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Innovative HVAC solutions: Impact of nanoparticles and fins on PCM incorporated system for peak load management#

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ABSTRACT

Indoor air quality is an important factor which affects the cognitive ability and performance of the occupants of a building, hence, fresh air is incorporated into indoor spaces. However, due to high ambient temperatures, typically in tropical zones, will further increase the energy consumption of HVAC systems. Phase change materials (PCM) are widely employed due to their high energy storage capacity as well as keeping the operating temperature unchanged. The study explores the effect of using a PCM-based heat exchanger for reducing the fresh air temperature and, hence reducing the fresh air ventilation load of a building. On using octadecane as PCM, the study observed that for 8 hours of operation, the average temperature reduction in the air for no fins is 1.80°C, which increases marginally to 1.82°C for 1% CuO and 4.15 °C on using 24 longitudinal fins. It leads to an energy saving of 3.51%, 3.83% and 7.75% over a conventional HVAC system for a system with no fin, 1% CuO, and 24 fins, respectively. Further, PCM is charged using exhaust air, and PCM solidifies completely in 4 hours. The study provides an energy-efficient solution for the sustainable use of HVAC systems for policy makers and HVAC engineers.

Keywords: building energy efficiency, latent energy storage, HVAC system, retrofitting techniques

NOMENCLATURE

Symbols	
ρ	Density
Cp :	specific heat [kJ kg-1 K-1]
h :	enthalpy (kJ/kg)
k :	thermal conductivity [W m-1 K-1]
Q	Heat Flow Rate (W)
T	Temperature (K)
W	Work Done (W)

1. INTRODUCTION

The increasing global temperatures and urbanization have increased the global demand for air conditioners. The United Nations Environment Programme in GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION mentioned that the growth of the number of air conditioning units is most prominent in developing nations, and by 2050, they will account for almost 55% of the total AC units in the world[1]. The energy used to maintain human thermal comfort in the buildings accounts for 50% of the total energy consumption of a building. The recommendation of fresh air into cooling spaces by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Washington State Department of Health to dilute the indoor air will further increase the energy demand as the ambient air is available at higher temperatures as compared to the one available in closed spaces [2,3]. The phase change materials (PCM), owing to their high energy density and providing almost isothermal operating conditions are widely explored and used in the buildings [4].

Phase change materials (PCMs) have been integrated with air conditioning units in various configurations to reduce energy consumption. Chaiyat[4] utilized RT 20 encapsulated in spherical shells within a bed of PCM to cool return air from an AC unit, achieving an energy savings of 9.1%. Numerical simulations conducted over a two-hour operation period, which varied the size, shape, and placement of PCM geometries, revealed that a staggered cylindrical layout consumed 12.5% less energy compared to standard AC units [5]. Additionally, a PCM-based pin fin heat exchanger designed using the minimum entropy generation technique demonstrated a 4.5% energy savings during peak load periods in the composite climate of Delhi [6].

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The literature indicates that PCM-based systems are effective in building thermal management, capable of reducing both ventilation and total HVAC system loads. In the present study, an HVAC system is retrofitted with a PCM-based heat exchanger to cool fresh air. The enthalpy-porosity technique is employed to study phase transformation and heat transfer in PCM. The cooling load for a room in the composite climate of Delhi is determined, accounting for varying occupant and computer loads. Furthermore, the impact of enhancing thermal properties with nanomaterials on energy savings and the ventilation load of the HVAC system is also analyzed.

2. MATERIAL AND METHODOLOGY

2.1 Material Characterization

In a latent heat energy storage system, PCM plays a dominant role in determining the performance of the system. The present study deals with cooling the fresh air to maintain the thermal comfort of the occupants. Hence, in the present study octadecane, an organic PCM with a fusion temperature of 28 °C, is taken for offsetting the peak load during the day.

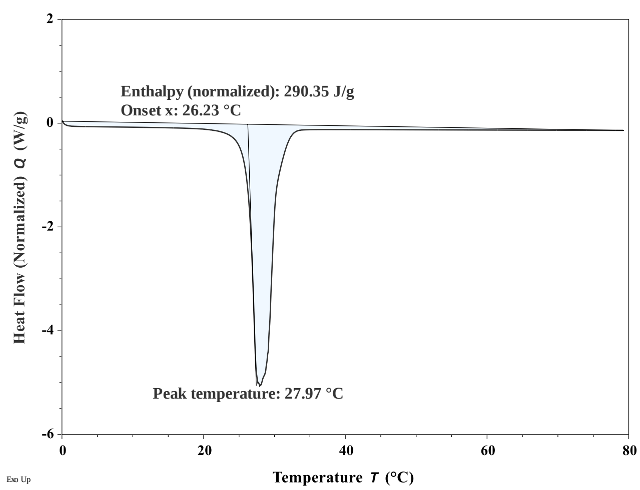

Fig. 1 Thermogram for Octadecane

Fig. 1, illustrates the normalized heat flow variation with temperature. Throughout the process, minimal heat absorption is observed until the onset of melting at 26.23°C, continuing until complete PCM melting at 27.97°C. The enthalpy of fusion was determined to be 290.35 J/g. Characterization of the PCM was performed thrice, resulting in a deviation of 1.1% for the latent heat of fusion and 0.15°C for the phase change temperature (PCT). Thus, for the study, the latent heat and melting temperature of octadecane were established at 290.35 J/g and 27.97°C, respectively.

2.2 HVAC system

The study examines the impact of combining a concentric tube heat exchanger (CTHE) with the HVAC system for cooling the fresh ventilation air on the overall energy consumption of the room's HVAC system. The current study focuses on an office space in Delhi's composite climate. An air conditioning unit with R410a refrigerant and 3ACH of fresh air is utilized to keep the space within the occupants' thermal comfort zone. The numerical model for the building simulates the ambient conditions for Delhi's composite climate on July 15, 2023.

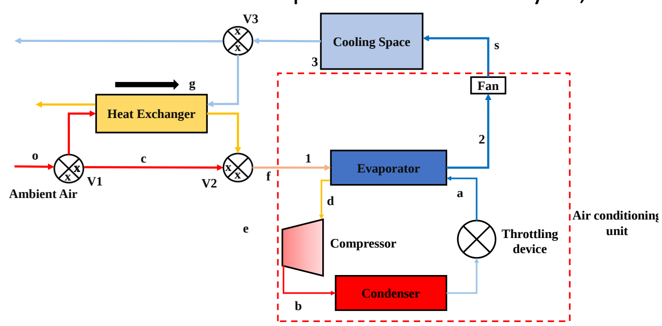

Fig. 2: Retrofitted HVAC system

Fig. 2 illustrates a space equipped with an HVAC system that has been incorporated with a Latent Heat Energy Storage System (LHESS)-based concentric tube heat exchanger (CTHE) to cool incoming fresh air. Under ambient conditions, the fresh air passes through the PCM-integrated CTHE, inducing a temperature gradient between the air and the PCM. This gradient enables the transfer of energy to the PCM. Subsequently, the air at state "f" is directed to the cooling unit, where it undergoes cooling to reach state "2," aligning with the designated set point temperature before being circulated into the space for cooling via a fan within the HVAC system. Finally, the stagnant air is expelled from the cooling space to the ambient environment at state "o," as per requirements. During the charging of PCM, valves V1 and V2 are adjusted to direct flow directly to an HVAC system, while V3 allows the return air to pass through the heat exchanger.

The indoor environment is kept at the human thermal comfort level standards of 24°C DBT and 50% relative humidity [7] by using an air conditioning system that operates on the VCR system. The fresh air is cooled before it enters the AC unit. The unit's condenser temperature is taken as ambient, while the evaporator is kept at a constant temperature of 12°C. The pressure loss in suction and pressure lines is estimated to be 0.5 kPa. Furthermore, superheating of 5°C at the evaporator outlet and subcooling of 2°C at the condenser exit are considered for the air conditioning unit's smooth operation.

The energy dissipated by the air ($Q_{chiller}$) when it is cooled from state f to the supply condition is a function of the enthalpy of air at point f and point 2, i.e., the fresh air and supply air, and is calculated using -

air and supply air, and is calculated using -

$$Q_{chiller} = \dot{m}_a(h_f - h_2) \quad (1)$$

The cooling system is a variable mass flow rate of the refrigerant system ($\dot{m}_{ref}$), which varies the mass flow rate of the system as per the demand and supply of the cooling load, which is estimated using equation (2)

$$\dot{m}_{ref} = \frac{Q_{chiller}}{(h_a - h_d)} \quad (2)$$

In a VCR system, the refrigerant in the vapour phase is handled by the compressor, and due to the large specific volume of vapour, along with the friction associated, the compressor's efficiency as a function of its operating pressures, i.e., suction pressure (p1) and delivery pressure (p2) [8], is represented by equation (3):

$$\eta_{comp} = \frac{h_{bs} - h_d}{h_b - h_d} = 0.85 - 0.046667\frac{p_2}{p_1} \quad (3)$$

The addition of the LHESS to an HVAC system changes the total demand and consumption of the HVAC system, which can be represented by $W_{modified}$. The reduction in energy consumption (energy savings) when compared to a conventional HVAC system ($W_{conventional}$) is computed as

$$\text{Energy Savings (\%)} = \left(\frac{W_{conventional} - W_{modified}}{W_{conventional}}\right) \times 100 \quad (4)$$

2.3 Numerical Domain of Heat Exchanger

The literature indicates that PCM-based systems are effective in building thermal management, capable of reducing both ventilation and total HVAC system loads. In the present study, an HVAC system is retrofitted with a PCM-based heat exchanger to cool fresh air. The enthalpy-porosity technique is employed to study phase transformation and heat transfer in PCM. The cooling load for a room in the composite climate of Delhi is determined, accounting for varying occupant and computer loads. Furthermore, the impact of enhancing thermal properties with nanomaterials on energy savings and the ventilation load of the HVAC system is also analyzed. Fig. 3 depicts a CTHE design with a tube length of 1500 mm, a diameter of 200 mm, and a thickness of 5 mm, as well as a 75 mm thick PCM in the annulus. Further, 24 longitudinal fins are used to enhance the heat transfer rate to PCM. The fresh air passes through the designated CTHE, and thermal energy is transmitted from the hot ambient air to the PCM placed in the annulus due to temperature differences. Gravitational acceleration acts along the airflow to the CTHE, which coincides with the longitudinal axis. The chosen PCM, octadecane, which has a phase change temperature of 28°C, is placed in the annulus and employed to remove heat from the heated ambient air. Furthermore, as stated in numerous literatures, CuO nanoparticle addition is an effective way to improve the thermal performance of a PCM-based system since it increases thermal conductivity, and hence heat diffusivity to the PCM [9].

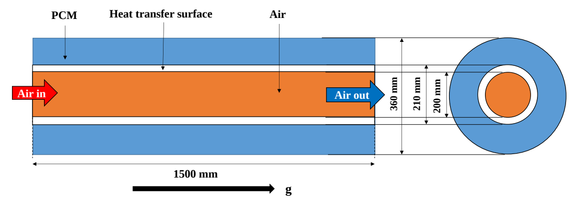

Fig. 3 Schematic of airflow and heat exchanger

A numerical model of a CTHE with PCM is created to investigate the heat transfer phenomenon and the phase transition of PCM. The conduction and convection phenomenon determines heat transfer in the CTHE. An axisymmetric 3-D numerical model is created to simulate the original heat exchanger and is used to investigate transient fluid flow and heat transfer properties. Furthermore, the enthalpy porosity technique is used to investigate the phase transition of octadecane in the heat exchanger. To simplify the investigation, it is assumed that the phase transition of PCM happens at a steady temperature with minor volume changes. Furthermore, the flow in PCM is laminar, and the thermophysical parameters remain consistent, with the exception of PCM density. Any alteration in density with temperature owing to the laminar flow of the PCM is described by the Boussinesq approximation, which is represented by equation (5).

$$\rho = \frac{\rho_l}{\beta(T - T_L) - 1} \quad (5)$$

Where the coefficient of thermal expansion is represented by β, while T_L and ρ_l represent temperature and density of the fluid.

The enthalpy porosity technique is applied to study the phase transition of PCM in the heat exchanger. Melt fraction (λ)[10] for the process obtains a value of 0 when the phase is solid and changes to 1 when the phase of PCM changes to a liquid. Hence, for the melting process, λ represents the portion of PCM that has melted.

$$\lambda = \begin{cases} 0, & T \le T_S \\ \dfrac{T - T_S}{T_L - T_S}, & T_S < T < T_L \\ 1, & T \ge T_L \end{cases} \quad (6)$$

Equation (7) represents the thermal energy accumulated in PCM (H),

$$H = h + \Delta H = h + \lambda h_{LH} \tag{7}$$

$$h = h_o + \int_{T_o}^{T} C_p \Delta T \tag{8}$$

The continuity, momentum, and energy equations with the assumptions are modified as equations (9), (10) and (11)[11] –

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \vec{u} = 0 \tag{9}$$

Momentum equation:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \nabla)\vec{u} = -\nabla P + \nabla \cdot (\mu(\nabla \vec{u} + (\nabla \vec{u})^T) + \vec{F}_b + \vec{F}_a \tag{10}$$

Energy equation:

$$\left(\rho c_{p_{eff}}\right)_{PCM} \frac{\partial T}{\partial t} + \nabla T \cdot \left(\rho C_p \vec{u}\right)_{PCM} = \nabla \cdot ((k(T))_{PCM} \nabla T) \tag{11}$$

The source term expression in the momentum conservation equation is for solving the mushy zone and is represented by equation (12)

$$S = A_{mush} \frac{(1-\lambda)^2}{(\lambda^3 + c)} V_i \tag{12}$$

A_{mush} represents the coefficient for the mushy zone, with a value of 10^{-5}, to prevent the equation from becoming indeterminant. The value of λ lies in the range of 0 to 1, where 0 specifies the PCM is in the solid state, whereas 1 denotes the fluid state.

The numerical model is investigated for heat transfer and flow using ANSYS FLUENT 2021, and the model is discretized using the finite volume method. The pressure equation is spatially discretized using the PRESTO scheme, and the velocity-pressure coupling utilizes the SIMPLE algorithm. Convergence criteria for continuity, momentum, and energy in the study are set at 10^{-3}, 10^{-3}, and 10^{-6}, respectively.

2.4 Boundary conditions

The ambient air temperature plays a pivotal role in determining the efficacy of an HVAC system, and in the study, ambient air temperature is taken for June 15, 2023, and a user-defined function (UDF), equation (13), is used to capture the temporal fluctuations of ambient temperature (T) in °C as a function of time (t) in seconds.

$$T = -1.76529 \times 10^{-8} t^2 + 6.8990 \times 10^{-4} t + 39.24 \tag{13}$$

Further as the study starts from 9:00 a.m., therefore t = 0 at 9:00 a.m.

The boundary conditions for the CTHE are as follows:

(i) At the walls of the air and PCM, a no-slip and impermeability condition is enforced, i.e., u=0.

(ii) At the air inlet, where z=0, the velocity in the axial direction (u_z) is equal to the inlet velocity (u_{in}), and the temperature (T_z) is equal to the inlet temperature at time t (T_{in}(t)).

(iii) At the air outlet, where z = L, a pressure outlet boundary condition is applied, i.e., P = 0.

(iv) The sidewalls and the outer surface of the LTESS are insulated.

(v) Symmetric boundary conditions are applied at the symmetry planes, which extend from θ = -7.5° to 7.5°.

The simple payback period (SPP) is estimated by -

$$SPP = \frac{Initial\ Investment\ Cost}{Annual\ Cost\ Savings} \tag{14}$$

3. RESULTS AND DISCUSSION

3.1 Melt Fraction

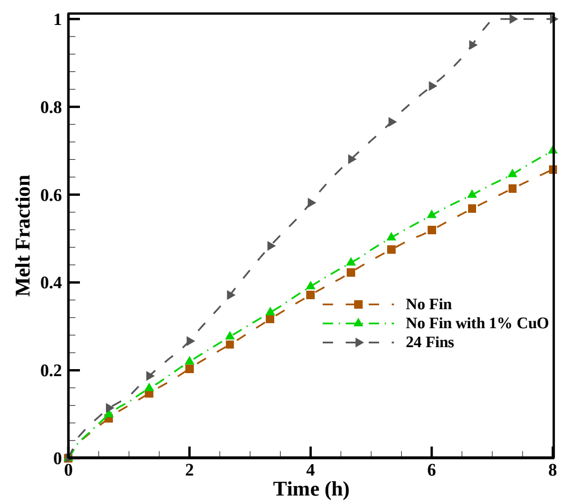

Fig. 4 Temporal variation of melt fraction

The heat exchanger functions by extracting thermal energy from the surrounding air and transferring it to PCM as latent heat. This process leads to the gradual transformation of PCM from a solid state to a liquid state. Figure 9 illustrates the change in the melt percentage of PCM, representing the amount of energy stored in the system as latent heat. For a CTES system without fins and a 75 mm PCM in the annulus, the PCM undergoes a melting process that occupies 65.7% of the total volume intended for thermal energy storage. The restricted amount of melting occurs as a result of the low thermal conductivity of the PCM, which is measured at 0.152 W/m-K. This low thermal conductivity leads to low thermal diffusivity, meaning that less heat is absorbed into the volume of the PCM.

CuO nanoparticles and fins are employed to enhance the thermal properties of the PCM and heat transfer to PCM, respectively. Fig. 4 demonstrates that this augmentation results in a 70% increase in PCM melting for 1% CuO addition after 8 hours of operation. Zhang et al. [11] have reported consistent results. Whereas with the inclusion of fins, the PCM is melting in 7 hours of operation, denoting an increase in heat transfer due to an increase in the surface area.

3.2 Air Temperature at the outlet

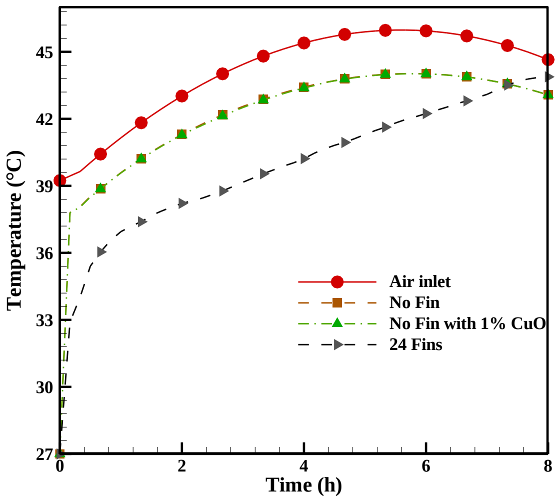

Fig. 5 Temporal variation of air temperature

The air PCM LHESS reduces the surrounding temperature of the air before it arrives at the AC unit. Fig. 5 illustrates the temporal variation of the air temperature near the outlet of the heat exchanger. The efficacy of the PCM-based CTHE in reducing air temperature is apparent. The heat exchanger utilizing phase change material (PCM) experiences a decrease in ambient air temperature ranging from 1.51°C to 1.99°C, with an average temperature difference of 1.80°C. Following 8 hours of operation, the temperature of the air being emitted from the outlet is 43.07°C, which is 1.57°C lower than the surrounding ambient temperature. Adding 1% CuO to the PCM leads to a rise in the average temperature differential, ranging from 1.82°C to 2.02°C. However, the outlet air temperature remains constant at 43.06°C, resulting in a temperature drop of 1.58°C.

For the LHESS with 24 fins and base PCM, the average temperature drops for the 8 h is 4.15°C, which is 130% more than the PCM with no fins and base PCM, whereas the temperature difference between inlet and outlet air varies from 0.76°C to 6.54°C. The PCM melts after 7 h, and consequently, a sudden increase temperature of outside air can be observed, demonstrating that the heat storage in the form of latent heat ceases.

3.3 Energy Savings

The expected decrease in energy usage resulting from the modification of the HVAC system translates to energy conservation compared to a conventional HVAC system. The estimation of these savings can be calculated using equation (4), while the temporal variation is depicted in Fig. 6. Integrating a heat exchanger into the HVAC system yields an average energy reduction of 3.28% during 8 hours of operation. At first, there is a 3.48% reduction in energy consumption because of efficient heat transfer from solid PCM. However, this reduction diminishes when the resistance caused by liquid PCM increases. Nevertheless, the rate of energy savings starts to rise once more after 1.5 hours due to the formation of convection currents. It reaches its highest point of 3.79% at the 5-hour mark but then gradually decreases as the temperature difference decreases with the surrounding temperature. The addition of 1% CuO by volume to PCM yields similar effects in enhancing its thermophysical properties. The mean energy conservation increases to 3.31%, with an initial conservation of 3.51% at a concentration of 1% CuO nanoparticles. The savings increase to 3.83% when the concentration of CuO nanoparticles is 1%.

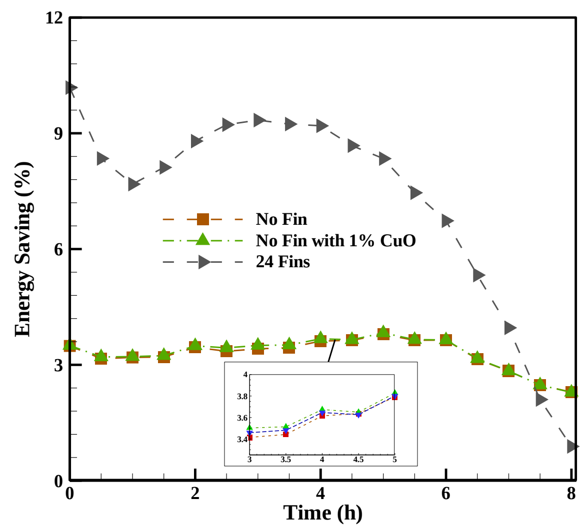

Fig. 6 Temporal variation of energy savings

The heat transmission is enhanced by the addition of 24 longitudinal fins, resulting in increased efficiency. The PCM-based CTHE with 24 fins achieves an average energy reduction of 7.27% throughout an operating duration of 8 hours. Additionally, once the melting process is fully completed, the rate of energy conservation diminishes fast and reaches a mere 0.88% after 8 hours. The PCM is solidified through the return air to regenerate it for the next cycle of operation. It is observed that for the best configuration, i.e., heat exchanger with 24 fins, the PCM solidifies completely in 4 hours of operation when the exhaust air from the room is passed through it.

4. CONCLUSIONS

The current study examines a strategy for the reduction of the fresh air load for a building located in Delhi's composite climate. A concentric heat exchanger that incorporates PCM is retrofitted with an HVAC system, enabling the investigation of its impact on the subsequent energy savings. The PCM employed for energy consumption reduction, octadecane, exhibits a melting point of 27.97°C and an enthalpy of fusion measuring 290 kJ/kg, as per characterization data. The HVAC system's energy consumption experiences a decrease of 3.28% with the heat exchanger having PCM and rises to 3.31% with the incorporation of 1% CuO into the base PCM. Further, with the addition of 24 longitudinal fins, the energy savings increase to 7.2% as compared to conventional HVAC systems. The PCM is charged using exhaust air from the room during off-peak hours and solidifies completely in 4 hours of operation. Further, the system saves 0.846 tCO_2 per year and has a payback time of 8.6 years. The research investigated the cooling loads of a building and proposed the integration of heat exchangers into an HVAC system as a viable strategy for reducing energy consumption, enhancing indoor air quality, and mitigating the transmission of diseases.

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