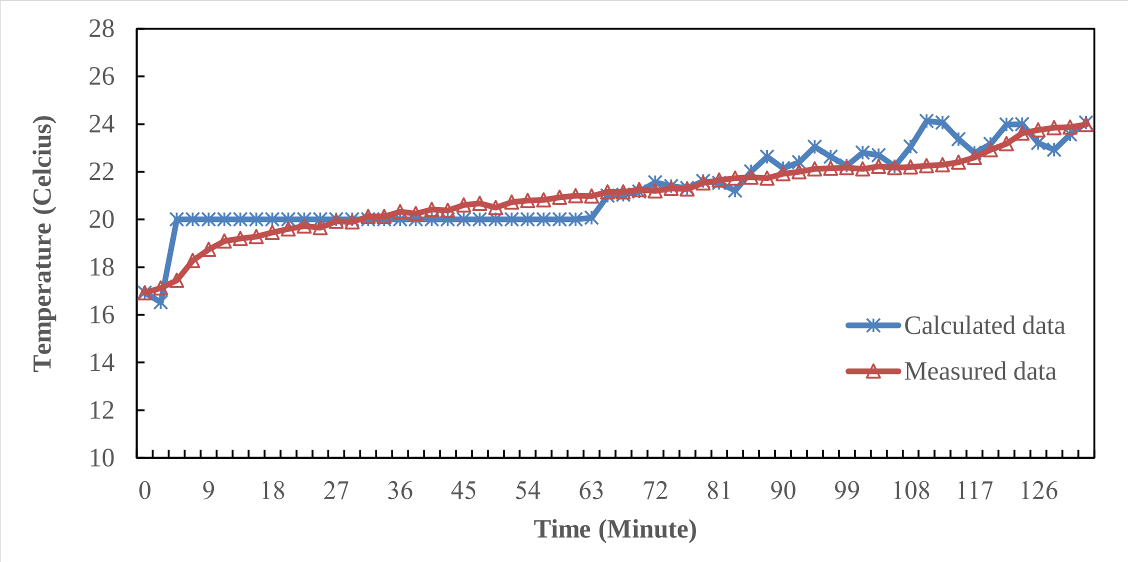


Figure 11 Comparison results of the measured data and the simulation results of the PCM temperature.

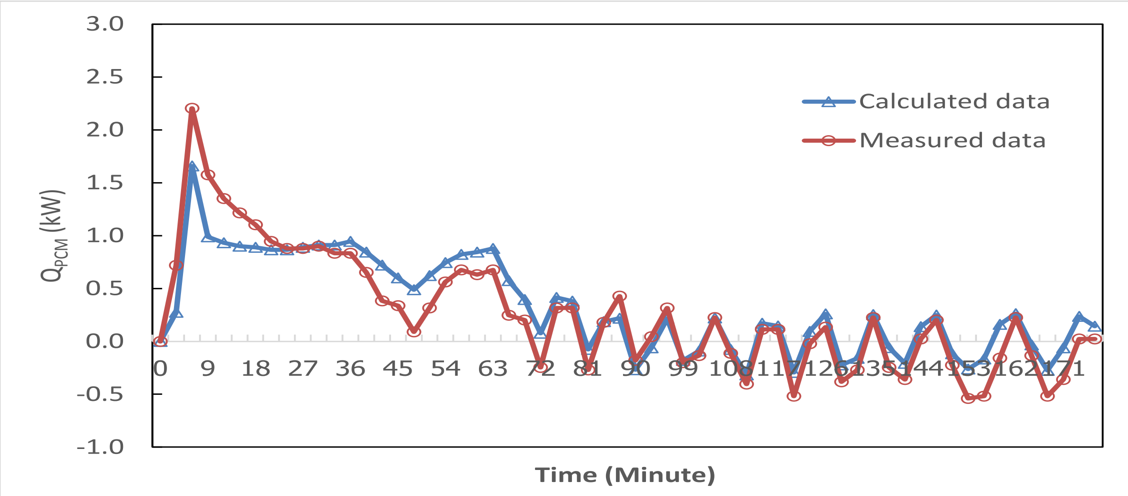


Figure 12 Comparison results of the measured data and the simulation results of the cooling capacity of PCM bed.

From the comparison results, it could be seen that the mathematical model could be used to simulate the performances of the PCM bed. In additional, the results in Figure 10-12 also corresponded with the study of Yamaha, & Misaki (2006, pp. 861-869)which presented the PCM ball of MT-19 (the melting temperature around 19 °C) in household. The results shown that the temperatures of PCM and air leaving of bed were nearly with the melting point of PCM.

In the next step, two concepts for installing the PCM packed ball bed were carried out the thermal performance of each case by using the mathematical model. Energy efficiency and economic result of the both cases had been compared to evaluate the best solution for using the PCM bed with the air-conditioner in Thailand.

Economics Result

Table 6 also shows the electrical power consumptions of the air-conditioner with and without the PCM bed assisted at thickness 40 cm. It could be found that the average daily electrical power consumption of using the PCM bed at the evaporator could be saved around 3.09 kWh/d from 39.36 kWh/d of the normal air-conditioner. For using the PCM bed at the condenser, it could be saved around 1.71 kWh/d. The electricity costs could be saved around 18.28 Baht/d (0.56 USD/d) and 12.43 Baht/d (0.38 USD/d). The general conditions for economic analysis of the systems were as follows:

A. Number of day for using the air-conditioner	300	d/y
B. Electricity charge (Time of use rate: TOU)	household	(1.2.2)
Voltage level of transmission line	< 22	kV
C. Operating time		
The normal air-conditioner system	12	h/d
	9.00-21.00	o'clock
The modified air-conditioner system	15	h/d
Charging mode	6:00-9:00	o'clock
	3	h/d
Discharging mode	9:00-12:00	o'clock
	3	h/d
Steady mode	12.00-21.00	o'clock
	9	h/d
D. Rubitherm 20	400	Baht/liter

Table 6 Electrical power consumption of the normal system and the modified systems.

Air-conditioner	Operating time (h/d)	Electrical power (kW)	Electrical power consumption (kWh/d)	Electricity cost (Baht/d)
The normal system	12	3.28	39.36	197.21
The modified system by using the PCM bed at the evaporator				
Charging period	3	0.84	2.52	5.50
Discharging period	3	1.41	4.23	17.93
Steady period	9	3.28	29.52	155.49
Total	15	-	36.27	178.93
Saving			3.09	18.28
The modified system by using the PCM bed at the condenser				
Charging period	3	0.84	2.52	5.50
Discharging period	3	1.87	5.61	23.78
Steady period	9	3.28	29.52	155.49
Total	15	-	37.65	184.78
Saving			1.71	12.43

The electrical power saving cost of the modified systems at the evaporator and condenser were 8.84% and 5.76%, respectively, compared with the normal system which the payback period were 4.27 y and 6.55 y, respectively, as shown the descriptions in Table 7 From the saving energy results, it could be found that this research output corresponded with which the PCM storage could reduce energy for cooling at around 10% depended on the air flow rate.

From the above results, it could be concluded that the PCM ball integrating with the evaporator was beneficial than installing at the condenser based on energy efficiency and economic results.

Table 7 The economic results of the modified system.

Descriptions	The normal system	The modified system	
		At the evaporator	At the condenser
PCM cost at 57.6 liter (Baht)	0	23,040	23,040
Electricity cost per year			
Peak 9.00 – 22.00 o'clock (Baht)	40,724.53	36,503.08	37,541.51
Off peak 22.00 – 9.00 o'clock (Baht)	1,534.13	1,838.15	2,053.30
Holiday 0.00 – 24.00 o'clock (Baht)	7,363.81	6,785.70	7,043.88
Ft (Baht)	6,966.72	6,419.79	6,664.05
Total cost per year (Baht/y)	61,041.17	55,645.73	57,524.68
Saving			
Percentage (%)	-	8.84	5.76
Cost (Baht/y)	-	5,395.43	3,516.49
Cost (Baht/y·TR)	-	2,697.72	1,758.24
Payback period (y)	-	4.27	6.55

Conclusion

From this study, the conclusions are as follows:

1. The PCM ball with using RT-20 could be improved the cooling efficient of the air-conditioner.

2. Pressure drops of the bed with and without bypass tubes was nearly the same results. Thus, the bed without bypass tubes was used for this study.

3. The simulated results of the PCM temperature and the air leaving PCM bed temperature agreed quite well with the experimental data at the discrepant around 2.73% and 4.61%, respectively.

4. In case of installing the PCM bed at the evaporator, the electrical power saving cost of the modified system was around 8.84% compared with the normal system which was around 5,395.43 Baht/y (165.16 USD/y) at payback period was 4.27 y.

5. In case of installing the PCM bed at the condenser, the electrical power saving cost of the modified system was around 5.76% compared with the normal system which was around 3,516.49 Baht/y (107.64 USD/y) at payback period was 6.55 y.

Acknowledgements

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Abbreviations and Symbols

Nomenclature

A	Area, (m^2)
Cp	Specific heat capacity, (kJ/kg·K)
D	Dimeter, (m)
e	The correction space value of PCM ball bed (Void faction)
G	Mass flow rate per area, (kg/s·m^2)
h	Enthalpy, (kJ/kg)
h_v	Convection heat transfer coefficient, (W/m^3·K)
$\dot{m}$	Mass flow rate, (kg/s)
T	Temperature, (°C)
v	velocity flow rate, (m/s)
W	Work, (kW)
x	Distance, (m)
Q	Heat capacity, (kW)

Greek symbol

ρ	Density, (kg/m^3)

Subscript

a	Air
AC	Air-conditioner
ave	Average
amb	Ambient
b	Bed
Comp	Compressor
e	Electrical power
E	Evaporator
i	Input
L	Liquid
n	Node
o	Output
PCM	Phase change material
S	Solid
Sys	System
th	Thermal
r	Room

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