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Performance enhancement of unitary and packaged air conditioners with phase change material

Abstract

A novel method of lowering condensing temperature of unitary and packaged air conditioners from 55⁰C to around 45⁰C is proposed with Phase Change Material (PCM) around the channels of Mini Channel Heat Exchanger (MCHE). Primary components of an air-conditioning system along with MCHE with PCM around its mini channels are modeled in MATLAB. A case study is performed considering the temperature-time profile of two Indian cities, viz. Jaipur, and Hyderabad to estimate the hourly energy consumption and saving in electrical energy input at various timings throughout the day, particularly in peak summer. Simulation results show that on an average there will be 15 to 25% reduction in power consumption with enhanced performance of an air conditioner throughout the year. Melting of PCM in MCHE begins at around 10.00 hours and continue up to around 22.00 hours during peak summer months depending on the geographical region and then onwards solidification begins and the entire PCM solidifies by around 10.00 hours depending on the temperature of outdoor air during the night. The maximum quantity of PCM required is estimated to be 375 kg per TR with latent heat of fusion of 201 kJ/kg.

Keywords: performance enhancement, mini channel heat exchanger, phase change material, energy saving

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Nomenclature

A_{fin} Condenser finned surface area, m²

A_i Condenser tube internal surface area, m²

A_{MCHE} MCHE outer surface area, m²

A_{min} Minimum flow area on fin side, m²

c_p Specific heat of refrigerant, kJ/kg-K

H Specific enthalpy of refrigerant, kJ/kg

h_{tp} Two phase condensing heat transfer coefficient, kW/m²-⁰C

h_a Fin side convective heat transfer coefficient, kW/m²-⁰C

h_{aMCHE} Micro channel inside convective heat transfer coefficient, kW/m²-⁰C

k_{PCM} Thermal conductivity of PCM, kW/m-⁰C

k_l Thermal conductivity of refrigerant, kW/m-⁰C

m Mass flow rate of refrigerant, kg/s

m_a Mass flow rate of coolant air, kg/s

L_{PCM} Latent heat of fusion of PCM, kJ/kg

Pr Prandtl number

Pcomp Compressor power consumption, kW

PCM_{melt} Rate of melting of PCM in MCHE, kg/hr

PCM_{freez} Rate of freezing of PCM in MCHE, kg/hr

P_r Reduced pressure

Q_0 Cooling load of building, kW

Q_{cond} Heat rejected at the condenser, kW

Q_{MCHE} Heat rejected at the MCHE, kW

Re Renolds number

St Stanton number

T Mean temperature difference,⁰C

U_c Overall heat transfer coefficient of condenser, kW/m²-⁰C

U_{MCHE} Overall heat transfer coefficient of MCHE, kW/m²-⁰C

x_{PCM} Mean thickness of PCM around micro channel, m

x Quality of refrigerant vapor

η_c Compressor efficiency

Introduction

During warmer months of the year, and in regions with year-round hot climates, much of the building's electricity demand comes from the air conditioning unit. Atmospheric temperature of 45⁰C is common in most parts of the world in peak summer and hence, the designed condensing temperature of an air conditioner is usually set around 55⁰C, considering 10⁰C temperature difference between the condensing refrigerant and coolant air for efficient heat transfer. Higher the condensing temperature, higher the corresponding condensing pressure, more the power consumption per Ton Refrigeration (TR), and lower the coefficient of performance of an air conditioner. Further, operating an air conditioner with designed peak discharge pressure throughout the day and throughout the year is not recommendable as high coolant air temperature will not prevail throughout the year and throughout 24 hours in a day at the cost of decreased performance. Hence, there must be a way out to tackle this problem and to design and operate an air conditioner with low condensing pressure considering the average temperature of atmospheric air during warmer months of the year. In the present work, a novel method of lowering the condensing temperature of an air-conditioning unit using PCM is proposed. The hourly saving in electrical energy and the quantity of PCM required per Ton Refrigeration is estimated.

Content

Reference citations

Nan Wang et al.,[1] presented the electricity consumption estimation model of a computer center in South Africa to evaluate the power consumption of air conditioner at different temperatures. Pere Moreno et al.,[2] presented a literature review of phase change materials applicable to domestic heat pumps. A shell and tube latent heat storage system using heptadecane for cooling of air was analyzed by MR Anisur[3], Antoni Gil et al.,[4] studied thermal energy storage using PCMs applicable to refrigeration systems. Nattaporn Chaiyat et al.,[5] conducted experiments in an air-conditioned room with a refrigeration load around 2 TR and calculated the electricity consumption for the ordinary system and the system with the PCM. Nattaporn Chaiyat[6] presented a concept of using PCM for improving coefficient of performance of an air-conditioner. A mathematical model with energy storage using PCM was presented and verified with the experimental results. Marcello De Falco et al.,[7] investigated the possibility of using a PCM-based thermal storage unit in a residential air conditioning system. Parameshwaran R et al.,[8] investigated a variable volume chilled water-based air conditioning system coupled with the thermal energy storage. Muriel Iten et al.,[9] investigated the effects of the air inlet temperatures and velocities on the charging/discharging time of the PCM panels. MA Said et al.,[10] investigated the effect of using nano-particles with a PCM on the performance of an air-conditioning unit. The micro channel heat transfer characteristics were reviewed by Yanhui Han et al.,[11] The performance of air conditioner with mini and micro channel heat exchanger was investigated by Shemal K Pamar.[12] The heat transfer coefficient and pressure drop in micro-channel and fin-and-tube heat exchanger were estimated by Rin Yun et al.[13] The performance improvement of air conditioner while using the same face area micro channel condenser with that of fin-and-tube condenser was investigated. Four types of micro channel heat exchangers were presented and analyzed by Gaku H[14] for the use in air-conditioners. Single phase convective heat transfer through micro-channels was reviewed by Gian LM,[15] Jing Zhou et al.,[16] compared the performance of heat pump system using micro channel heat exchangers with that of heat pump system using tube and fin heat exchangers. G Hetsroni et al.,[17] investigated the heat transfer characteristics of micro channels with the liquid and gas flow. The pressure drop and heat transfer characteristics of a single phase micro channel heat sink were investigated by Weilin Qu et al.,[18] SS Mehendale et al.,[19] presented the unresolved thermal-hydraulic issues related to micro channel heat exchangers. Suhayla Younis Hussain[20] presented the experimental values of condensing heat transfer coefficient of R12 and R134a in a horizontal copper finned tube heat exchanger.

System description

The proposed air-conditioning system, shown in Figure 1, comprises a MCHE in addition to primary components such as evaporator, compressor, air cooled condenser and throttling device. The MCHE, shown in Figure 2, can specially be designed to have two banks of mini channels (0.96mm hydraulic diameter rectangular channel), one bank of channel to carry refrigerant and another bank of channel to carry air stream and is placed between condenser and throttling device. The super heated vapor discharged by the compressor condenses in the condenser when coolant air temperature is low and condensate flows from condenser to evaporator through throttling device bypassing MCHE. When the coolant air temperature is nearer to and above 38^{0}C, vapor discharged from the compressor is only de-superheated or de-superheated and partially condensed in the condenser and condensation mainly occurs in MCHE wherein the latent heat of condensing refrigerant is transferred to PCM which melts at 38^{0}C. When the coolant air temperature is nearer to or above melting temperature of PCM, the air flow through the MCHE is cut off and consequently the entire latent heat of vaporization liberated by the condensing refrigerant is absorbed by PCM. When the coolant air temperature drops below melting temperature of PCM, The air flow through the MCHE is set on and consequently the coolant air absorbs heat from PCM and solidifies it.

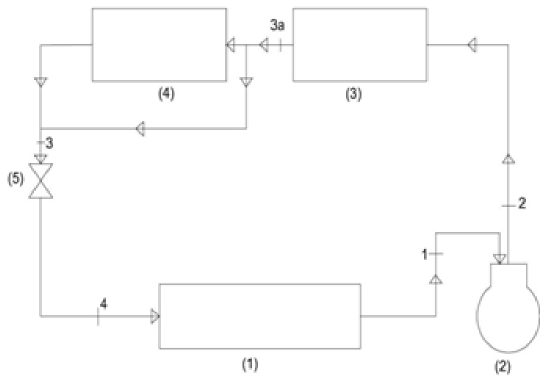

Figure 1 Air-conditioning system with PCM around MCHE, ((1) Evaporator, (2) Compressor, (3) Condenser, (4) MCHE, (5) Throttling device).

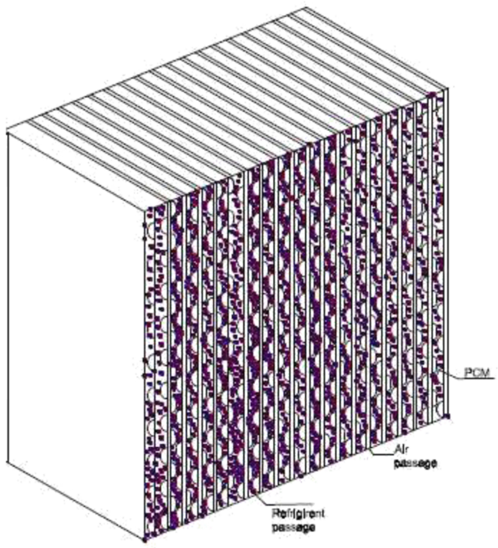

Figure 2 Mini-channel heat exchanger.

In this way, the air conditioner operates with low designed condensing temperature throughout the day and year and thus consumes less power per TR. The additional cost of MCHE is partially compensated by reduction in manufacturing cost of compressor and other units due to low operating pressure on the discharge side of compressor.

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Cooling load estimation

A typical residential building of size 12mx9mx3m is considered for cooling load estimation. The heat gain by the building from different sources is considered and the cooling load on air-conditioner is estimated as[1]

$$Q_0 = Q_{wall} + Q_{ceiling} + Q_{floor} + Q_{glass} + Q_{infiltration} + Q_{light} + Q_{miss} \quad (1)$$

Mathematical model

Thermodynamic analysis

Thermodynamic cycle of the proposed air-conditioning system is shown in Figure 3. Process 1-2 is the compression of refrigerant vapor in the compressor, process 2-3a is the heat rejection in the condenser at constant pressure, process 3a-3 is the heat rejection in the MCHE at constant pressure, and process 3-4 is the expansion of liquid refrigerant in the throttling device.

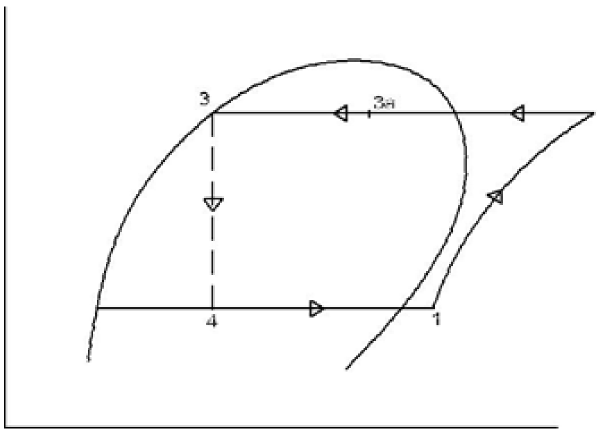

Figure 3 Thermodynamic cycle.

The heat rejected at the condenser and MCHE and the power consumption is estimated as follows

$$Q_0 = m\left(H_1 - H_4\right) \quad (2)$$

$$Q_{cond} = m(H_2 - H_{3a}) = U_c . A_{fin} T_{cond} \quad (3)$$

$$Q_{MCHE} = m(H_{3a} - H_3) = U_{MCHE} . A_{MCHE} T_{MCHE} = 3600 PCM_{melt} . L_{PCM} \quad (4)$$

$$P_{comp.} = m(H_2 - H_1) \;/\; \eta_c \quad (5)$$

Heat transfer model

The condenser and MCHE are modeled to determine the rate of melting/freezing of PCM around the mini channels of MCHE as given below.

Condenser

Horizontal copper finned tube of 15 mm internal diameter is considered with A_{fin}/A_i =12.0.

The two phase condensing heat transfer coefficient is estimated as[20]

$$h_{tp} = h_l (1-x)^{0.8} + \frac{3.8x^{0.76}(1-x)^{0.04}}{\mathrm{P_r}_{0.38}} \quad (6)$$

where, h_l is the liquid phase refrigerant side heat transfer coefficient and is calculated as,

$$h_l = 0.023 \frac{k_l}{d_{hi}} \mathrm{Re}_l^{0.8} \mathrm{Pr}_l^{0.4} \quad (7)$$

Fin side convective heat transfer coefficient is estimated as[20]

$$h_a = Stc_p m_a \;/\; A_{\min} \quad (8)$$

The overall heat transfer coefficient of condenser is calculated as

$$\frac{1}{U_c} = \frac{1}{h_{ap}} \frac{A_{fin}}{A_i} + \frac{1}{h_a} \quad (9)$$

MCHE - Melting of PCM around micro channels

The condensing heat transfer coefficient on the inner surface of micro channel is estimated by using the equations (6) and (7) as given above.

The overall heat transfer coefficient of MCHE is calculated as

$$\frac{1}{U_{MCHE}} = \frac{1}{h_{tp}} = \frac{x_{PCM}}{k_{PCM}} \quad (10)$$

MCHE - Freezing of PCM around micro channels

For the coolant air flow, the convective heat transfer coefficient on inner surface of micro channel is estimated as[18]

$$h_{aMCHE} = 0.00805 \frac{k_a}{d_{hi}} \mathrm{Re}\, dh^{0.8}\, \mathrm{Pr}^{1/3} \quad (11)$$

$$\frac{1}{U_{MCHE}} = \frac{1}{h_{aMCHE}} = \frac{x_{PCM}}{k_{PCM}} \quad (12)$$

Thermo-physical properties of PCM

Thermo-physical properties of hepta-decanone (PCM) are given in Table 1.

Table 1 Thermo-physical properties of hepta-decanone

Property	Value
Melting temperature, T_{melt}	38^{0C}
Latent heat of fusion, L_{pcm}	201 kJ/kg
Thermal conductivity, k_{PCM}	0.00021 kW/m-k

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Results and discussion

The power consumption of the air-conditioner at condensing temperatures of 55^{0}C, 50^{0}C, and 45^{0}C is plotted at different timings in Figure 4 for Jaipur weather conditions corresponding to May 15, 2018. The power consumption at 45^{0}C condensing temperature with PCM around mini channels of MCHE is less than that at 55^{0}C condensing temperature without MCHE. Hence, the proposed system of lowering the condensing temperature reduces the power consumption and saves electrical energy enormously throughout the year.

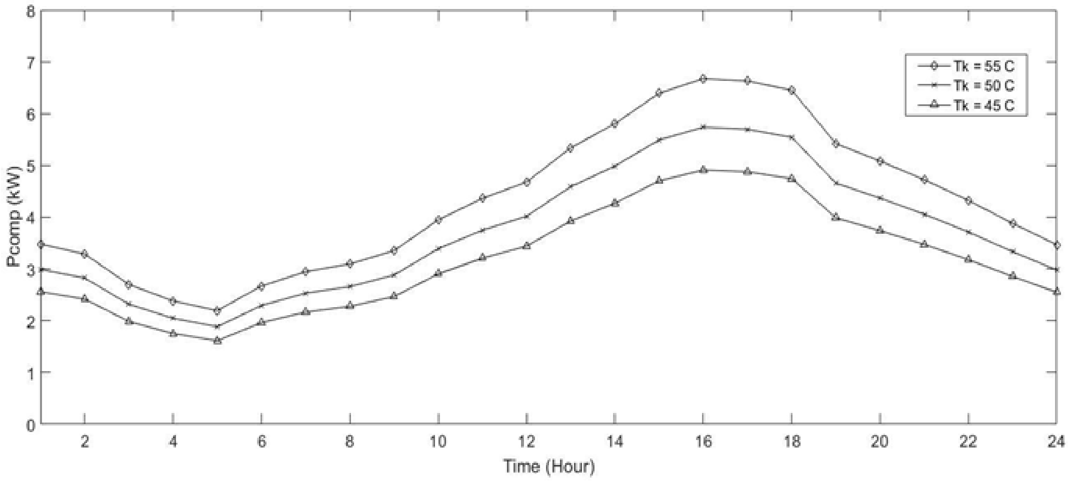

Figure 4 Power consumption of air-conditioner at different condensing temperatures against time.

Figure 5 shows the variation of cooling load of building, the heat rejected at the condenser and MCHE, and the power consumption of compressor of air-conditioning system at different timings of the day in peak summer corresponding to weather conditions in Jaipur on May 15, 2018. The cooling load of the building increases from 6 hours to 16 hours and then decreases. During peak hours of high outdoor air temperature, the heat rejection occurs at both the condenser and MCHE from 10 hours to 22 hours. Later on, the entire heat is rejected at the condenser when the temperature of outdoor coolant air is low and sufficient enough to condense the refrigerant vapor in the condenser itself.

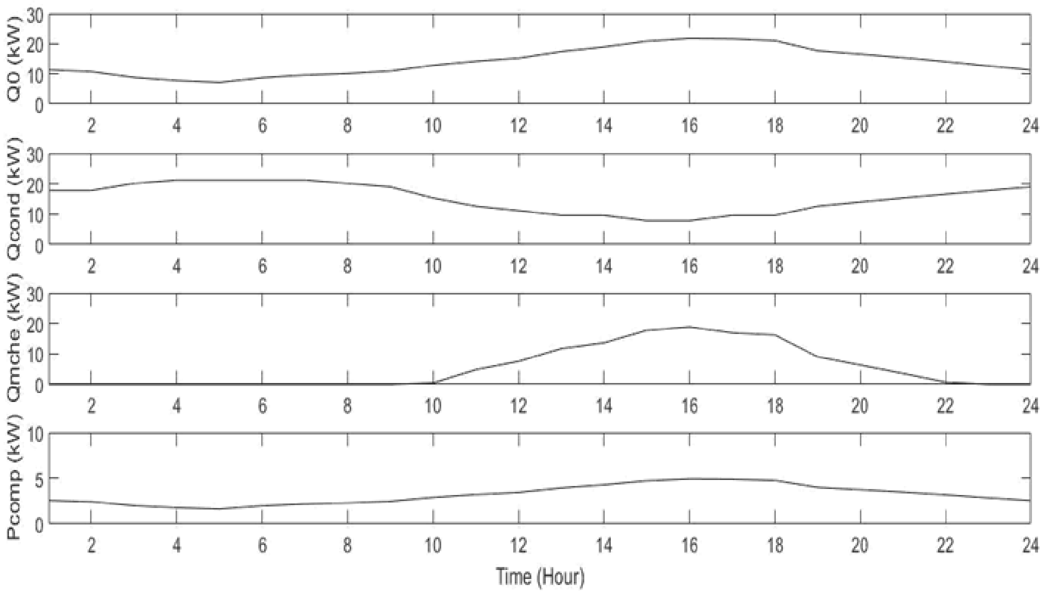

Figure 5 Heat loads on different units of proposed air-conditioning system against time for Jaipur.

During peak hours of operation, de-superheating and partial condensation of refrigerant occurs in the main condenser as the outdoor air temperature is high and the remaining condensation takes place in the MCHE. Because of this, the PCM starts melting by absorbing latent heat of condensing refrigerant. When the outdoor air temperature is low enough to condense the refrigerant entirely in the condenser the PCM around the mini channels of MCHE stars freezing. The rate of melting/freezing of PCM around the mini channels of MCHE is presented in Figure 6. PCM starts melting around the mini channels of MCHE at 10 hours and continues up to 20 hours.

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Later, PCM starts freezing from 20 hours to 10 hours due to flow of heat from PCM to coolant air when the coolant air stars flowing through the mini channels of MCHE. The maximum quantity of PCM required is estimated to be 375 kg per TR with latent heat of fusion of 201kJ/kg. Similar graphs are plotted in Figure 7 & Figure 8 for Hyderabad weather condition, respectively, to assess the versatility of the proposed air conditioning system for any tropical region.

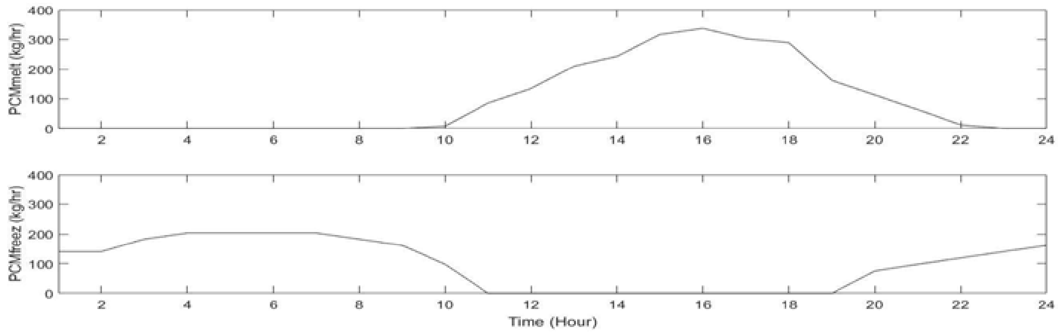

Figure 6 Rate of melting/freezing of PCM in MCHE against time for Jaipur.

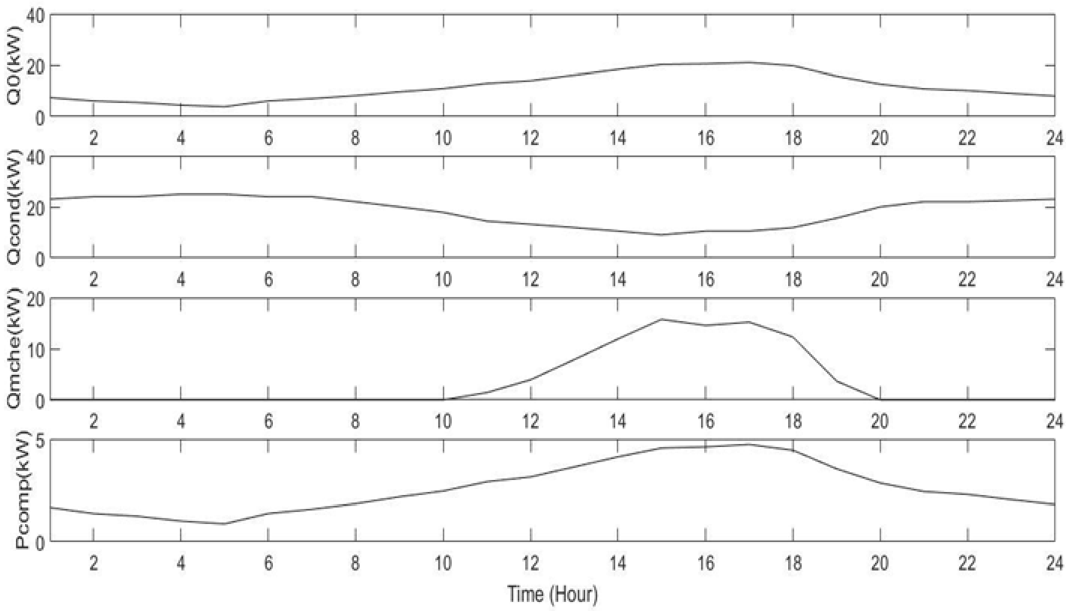

Figure 7 Heat loads at different units of proposed air-conditioning system against time for Hyderabad.

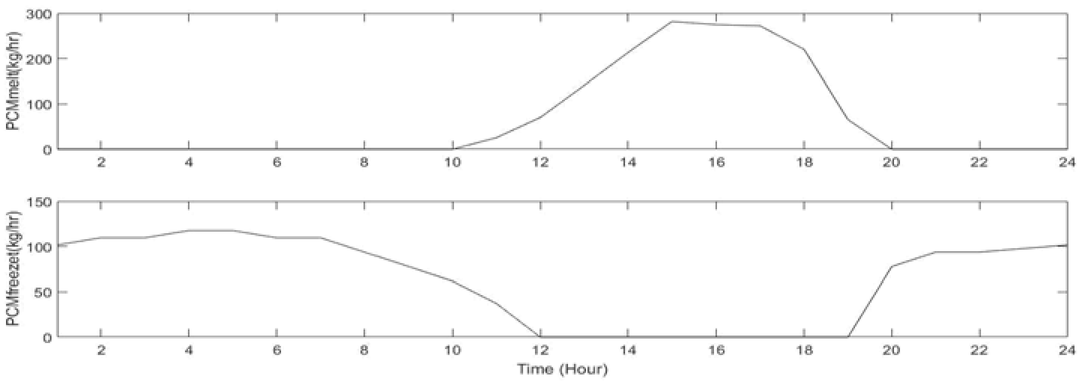

Figure 8 Rate of melting / freezing of PCM in MCHE against time for Hyderabad.

Conclusions

The performance of an air-conditioner can be improved with PCM around the mini channels of MCHE by employing lower condensing temperature.

The power consumption of an air-conditioner can be decreased by about 25% at peak load with PCM.

The maximum quantity of PCM required is estimated to be 375 kg per TR with latent heat of fusion of 201kJ/kg.

The proposed air conditioner with PCM around mini channels of MCHE can work satisfactorily in any tropical region where temperatures exceed 40^{0}C during summer days.

However, the complication involved in the design of MCHE with PCM around its' mini channels is to be addressed. If MCHE can be designed suitably, there will be a lot of power saving with improved performance of air conditioner throughout the year.

Acknowledgments

None.

Conflicts of interest

The author declares there is no conflicts of interest.

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