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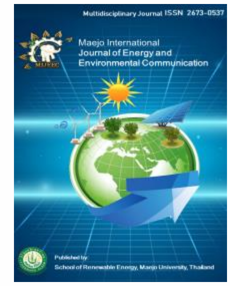

ARTICLE

Passive cooling of buildings with phase change materials using fins to increase the effectiveness of thermal storage units

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Buildings consume substantial energy annually, primarily for lighting, cooling, and air conditioning. Alternative cooling technologies like free cooling are being explored in response to environmental concerns. This study investigates using phase change material (PCM) for passive cooling, reducing reliance on conventional air conditioning. PCM is charged at night using cooler ambient air and discharged to cool indoor spaces during the day. The PCM selected for this study, OM 21, has a phase change temperature of 21 °C and a latent heat of 180 kJ/kg, making it suitable for the temperature range between night-time ambient air (16-17 °C) and the desired room temperature (25 °C). Experimental setups included heat exchangers of 7-meter copper tubes surrounded by 0.5 mm thick aluminum fins. The setups tested various configurations of condenser blocks, including both series and parallel arrangements, to optimize thermal contact and heat transfer. Results indicated that series-connected condenser blocks provide more uniform charging and discharging, enhancing the system's effectiveness. The study highlights the potential of PCM-based systems to offer a sustainable and scalable solution for building cooling. Future research will further optimize these systems, explore PCM variants, and utilize CFD modeling to improve design precision and system performance.

1. Introduction

Fossil fuels have globally dominated the demands for energy consumption, with report estimates indicating that fossil fuels will continue to produce around 80% of the world's primary energy by 2030 (Saengsawang et al., 2020; Sharma et al., 2023). Concerns have been made to control non-renewable fuel usage in all economic sectors worldwide (Manmai et al., 2021; Dussadee et al., 2022). Buildings consume 30-40% of total energy, mainly for electricity, cooling, and heating (Dussadee et al., 2018). They, thus, are directly responsible for the emission of one-third of greenhouse gases. Greenhouse gases are responsible for global warming (Tsai et al., 2023). Global concern for The environmental impacts of fossil fuel usage have increased the interest in reducing energy consumption through HVAC equipment and searching for passive techniques for heating and cooling buildings. Passive cooling is a technique in which buildings are cooled using minimum or very little electricity consumption (Coninx et al., 2024). The term "Passive" does not exclude cooling techniques that use a fan or pump to enhance the cooling performance.

Buildings can be cooled using several passive cooling techniques, almost all requiring thermal energy storage (Faraj et al., 2020). Various thermal energy storage options are discussed briefly in the next section.

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Thermal energy storage is an essential area in mechanical engineering and its applications. The primary issue these days is always a mismatch between demand and supply. Using passive cooling techniques ensures the need to collect the ambient energy available at once, store it sufficiently long without much loss, and utilize it whenever needed. A study was conducted by Turnpenny et al. (2001) using heat pipes embedded in PCM storage units. It was concluded that a higher temperature difference between the PCM melting point and charging air was beneficial to freeze the PCM, given that the period is meant to be constant. However, high flow rates can also help to solidify the PCM (Turnpenny et al., 2001).

Yanbing et al. (2003) studied night ventilation coupled with PCM bed storage, which indicated the COP of the whole system (ratio between cold discharged from PCM and fan power used) as 80. Takeda et al. (2004) studied PCM-packed bed thermal storage to reduce the ventilation load of buildings, in which the PCM was placed in the ventilation system of a building operating on a free cooling concept (Takeda et al., 2004). Nagano et al. (2006) applied the passive cooling principles using commercially available PCM granules in conjunction with an air conditioning system, and it was found that cold stored in PCM reduced cooling load by up to 92%

Waqas & Din (2013) have presented a comprehensive study of worldwide literature on the free cooling of buildings using phase change material. The paper explains various techniques for charging and discharging PCM, including results from other literature that indicate the dependency of the PCM Charging and Discharging cycle on mass flow rate and temperature difference. The melting point of PCM is suggested to be around the range of 20 – 26 ^{o}C. However, the best working temperature is 21^{o} C. An Effectiveness-NTU technique discusses a thermal storage system's design, analysis, and optimization with phase change material. A simplified approach is presented based on the effectiveness of the number of transfer units (Waqas & Din (2013).

A mathematical model has been developed using this technique for a cylindrical tank filled with PCM with one, two, and four coils of tubes to validate this technique. This study showed that this e-NTU technique can accurately predict the average heat exchanger effectiveness of the thermal storage system (Tay et al., 2012a). For the mentioned setup of the tube in the tank, the thermal resistance in the PCM was one of the significant factors affecting the effectiveness of the heat exchanger. Effectiveness considerably increased when high heat transfer surface area was experimented with during charging and discharging (Tay et al., 2012b).

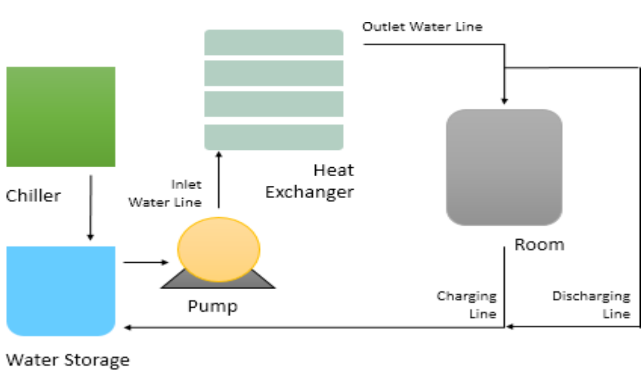

Figure 1. Air condition cycle of a room

Tay et al. (2012b) characterized PCM thermal storage systems using the effectiveness-NTU approach to discuss their energy efficiency. The phase change profiles identified by running various simulations have been analytically formulated to determine thermal storage unit effectiveness using the familiar e-NTU approach. As a result, one-dimensional and two formulations concerning phase change fraction were developed (Tay et al., 2012b). The results helped define various parameter functions that can be used to determine the optimum size of the thermal storage unit by eliminating redundant amounts of PCM.

Furthermore, by optimizing design parameters, energy losses can be minimized by maximizing the effectiveness of the complete charging and discharging cycle (Tay et al., 2012c). This study's conclusive result shows that for air-based systems, phase change can be represented in one dimension; however, for liquid-based systems, two-dimensional phase change needs to be considered. Designing a PCM storage system using the effectiveness-number of transfer unit method low energy cooling of buildings by Tay et al. (2012c) involved determining the actual sound energy within a phase change material storage system coupled to a low-energy night-time cooling system using a cooling tower. The e-NTU method was used to determine the amount of sound energy that can be stored in a PCM-based storage system (Tay et al., 2012c). This storage effectiveness was optimized, delivering a total of 68% to 75%.

2. Materials and methods

2.1 Empirical NTU effectiveness: method and mathematical formulation

Heat exchanger effectiveness indicates the system's performance. It is defined as a ratio of actual heat discharged over the theoretical maximum possible heat discharged.

$$\epsilon = \frac{(T_{in} - T_{out})}{(T_{in} - T_{PCM})} \qquad \textbf{[1]}$$

$$\bar{\epsilon} = \int_0^t \epsilon \, dt \qquad \textbf{[2]}$$

Equation 1 represents the effectiveness of the heat exchanger at any point in time, while equation 2 indicates average effectiveness during the phase change period. PCM stores most of the energy as latent heat, and a tiny fraction of heat energy is stored as sensible heat.

The effectiveness of a heat exchanger varies between zero and one. It is maximum during discharging when the outlet temperature of heat transfer fluid is equivalent to the fusion temperature of phase change material. As the outlet temperature of heat transfer fluid approaches its inlet temperature, the efficiency of the thermal storage system starts approaching zero.

Effectiveness can be defined using several transfer units (NTU). The relation between the effectiveness of heat exchanger and NTU is defined as:

$$\epsilon = 1 - e^{-(NTU)} \qquad \textbf{[3]}$$

$$NTU = \frac{UA}{\dot{m}C_p} \qquad \textbf{[4]}$$

NTU defines the average thermal resistance and heat transfer ratio between PCM and HTF. This mathematical model assumes a constant initial velocity and temperature of HTF. The outer walls of the tank are assumed adiabatic to nullify the effect of any heat escape through them. The initial temperature is assumed constant for the latent heat storage unit, and the PCM is assumed to be in the solid and liquid phases for melting and freezing, respectively (Takeda et al., 2004; Nagano et al., 2006).

They ignore natural convection inside the PCM since PCM is in stable form and not moving, unlike heat transfer fluid, which is in motion at constant velocity inside the copper tubes. Thermo-physical properties of heat transfer fluid, walls, and phase change material are constant and do not vary with temperature. The model is considered axisymmetric (Nagano et al., 2006). The heat exchanger comprises a long metal tube surrounded by phase-change materials. The tube is considered straight, and the impact of bends is ignored since they compose a tiny fraction of the total length of the tube. It can be imagined as concentric cylinders, as indicated in Figure 2.

R_i and R_o are the inner diameter and external diameter of the metal tube, respectively. The length of the metal tube is L. PCM encloses the cylindrical metal tube, starting from the surface of the metal tube up to radius RMAX. The total thermal resistance of the heat exchanger is required to determine the effectiveness of the thermal storage unit. R_T defines the total thermal resistance as in equation 5.

$$R_T = R_{HTF} + R_{WALL} + R_{PCM} \quad \textbf{[5]}$$

$$R_T = \frac{1}{2\pi R_l L h_f} + \frac{ln\frac{R_0}{R_l}}{2\pi k w_l} + \frac{ln\frac{R_0}{R_l}}{2\pi k_{PCM} L} \quad \textbf{[6]}$$

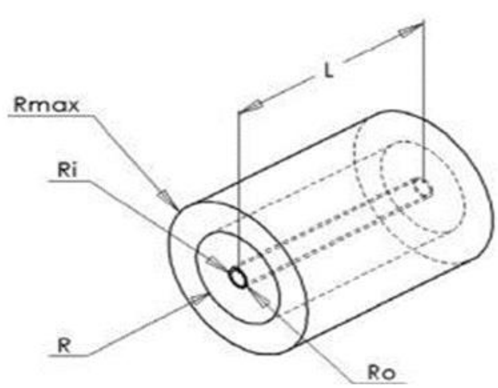

Figure 2. Schematic diagram of concentric cylinder

Total resistance is composed of three resistances. R_{HTF} is the resistance of heat transfer fluid flowing inside the metal tubes. R_{WALL} is the resistance offered by the tube walls. R_{PCM} is the resistance of the PCM enclosing the metal tubes. The total resistance indicates obstruction in the path of Heat, travelling from heat transfer fluid through the cylindrical metal tube to the phase change front of PCM. The phase change front represents a boundary between solid and liquid PCM states.

During the discharging cycle, the phase change material melts, transforming to a liquid state. The phase change front, therefore, starts to expand outwards from the metal tube, represented by R. At the start of the discharging cycle, the phase change front occupies the radius R_O, indicating the solid state of PCM. As the discharging cycle progresses, the phase change front expands towards R_{MAX}. As the discharging cycle progresses, the PCM starts to melt. At the end of the discharging cycle, PCM transforms completely into a liquid state. Phase change front is theoretically marked at R. During the charging cycle, PCM starts to freeze in a similar pattern, beginning at the surface of the metal tube. As the freezing cycle progresses, the phase change front expands outwards, and at the end of the freezing cycle, all the phase Change Material transforms into a Solid State.

The resistance of Heat Transfer Fluids and Metal Tubes remains constant throughout the Discharging or Charging process. The resistance of phase change material varies with time due to the melting or freezing of PCM along with the phase change Front. The resistance variation is calculated based on phase change fraction (δ). The phase change fraction relates directly to the solid-liquid line within PCM. It is indicated by radius R, which varies between the values of RO and RMAX. Phase change fraction is the portion of material that is yet to change phase. A tube surrounded by a cylindrical enclosure of PCM is defined below:

$$\delta = \frac{A_r - A_0}{A_{max} - A_0} = \frac{R^2 - R_0^2}{R_{max}^2 - R_0^2} \quad \textbf{[7]}$$

Where A_r ¸ A_o and A_{max} are the changing of PCM during phase change, outer tube area, and the maximum area of the PCM after phase change. Therefore,

$$R = \{\delta(R_{max}^2 - R_0^2) + R_0^2\}^{1/2} \quad \textbf{[8]}$$

From this relation, the total resistance of the heat exchanger process for the charging or discharging process can be stated as follows:

$$R_T = \frac{1}{2\pi R_l L h_f} + \frac{ln\frac{R_0}{R_l}}{2\pi k_w L} + \frac{ln\frac{\{\delta(R_{max}^2 - R_0^2) + R_0^2\}^{1/2}}{R_0}}{2\pi k_{PCM} L} \quad \textbf{[9]}$$

Therefore, heat exchanger effectiveness can be written as:

$$\in = 1 - e^{\left(\frac{-1}{mC_p R_t}\right)} \quad \textbf{[10]}$$

The following formulae are used for the calculation of h_f:

$$\text{Prandlt number, } P_r = \frac{\mu_f}{C_p} \quad \textbf{[11]}$$

Where μ_fIs the dynamic viscosity of the HTF and C_pIs the specific heat of the HTF.

Reynolds Number,

$$R_e = \frac{\dot{m} d_i}{A_c \mu_f} \quad \textbf{[12]}$$

The mass flow rate of heat transfer fluid is represented by. $\dot{m}$,I and A are the diameters and Cross-sectional area of the inner tube. Nusselt number varies for both laminar and turbulent flows. The equations of both are shown as follows:

For laminar flow,

$$Nu = 3.66 + \frac{0.0668(\frac{d_i}{L})R_eP_r}{(1+0.04[(\frac{d_i}{L})R_eP_r]^{2/3})} \quad [13]$$

For turbulent flow,

$$Nu = 0.023R_e^{0.8}Pr^n \quad [14]$$

Where n=0.3 for cooling and n=0.4 for heating.

The phase change front moves outwards during the charging or discharging process. The effectiveness of thermal storage systems, therefore, varies with time. For identifying a single parameter to understand the performance of heat exchangers, average effectiveness is calculated. Average effectiveness is an average of experimentally determined effectiveness values when PCM charges or discharges completely during a cycle. The average effectiveness of the $\overline{\in}$ is defined as:

$$\overline{\in} = \int_{\delta=0}^{\delta=1} \in d\delta \quad [15]$$

2.2 Experimental setup

The selection of PCM plays a vital role in passive building cooling. PCM was selected based on two parameters. The phase change temperature of PCM should lie between the ambient air temperature at night and the desired room temperature during daytime (Figure 1). During charging, a higher temperature difference between ambient air and PCM's freezing point ensures efficient heat transfer from PCM to cold air. Similarly, a higher temperature difference ensures faster cooling of building spaces during discharging and cooling room air (Figure 2).

PCM with a phase change temperature of 21 °C is used in studies, which lies between ambient air temperature at night time of 16-17 °C and comfort cooling temperature of 25 °C. The night-time temperature was found by taking the average temperature from 12 PM to 6 AM for ambient temperature during nighttime. The second important parameter for PCM selection is the latent heat of fusion, defined as the amount of heat stored or released by PCM during the discharging and charging cycle. PCM should possess high latent heat to exchange and release heat during nighttime and provide cooling during daytime.

PCM with a fusion temperature of 21 °C and latent heat of 180 Kilojoule/Kg was chosen for study. This PCM, named locally as OM 21, is a mixture of organic material and fatty acids. Other factors affect the selection of PCM-specific heat in solid and liquid states and the thermal conductivity of liquid and solid PCM. Density variation from solid to liquid state and vice versa should be as low as possible. This is to ensure that PCM is always in contact with condenser blocks. PCM should not react with any of the metals used in the experiments. This is to prevent corrosion from PCM in the long run. For safe handling of equipment, a non-toxic and non-flammable PCM is required.

Water is chosen as heat transfer fluid because the specific heat of water is 4.186 Joule/Gram °C compared to air, 1.003 Joule/Gram °C. It can effectively exchange heat with a Heat exchanger during the Charging and discharging cycle with minimum pump energy losses. Air is used in a secondary circuit to cool the atmospheric room, where air conditioning is required. Heat exchanger material was selected because of the resistance it offers to the flow of heat. Copper with a thermal conductivity of 401 W/ (m K) is selected as the material for metal tubes. It provides minimal obstruction to the heat flow.

Figure 3. Setup 1 without fins

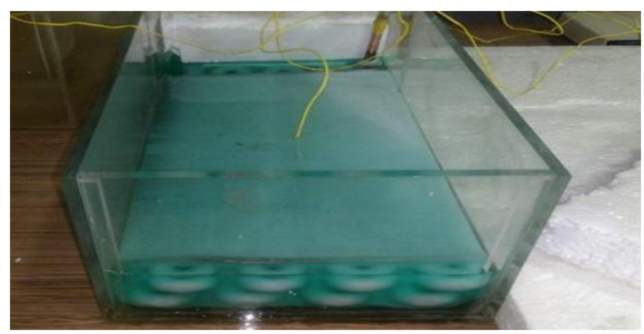

Figure 4. Setup 1 with fins

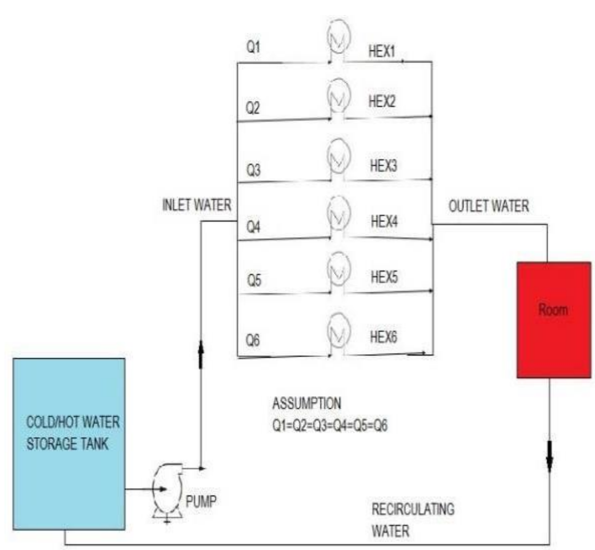

Figure 5. Schematic diagram of setup 2 where condensers are in parallel

At the beginning of the experiment, only a copper tube of length 1m without fins was dipped inside an acrylic box of 5 Litre volume, as shown in Figure 3. Later, the model was modified, and fins were used with the heat exchanger. A single condenser block as a heat exchanger made up of a copper tube 7m long surrounded by thin aluminum fins with a thickness of 0.5 mm was placed inside a box of the size such that the condenser fits the box comfortably, as shown in Figure 4. Later on, another setup is tested, composed of several condenser blocks joined to each other via connecting pipes. Each condenser block has 7-meter-long copper tubes surrounded by thin aluminum fins. The thickness of aluminum fins is 0.5mm, occupying a space of 12 fins per inch of copper tubes, as shown in Figure 4.

Where condensers are connected in parallel, PCM encloses all the space outside the copper tubes and between the fins. This design increases the thermal contact area with PCM, allowing for easy transfer of heat energy. Several condenser blocks can be connected in series or parallel to pass heat transfer fluid through the copper tubes. As shown in the schematic diagram of Figure 5, six condenser blocks for the second design are connected in a parallel arrangement. The third and final design setup involved connecting the condenser blocks in a series connection, as indicated by Figure 6.

Figure 6. Setup 3 where condensers are in series

For both experiments, the heat exchangers are connected in either series or parallel connections and are placed inside metal containers. The metal container is a rectangular stainless steel box surrounded by four walls with a top lid. All sides of the metal container are insulated by covering to prevent heat loss through the walls. PCM is poured inside the stainless steel box. The schematic diagram of setup 3, in which the arrangement is in parallel, is shown in Figure 5, and the arrangement in series is shown in Figure 6.

3. Results and Discussion

The results of the charging cycle for all three experiments are indicated. Water at a temperature of 15-18 °C is taken to freeze the PCM. As PCM starts freezing, its temperature starts to decrease. On reaching a temperature below the phase change temperature of PCM, the experiment is concluded for each design (Yanbing et al., 2003). The readings considered are the inlet and outlet temperature of the water and the average temperature of PCM. For copper tubes in tank design, i.e., design one, results are shown in Figure 7. As indicated, the effectiveness of thermal storage units gradually decreases with time. As time passes, PCM starts to solidify near the copper walls. This solid layer gradually moves towards the outside, increasing heat flow resistance (Takeda et al., 2004; Nagano et al., 2006).

The resistance of PCM starts to increase, which in turn decreases the efficiency of the heat exchanger as time progresses. The primary objective is to assess the efficacy of these designs in sustaining thermal efficiency over a prolonged period. The studies utilized water within a temperature range of 15-18 °C to solidify the PCM. The main measurements consisted of recording the temperatures of the incoming and outgoing water and the average temperature of the PCM during the charging process. Design 1 involves the use of copper tubes placed inside a tank. In Design 1, copper tubes were submerged in a tank containing Phase Change Material (PCM). As the water passes through the tubes, it triggers the solidification of the phase change material (PCM). The findings for this particular design, as illustrated in Figure 7, demonstrate a progressive decline in the efficiency of the thermal storage unit as time progresses.

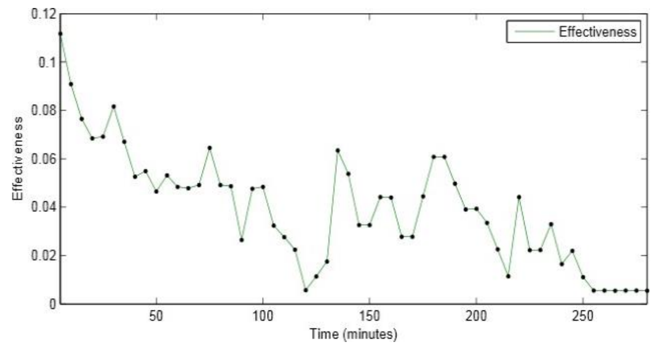

Figure 7. Time vs Effectiveness for Charging Cycle of Setup 1

At first, heat transfer between the water and the PCM is effective, causing the PCM to solidify quickly along the copper walls. Nevertheless, when the solid layer of phase change material (PCM) becomes thicker, it expands away from the copper walls, forming a barrier that hinders heat transfer and raises the thermal resistance (Takeda et al., 2004; Nagano et al., 2006). The reason for this behavior can be ascribed to the decreased heat conductivity of the solidified phase change material (PCM) compared to its liquid condition. The heat transfer rate decreases as the solid layer's thickness increases, resulting in a slower freezing process. As a result, the heat exchanger becomes less effective, leading to a decrease in total efficiency. This result highlights a crucial difficulty in constructing thermal storage units based on phase change materials (PCM): effectively controlling the thermal resistance during the transition of the PCM from liquid to solid state.

Design 2 involves arranging the condenser blocks in a parallel configuration. A second design was evaluated to overcome the restrictions identified in Design 1. This design involved using six condenser blocks interconnected in a parallel arrangement. Every condenser block consisted of copper tubes enveloped by aluminum fins, augmenting the surface area available for heat transfer. The purpose of the parallel arrangement was to uniformly disperse the thermal load across many channels, hence decreasing the thermal resistance experienced in Design 1. Figure 8 demonstrates a notable enhancement in the effectiveness of Design 2 when compared to Design 1.

The utilization of a parallel design facilitated a more homogeneous solidification of the phase change material (PCM), since the transfer of heat was evenly dispersed across a greater extent of the surface. This design effectively reduced the occurrence of large solid layers near the heat transfer surfaces, resulting in sustained greater efficiency throughout the charging cycle (Takeda et al., 2004; Nagano et al., 2006).

The findings indicate that the enlarged contact surface between the phase change material (PCM) and the heat exchanger, along with the simultaneous flow of water in the same direction, enhances the efficiency of thermal regulation. Design 2's enhanced performance can be attributed to a decreased thermal gradient between the temperatures at the intake and output (Turnpenny et al., 2001).

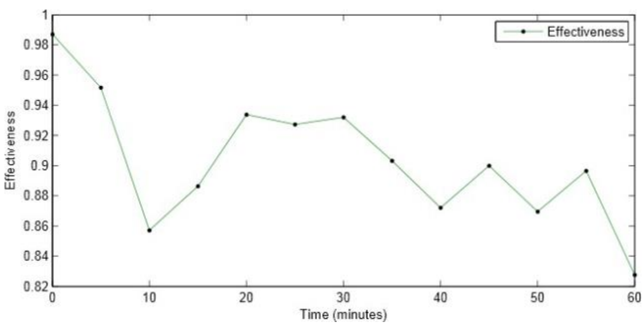

Figure 8. Time vs. Effectiveness graph for charging cycle of setup 2

Design 1 had a single conduit for heat transfer, which caused a greater decrease in temperature throughout the PCM. This made the insulating properties of the solidified layer worse. Design 2, in contrast, had a parallel arrangement that effectively maintained a uniform temperature distribution, resulting in a sustained and increased heat transfer rate (Tay et al., 2012a,b,c). Design 3 involves arranging the condenser blocks in a series arrangement. Following the successful implementation of Design 2, a third design was evaluated, which utilized a sequential arrangement of the condenser blocks. In this configuration, the water passed through each condenser block sequentially, gradually decreasing temperature at each stage. The hypothesis proposed that arranging the series would enhance control over the charging process by guaranteeing that each condenser block operates at decreasing temperatures, thus optimizing the solidification of the PCM.

Figure 9 illustrates that Design 3 was more effective than the preceding designs. The utilization of a series structure facilitated a regulated and gradual freezing process, hence reducing the occurrence of thermal bottlenecks. The series arrangement of condenser blocks meant that the phase change material (PCM) was consistently exposed to the ideal freezing conditions, resulting in a more uniform solidification (Nagano et al., 2006). This was achieved by gradually reducing the water temperature as it passed through each condenser block.

In addition, the series connection facilitated more efficient usage of the thermal storage capacity of each condenser block. In contrast to the parallel structure, in which certain blocks may reach their maximal solidification capacity before others, the series arrangement ensured that each block significantly contributed to the total heat transfer process (Turnpenny et al., 2001). This not only enhanced the effectiveness of the thermal storage unit but also prolonged the duration of the charging cycle (Takeda et al., 2004). The comparative examination of the three designs provides valuable insights into optimizing thermal storage systems based on phase change materials (PCM). Design 1, although simple, had notable drawbacks caused by the higher thermal resistance as the PCM solidified. The main problem was the inadequate surface area for heat transfer, rapidly decreasing efficiency as the charging cycle advanced.

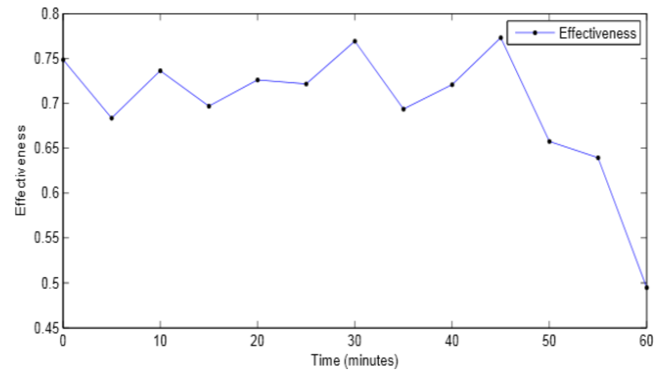

Figure 9. Time vs. Effectiveness graph for charging cycle of setup 3

Design 2 overcame these limits by enhancing the surface area using aluminum fins and dispersing the thermal load across many parallel routes. This method effectively prevented the development of insulating layers and consistently maintained greater efficiency throughout the whole cycle. Nevertheless, the parallel configuration also posed difficulties in achieving consistent charging across all condenser blocks, as certain blocks hit their temperature limit before others (Waqas & Din, 2013). Design 3 successfully addressed these issues by implementing a series configuration, which allowed for a more precise and gradual freezing procedure. The gradual decrease in temperature across the condenser blocks meant that each block functioned at its best circumstances, resulting in a charging cycle that was both consistent and effective. The sequential configuration further optimized the system's thermal storage capability, leading to the highest overall efficiency compared to the other two designs.

The results of these tests emphasize several opportunities for future investigation and advancement. The problem of thermal resistance in systems that use phase change materials (PCM) is still a significant obstacle that needs to be studied more extensively. Utilizing advanced materials with increased thermal conductivity or implementing unique heat exchanger designs that reduce the development of insulating layers could greatly improve the system's performance.

The utilization of a modular approach in Designs 2 and 3 presents a promising path for the development of thermal storage systems that are both scalable and versatile (Turnpenny et al., 2001). The capacity to assemble condenser blocks in series or parallel configurations offers the adaptability to customize the system according to unique application needs. Potential future research might investigate incorporating these modular components into more extensive systems and the influence of different flow rates, PCM compositions, and geometric arrangements on overall effectiveness (Tay et al., 2012a).
Furthermore, the utilization of Computational Fluid Dynamics (CFD) modeling has the potential to offer significant knowledge regarding the intricate thermal dynamics of systems based on Phase Change

Materials (PCM). By simulating freezing and melting processes in two or three dimensions, researchers can enhance their comprehension of the aspects that impact system performance and discover methods for future optimization (Tay et al., 2012b). Furthermore, conducting practical tests to confirm the accuracy of computational fluid dynamics (CFD) models can enhance the precision of system behavior predictions (Tay et al., 2012c). This, in turn, could facilitate the advancement of next-generation cooling technologies that utilize phase change materials (PCM).

The experimental results showcase the capacity of PCM-based thermal storage systems to be used for passive cooling of buildings, with notable discrepancies in effectiveness based on the design configuration. Although the first design encountered difficulties caused by thermal resistance, implementing parallel and series configurations resulted in significant enhancements in system performance (Waqas & Din (2013). The knowledge acquired from these trials establishes a basis for additional investigation and advancement to surpass current constraints and improve the economic feasibility of PCM-based cooling solutions. To maximize the performance of thermal storage systems, it is necessary to optimize the design and arrangement of heat exchangers and carefully pick phase change material (PCM) components. To fully harness the potential of PCM-based technologies in pursuing sustainable and energy-efficient building cooling solutions, further exploring modular design concepts and advanced modeling approaches is crucial.

4. Conclusion

Phase Change Materials (PCMs) offer a favorable alternative to traditional air conditioning systems that rely on compressors for cooling buildings. Choosing the proper phase change material (PCM) is essential for optimal performance, considering its freezing temperature and latent heat. This work highlighted the need to develop effective heat exchangers to facilitate the appropriate transfer of thermal energy in and out of phase change materials (PCM) during diurnal cycles. The study suggested using modular thermal storage units of interconnected condenser blocks, which provide a scalable and cost-efficient option for cooling systems that use phase change materials (PCM). Out of the designs examined, the finned copper tube configurations demonstrated higher effectiveness since they had improved heat transmission. Using series-connected condenser blocks resulted in a consistent charging and discharging, enhancing system efficiency. Future studies should investigate the freezing and melting dynamics of phase change materials (PCM) in two and three dimensions. Additionally, it should examine the influence of mass flow rate on the effectiveness of thermal storage. Furthermore, computational fluid dynamics (CFD) modeling should be explored for a more complete analysis. The modular architecture facilitates seamless scalability, empowering the system to effortlessly accommodate evolving needs and demands. Ultimately, PCM-based cooling systems show promise as a feasible option. However, further investigation and refinement are required to address current obstacles and fully exploit their capabilities in building applications.

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