

THERMAL DESIGN, FABRICATION AND ANALYSIS OF PHASE CHANGE MATERIAL BASED AIR COOLER

Pasupuleti Ravindra Kumar
Department of Mechanical Engineering
Lakireddy Bali Reddy College of Engineering
(Autonomous) Mylavaram, Vijayawada,
Krishna (Dt),521230
Andhra Pradesh, India
pasupuletik@gmail.com

Nelakuditi Naresh Babu
Department of Mechanical Engineering
DVR & Dr HS MIC College of Technology
(Autonomous) Kanchikacherla, Vijayawada,
Krishna (Dt),521180
Andhra Pradesh, India
naresh338babu@gmail.com

ABSTRACT

Phase change material (PCM) based air coolers have gained significant attention in recent years due to their potential for efficient and sustainable cooling applications. PCM-based air coolers utilize the latent heat of phase change materials to store and release thermal energy during the phase transition process. The growing demand for air coolers due to the current situation has led to increased electricity consumption, mainly sourced from fossil fuels which are being gradually phased out. Consequently, there is a need for alternative cooling methods. One promising solution is the utilization of phase-change material (PCM) air coolers. This study focuses on the development of an air-cooling system by employing a modified PCM air cooler, involving design, experimental modeling, and analysis. The PCM air cooler absorbs heat from the room, causing the PCM to melt and maintain a cool temperature until complete melting occurs. This cooling mechanism provides a highly comfortable environment for humans. The PCM materials investigated in this research include paraffin wax, $\text{CaCl}_2\cdot\text{H}_2\text{O}$, and Polyethylene Glycol E600, which are utilized to evaluate the performance of the air cooler. The analytical design calculations for the PCM air cooler are conducted using Ansys Software and show good appropriate results with design calculations.

Keywords— Phase Change Material (PCM), PCM Air Cooler, heat transfer coefficient, CATIA V5 and ANSYS R19.2

I. INTRODUCTION

Global energy demand is rapidly increasing day by day, which increases the usage of fossil fuels. This results in increased greenhouse gas emissions, primarily carbon dioxide, which may lead to an impact on the environment, such as ozone layer depletion gas emissions, global warming, and climate change. The building sector consumes more than 34% of total energy and emits roughly 30% of total CO_2 emissions. According to the International Energy Agency (IEA), Air conditioning is another source of greenhouse gas emissions in the construction industry. Air conditioning is described as the act of eliminating heat and managing the humidity of air in an enclosed area using electric power to create a more pleasant indoorspace for humans.

The performance can be evaluated based on experimental methods for assessing PCM-based air cooler performance, thermal storage capacity and energy efficiency analysis, heat transfer enhancement techniques, Comparison with conventional cooling systems. Latent heat energy storage in PCM (Phase Change Materials) is a fascinating and innovative technology used for thermal energy storage. PCM materials have the unique property of being able to store and release large amounts of heat during their phase transition from solid to liquid and vice versa, without experiencing a significant change in temperature. This property makes them ideal for a wide range of applications, especially in the field of thermal energy storage. PCM stores 5-14 times more heat per unit volume. PCMs can be used for a wide range of temperature applications from $-10\text{ }^\circ\text{C}$ and $300\text{ }^\circ\text{C}$ and the phase transition occurs at constant temperature. Phase Change Materials (PCMs) come in various types based on their phase transition temperatures against time shown in figure1, and each type serves different applications:

Low Temperature PCM: These PCMs have phase transition temperatures below 15°C. They are specifically employed in air conditioning applications to store coolness. By absorbing excess heat during warmer periods and releasing it when needed, they aid in maintaining a consistent and comfortable indoor temperature.

Mid Temperature PCM: Falling within the range of 15°C to 90°C, mid-temperature PCMs find utility in diverse fields. In the medical sector, they are utilized for temperature-sensitive storage of pharmaceuticals and vaccines. Additionally, they are incorporated in textiles to create temperature-regulating fabrics. In building design, these PCMs contribute to energy-saving initiatives by absorbing and releasing heat to balance the building's thermal load effectively.

High Temperature PCM: Designed with phase transition points above 90°C, high-temperature PCMs are tailored for demanding applications in industrial and aerospace sectors. They play a critical role in processes requiring precise temperature control, thermal management, and heat storage in extreme conditions.

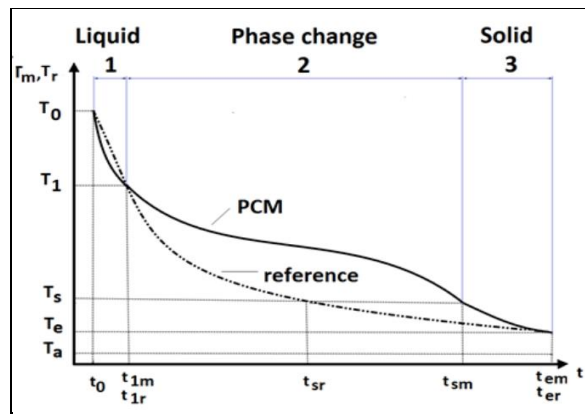


Figure 1 PCM materials conversion at different temperatures against time

Designing PCM cooling devices involves considering three general classes of PCM materials: salt-hydrates, n-alkanes, and non-paraffin organics. To select the most suitable PCM, five crucial factors need to be assessed: These are thermal characteristics, cost, safety, toxicity, environmental impact, useful life and proper packaging respectively.

Salt-hydrates, like Glauber's salt, are commonly used but can experience reduced thermal properties due to thermal cycling. This issue can be mitigated with the addition of nucleators and mechanical agitation. The cost of Glauber's salt is generally low, and it poses minimal health risks based on MSDS data. However, the suitability of each hydrated salt must be evaluated for specific applications.

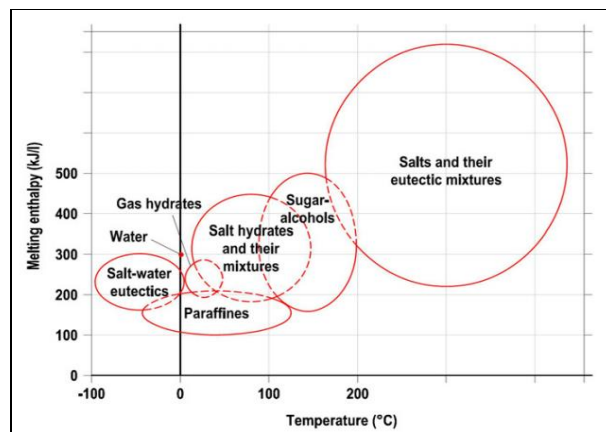


Figure 2. Melting enthalpy and temperature for the different groups of phase change materials [14].

N-alkanes, paraffins shown in figure 2, and other organic materials offer the advantage of a wide range of phase change temperatures (0 to 120°C). The literature reviews indicate that paraffins generally present no significant health or safety hazards. Mixing hydrocarbons within paraffin blends can allow for phase change over

a narrow temperature range. Paraffins exhibit a melting temperature spanning from $-12\text{ }^{\circ}\text{C}$ to $71\text{ }^{\circ}\text{C}$, and they possess a heat of fusion ranging from 190 to 260 J/g. Their advantages include a lack of tendency to separate and supercool, as well as a notably high heat of fusion. However, they do have drawbacks, such as low thermal conductivity, flammability, and a significant change in volume during phase transition.

Non-paraffin organics, while more expensive than the other PCM types, may be necessary in certain cases if they meet the required thermal and safety criteria. On the other hand, non-paraffins or fatty acids have a melting point that falls within the range of $7.8\text{ }^{\circ}\text{C}$ to $187\text{ }^{\circ}\text{C}$, with a heat of fusion between 130 to 250 J/g. One of their advantages is a sharper phase transformation during melting. However, they come with the disadvantages of being mildly corrosive and flammable.

Salt hydrates offer a melting point varying from $11\text{ }^{\circ}\text{C}$ to $120\text{ }^{\circ}\text{C}$, and their heat of fusion ranges from 100 to 200 J/g. They boast a sharp melting point, high thermal conductivity, low volume change, and high density as advantages. Nonetheless, they may experience supercooling and can cause corrosion on metal containers.

Eutectics present a melting point that varies from $4\text{ }^{\circ}\text{C}$ to $93\text{ }^{\circ}\text{C}$, and their heat of fusion ranges from 100 to 230 J/g. They offer the advantage of a high heat of fusion per unit volume and high conductivity. However, a disadvantage is that they have a relatively low heat of fusion per unit weight.

Four primary methods are utilized to determine the physical properties of materials, including phase change materials (PCM): conventional calorimetry, differential thermal analysis (DTA), differential scanning calorimetry (DSC), and the T-History method.

Among the available techniques, differential thermal analysis (DTA) and differential scanning calorimetry (DSC) are the most widely used and refined for assessing thermophysical properties. However, they have certain limitations. These methods involve small sample sizes ranging from 10 to 150 mg (DTA) and 1 to 50 mg (DSC), leading to discrepancies when dealing with larger volumes of PCM. Additionally, these techniques cannot evaluate properties of multiple PCM samples simultaneously.

An alternative approach frequently employed is the T-History method. In contrast to DSC and DTA, this method enables the determination of properties for larger-sized samples, up to 15,000 mg of PCM. Moreover, it facilitates the concurrent testing of multiple PCM samples. The T-History method stands out for its cost-effectiveness, ease of maintenance, and ability to be constructed using basic laboratory equipment.

When designing a passive PCM cooling system, several critical issues require careful consideration:

Heat adsorption during power-on: This involves assessing the amount of energy to be absorbed during the system's operation, including any solar load present if the system is outdoors.

Heat rejection during off-peak times: During periods of inactivity, such as at night or when the system is powered off, heat rejection needs to be managed effectively.

Stress levels within the reservoir: Evaluating the stress levels that the PCM reservoir may experience to ensure the system's structural integrity.

Container compatibility with the PCM: Selecting a suitable container that is compatible with the PCM's properties to prevent leakage or other issues.

The volume of PCM required in the heat exchanger directly depends on the energy absorbed during the power-on period. This energy absorption is determined by the total thermal load, including solar load and energy generated by electronics. Conducting a steady-state analysis of the entire system helps to calculate the design load and the PCM's ability to absorb the maximum thermal load.

A CLASSIFICATION OF AIR COOLERS

Air coolers are cooling systems designed to lower the temperature of enclosed spaces by utilizing evaporative cooling. Each air cooler consists of three main components: a water tank, an absorbent sheet, and a fan. The fan draws in hot, dry air and passes it through a wet pad or filter, where the air absorbs moisture, and the heat energy evaporates the water. This process disperses cool air throughout the room, and the cooler air is

then recirculated back into the space. Due to this evaporative cooling principle, air coolers are also known as evaporative coolers or swamp coolers.

Air coolers offer a cost-effective alternative to air conditioners, not only in terms of initial prices but also in energy consumption, while still being quite effective. However, they are better suited for hot and dry climates and may not be as effective in humid regions. Just like air conditioners, there are numerous air cooler models available in the market, making it overwhelming to choose the right one. To help you decide, we'll provide an overview of the different types of air coolers available, and their suitability based on your requirements.

Desert Air Coolers:

Desert air coolers are the largest among the three types, with a water capacity ranging from 40 to 100 liters. They are mainly intended for use in large-sized rooms or outdoor settings due to their large water tanks and powerful fans, which can distribute cool air to distant corners of the room. Desert air coolers work best in dry regions with low humidity. If you have a large household and need to cool a room ranging from 150 to 500 square feet in size, a desert air cooler might be the right choice.

Personal Air Coolers:

Personal air coolers are further divided into two common types: room air coolers and tower air coolers.

Room Air Coolers:

As the name suggests, room air coolers are primarily meant for indoor use and are smaller in size compared to desert air coolers. They typically have a water capacity ranging from 15 to 40 liters. Room air coolers use a blower to circulate air in the room, which can produce slightly more noise compared to a fan. However, they are portable and come with wheels for easy mobility, allowing you to position them according to your comfort and convenience. Room air coolers are ideal for small to medium-sized rooms ranging from 100 to 150 square feet.

Tower Air Coolers:

Tower air coolers are a slimmer and lighter variation of conventional room air coolers. They are well-suited for use by individuals living alone in smaller spaces, such as bachelors or students. Their water capacity typically ranges from 10 to 40 liters, depending on the size and model. Tower coolers are the most portable of all three types, and their tall and sleek form factor ensures they do not clutter your home.

B OBJECTIVE OF THE PROPOSED RESEARCH METHODOLOGY AND MOTIVATION

1. **Thermal Comfort:** PCM-based air coolers can provide enhanced thermal comfort by maintaining a more stable and comfortable indoor temperature.
2. **Sustainability:** PCM technology aligns with sustainability goals as it allows for the utilization of renewable energy sources and reduces greenhouse gas emissions associated with traditional cooling methods.

Overview of recent research studies and technological innovations and applications

Overall, recent research in PCM-based air coolers has focused on improving heat transfer, selecting suitable PCM materials, enhancing system design, integrating renewable energy sources, and developing advanced control strategies. These developments aim to enhance energy efficiency, reduce environmental impact, and provide effective and sustainable cooling solutions for various applications.

- i. Novel PCM materials and composites
- ii. Advanced heat exchanger designs and integration techniques
- iii. Numerical modeling and simulation approaches
- iv. Building cooling systems and energy efficiency in construction
- v. Automotive cooling and waste heat recovery

II. LITERATURE SURVEY

This literature review provides a comprehensive analysis of PCM-based air coolers, highlighting their potential as a sustainable and efficient cooling solution. It serves as a valuable resource for researchers, engineers, and practitioners in the field, aiding in the development of advanced PCM-based air-cooling technologies and applications.

In Mozhevelov's (2004) study [1], The study encompassed 3D transient simulations were carried out in two distinct settings: a full-scale room and a portable storage unit. The enclosure featured diverse cooling elements of varying shapes, such as vertical plates, horizontal plates, horizontal square tubes arranged both in-line and staggered configurations, and vertical square tubes arranged in-line. Furthermore, Arye and Guedj (2004) undertook experiments utilizing a shell-and-tube system, with vertically oriented tubes filled with PCM.

Mozhevelov et al. (2005) [2] The primary focus of the study revolved around the examination of slender vertical storage units, placed in parallel to the room's walls. Additionally, Letan and Ziskind (2005) conducted a case study wherein they explored the cooling of a full-scale room during daytime through the implementation of a latent heat storage unit.

Zhengguo Zhang and Xiaoming Fang, (2006) [3] study demonstrated the successful development of a paraffin/expanded graphite composite PCM with improved thermal conductivity and stability and shown the results on addition of expanded graphite significantly improved the thermal conductivity of the paraffin composite. This enhancement was attributed to the high aspect ratio and thermal conductivity of expanded graphite particles. The composite exhibited an increased latent heat capacity, indicating a potential for higher energy storage. The thermal stability tests revealed that the composite maintained its structural integrity during multiple thermal cycling, suggesting good durability.

E.K. Berroug, et.al (2011) [4] demonstrated the positive impact of incorporating a PCM-enhanced north wall on the thermal performance of a greenhouse. The results indicated that the PCM effectively regulated temperature fluctuations, creating a more stable and energy-efficient environment for plant cultivation. The research contributes to the understanding of PCM applications in greenhouse systems and provides valuable insights for optimizing thermal management and energy consumption in agricultural practices.

Pramod B. Salunkhe and Prashant S. Shembekar's (2012) [5] review article focuses on summarizing and analyzing the research conducted on the effect of phase change material (PCM) encapsulation on the thermal performance of various systems. The authors aimed to provide an overview of the different encapsulation techniques used for PCM and their impact on system performance, as well as to identify the challenges and opportunities in this field.

Tiago Silva et. al. (2016) [6] The study verifies a numerical model used to assess the thermal efficiency of a window shutter that incorporates Phase Change Material (PCM). The results demonstrate the effectiveness of the PCM-enhanced shutter in reducing heat transfer and improving energy efficiency in buildings.

Mohammed Mumtaz A. Khan, et.al. (2017) [7] review provides a comprehensive analysis of the use of PCMs in solar absorption refrigeration systems. The paper begins by discussing the importance of refrigeration systems in various sectors and the growing interest in developing sustainable and energy-efficient cooling technologies.

Devendra Dandotiya and N. D. Banker's (2017) [8] The research offers a numerical exploration of how fins can enhance heat transfer in a multitube thermal energy storage heat exchanger. The results highlight the positive impact of fins on heat transfer efficiency and emphasize their potential in improving the overall thermal performance of the system.

K. Panchabikesan, et.,al. (2018) [9] The study showcases how integrating a PCM-based storage system with a DEC (Direct Evaporative Cooling) unit enhances the potential for free cooling. The results emphasize the improved cooling performance and energy efficiency achieved by combining these technologies. The research contributes to the understanding of PCM and DEC integration in building cooling systems and provides valuable insights for optimizing energy-efficient cooling strategies.

Antoni Gil, et., al. (2018) [10] presents experimental findings on how fined tubes contribute to the enhancement of effective thermal conductivity in high-temperature bulk tanks containing PCM (Phase Change Material). The results highlight the significant improvement in thermal performance achieved through the incorporation of fined tubes. The study adds to the comprehension of heat transfer enhancement methods for

thermal energy storage systems utilizing PCM (Phase Change Material) and offers valuable insights for optimizing energy storage solutions.

De-Xin Zhang, et., al. (2019) [11] review provides an overview of PCMs for energy efficiency in buildings, with a focus on their use in mortars. The paper emphasizes the potential of PCM-enhanced mortars in improving thermal performance and energy conservation.

Sung Ho Choi, et., al. (2020) [12] study demonstrates the reduction of heat penetration through PCM walls via bubble injections. The results highlight the effectiveness of this novel approach in enhancing thermal performance of PCM walls and mitigating heat transfer.

Exploring the applications of PCM materials in estimating heat transfer under ambient conditions, the most justifiable solution can be achieved through conducting experiments with diverse PCM materials at various locations and atmospheric temperatures. This approach allows for comprehensive insights into their effectiveness in different scenarios.

Nomenclature:

Symbol	Content	Dimension
N_n	Number of tubes in a row normal to flow	5
N_p	Number of tubes in a row parallel to flow	10
N	Total number of tubes	50
W	Width of the configuration	25mm
L	length of the configuration	25cm
d	Diameter of the tube	15 mm
ρ_l	Density of the liquid	750 kg/m ³
h_o	Outside heat transfer coefficient	44.29 W/m ² K

III. STEPS TO DESIGN THE PCM BASED AIR COOLER

Here are the steps involved in the thermal design and simulation of a PCM based air cooler:

System Design: Begin by defining the requirements of the air cooler, including the desired cooling capacity, temperature range, and operating conditions. Determine the size and layout of the system components such as the heat exchanger, PCM containers, fans, and air ducts.

PCM Selection: Choose a suitable phase change material based on its thermal properties, such as melting point, latent heat of fusion, thermal conductivity, and compatibility with the operating temperature range. Consider factors like cost, availability, and environmental impact when selecting the PCM.

Heat Transfer Analysis: Perform a heat transfer analysis to determine the amount of heat that needs to be absorbed or released by the PCM to achieve the desired cooling effect. Consider the heat transfer mechanisms involved, such as conduction, convection, and radiation.

Design of Heat Exchanger: Design a heat exchanger that facilitates good heat transfer rate between the air and the PCM. The heat exchanger should provide a large surface area for heat exchange and ensure good contact between the air and the PCM.

Simulation Software: Utilize thermal simulation software such as COMSOL, ANSYS Fluent, or SolidWorks Flow Simulation to model and simulate the thermal behavior of the PCM air cooler. These software tools allow you to create a virtual prototype of the system and analyze its performance under different operating conditions.

Model Creation: Develop a detailed 3D model of the PCM air cooler system within the simulation software. Include all relevant components, such as the PCM containers, heat exchanger, fans, and surrounding environment.

Boundary Conditions: Describe the boundary conditions for the simulation, including the airflow rate, temperature, and humidity of the incoming air. Specify the initial conditions of the PCM, such as its initial temperature and phase.

Solver Configuration: Set up the solver parameters, such as the discretization scheme, time step, and convergence criteria, for the simulation. These settings ensure accurate and efficient simulation results.

Run the Simulation: Execute the simulation within the software and monitor the results. Analyze important parameters like temperature distribution, heat transfer rates, and cooling capacity to evaluate the performance of the PCM air cooler.

Optimization and Validation: Modify the design parameters and repeat the simulation to optimize the system's performance. Validate the simulation results by comparing them with experimental data or published literature on similar PCM cooling systems.

Design Refinement:

Based on the simulation results and optimization, refine the design of the PCM air cooler to enhance its efficiency, reliability, and cost-effectiveness.

By following these steps, it can be effectively designed and simulate a phase change material air cooler, optimizing its thermal performance and ensuring it meets the desired cooling requirements.

Width of the configuration = $W = N_n \cdot S_n = N_n \cdot (3 \times d)$

Length of the configuration is $L = N_p \cdot S_p = N_p \cdot (3 \times d)$

Total number of tubes in the cooler is $N = N_n \cdot N_p$

PCM mass in tubes $M_{pcm} = N \cdot V_{tube} \cdot \rho_l$

Heat-transfer area A is the surface of the tubes = $A = N \cdot \pi \cdot d \cdot H$

Convection heat-transfer coefficient outside the tubes h_o :

The Grimson correlation is a widely used formula for estimating the cross flow of air. It considers parameters such as the velocity of the air, the angle of incidence, and the surface area through which the air is flowing. The correlation provides an approximation of the crossflow velocity, which is useful for various engineering applications.

The Grimson correlation shown below is derived from a combination of experimental data and theoretical analysis. It is a reliable method for estimating the cross flow of air, but it may have limitations in certain situations or when specific conditions are not met. It is important to consider the specific requirements and conditions of the application when using the Grimson correlation.

- Grimson
 - For airflow ($Pr=0.7$) across bundles of 10 or more rows ($N_L \geq 10$):

$$\overline{Nu_D} = C_1 Re_{D,max}^m$$
 - Modification for other fluids across tube bundles:

$$\overline{Nu_D} = 1.13 C_1 Re_{D,max}^m Pr^{1/3} \quad Re_{D,max} = \frac{\rho V_{max} D}{\mu}$$

- Properties at T_f
- Number of rows $N_L \geq 10$
- $2000 < Re_{D,max} < 40,000$
- $Pr \geq 0.7$

$$V_{max} = \frac{S_T}{S_T - D} V \quad \text{aligned}$$

$$V_{max} = \frac{S_T}{2(S_D - D)} V \quad \text{staggered}$$



Figure 3 PCM based air cooler in different orientations.

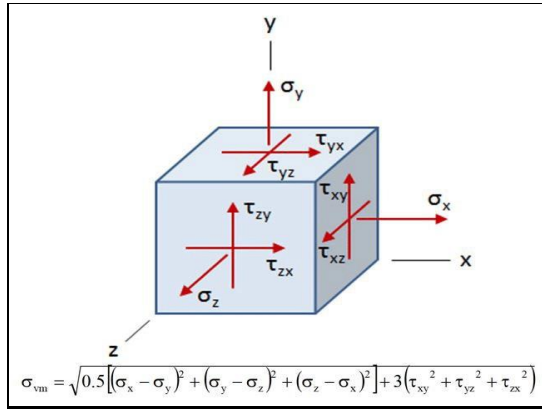


Figure 4 Vonmises stress formulae used in tube element

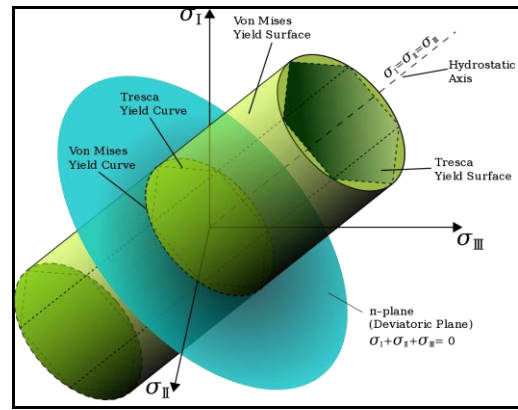


Figure 5 Vonmises yield curve in PCM tube.

A. Modelling of phase change material air cooler using CATIA V5

The base frame for phase change material is designed on the CATIAV5 Software to design the arm shown in figures 5 (a), (b) and (c). The procedure is given below.

1. Go to part design work bench select a plane and sketch of arm.
2. In part design work bench find PAD and POCKET to add remove material respectively.
3. Go to part design work bench select a plane and sketch of arm.
4. In part design work bench find PAD and POCKET to add remove material respectively. The tubes for phase change material are designed on the CATIA V5

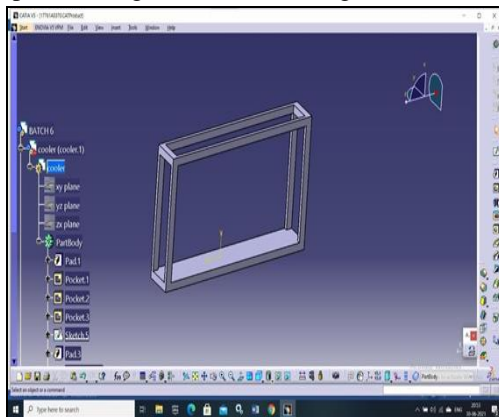


Figure (5a)

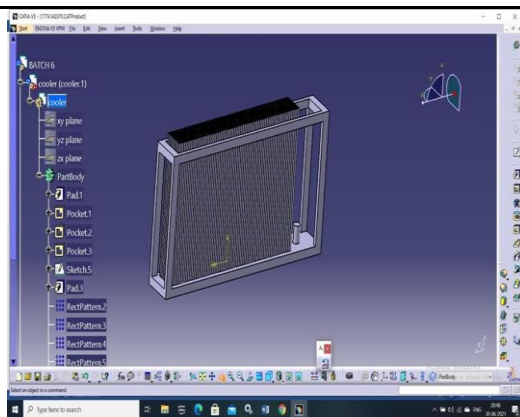


Figure (5b)

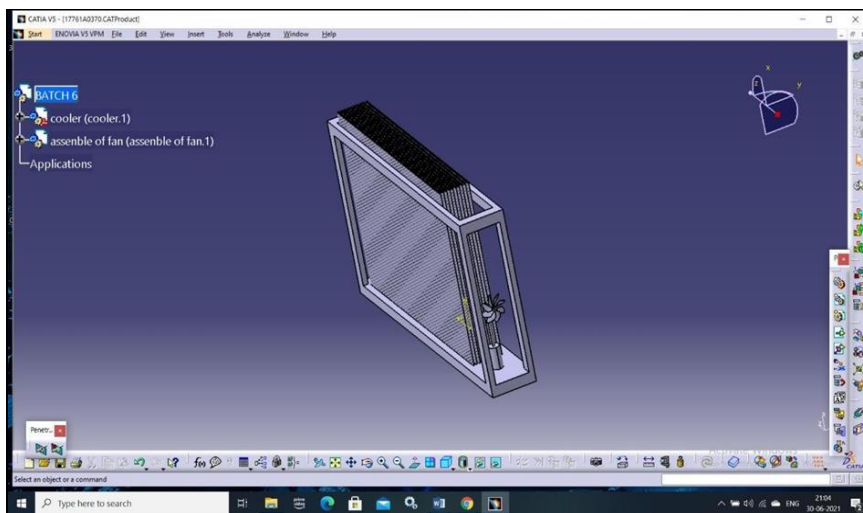


Figure (5c)

Figure 5 (a), (b), (c) Modelling of PCM based air cooler in CATIA V5.

B. Analysis of phase change material air cooler using ANSYS R18

Ansys meshing capabilities help reduce the amount of time and effort spent to get accurate results. Since meshing typically consumes a significant portion of the time it takes to get simulation results, Ansys helps by making better and more automated meshing tools.

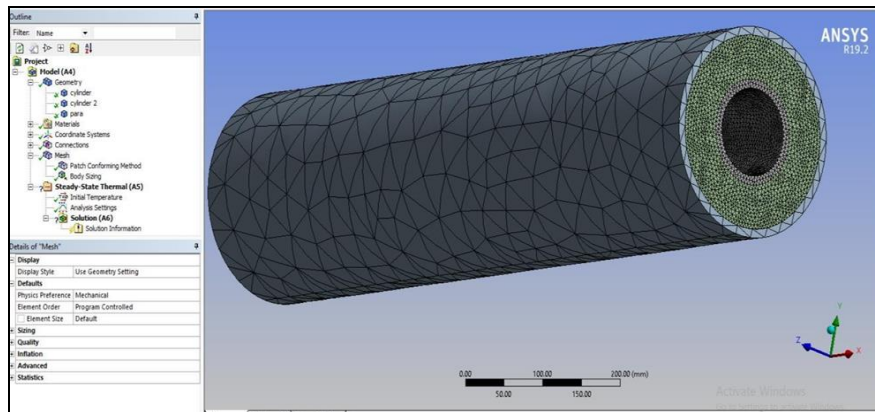


Figure (6a) Mesh generation tube

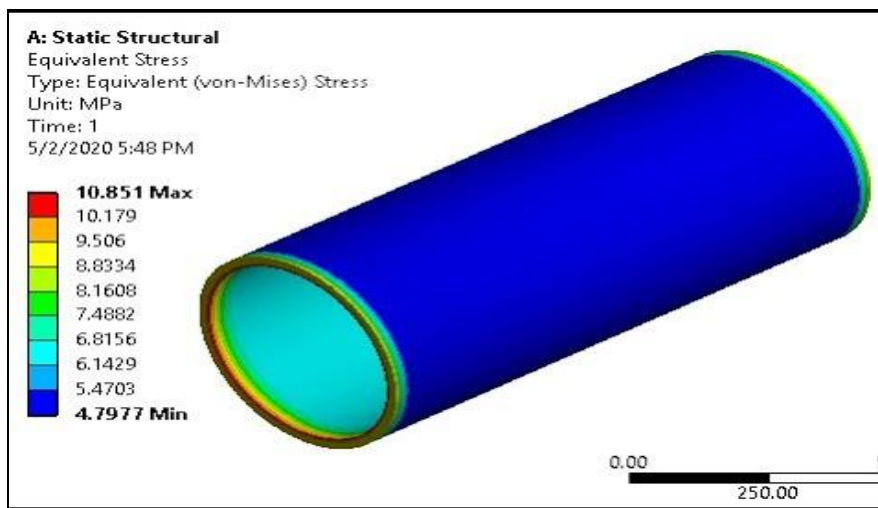


Figure (6b) Calculation of Vonmises stress in a PCM based tube.

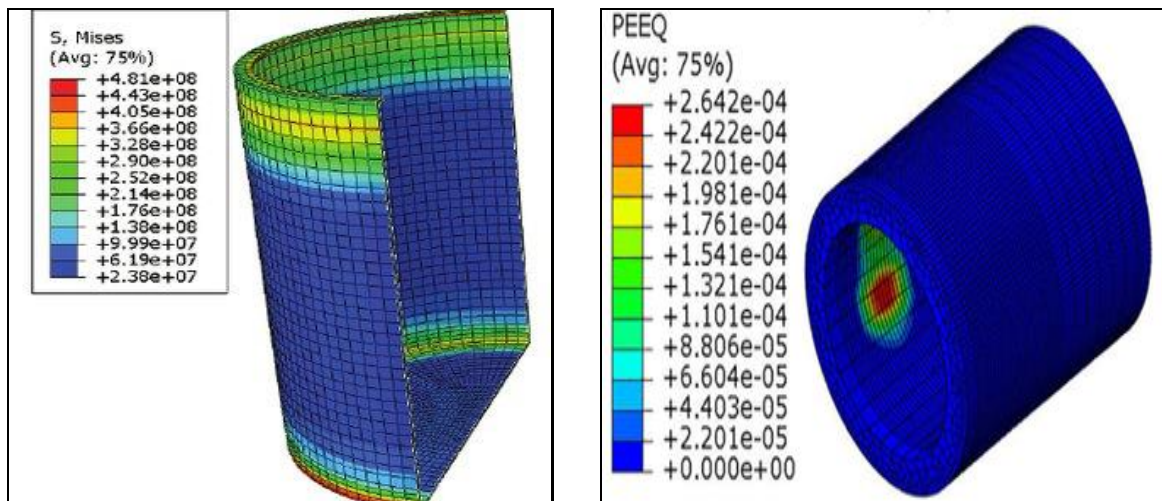


Figure (6c, 6d) Vonmises stress and strain variation in a PCM based tube.

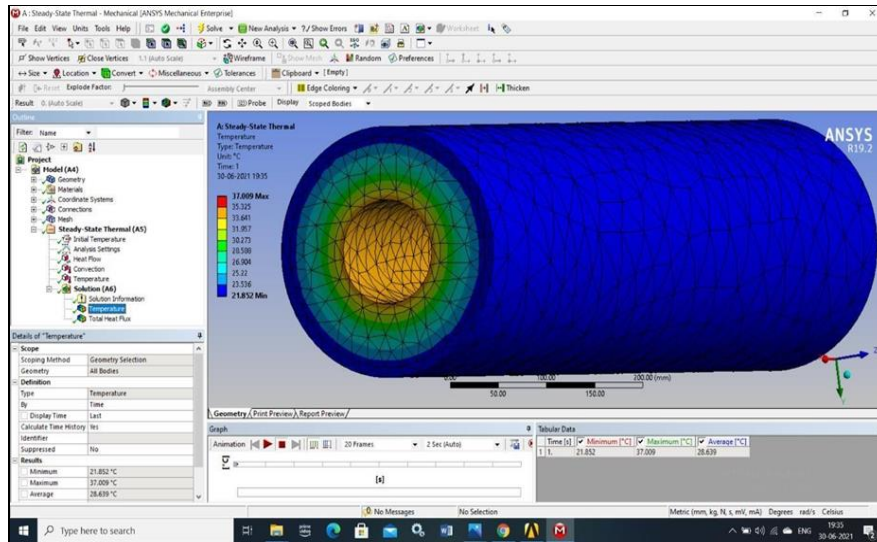


Figure (6e) Steady state thermal analysis of PCM based air cooler tube.

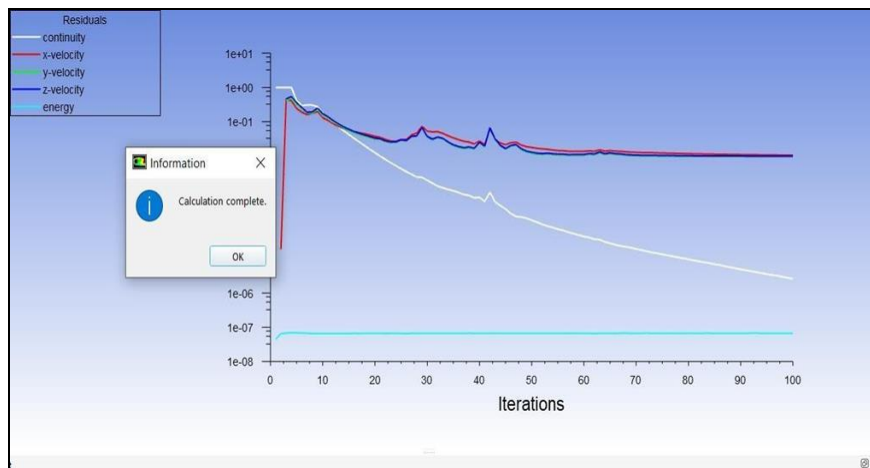


Figure (6f) converged solution results of PCM based air cooler tube.

Figure 6 (a), (b), (c), (d) (e) and (f) Analysis of PCM based air cooler in ANSYS.R18

The availability of organic PCM materials in the market are Lauric acid, Capric acid, n-Octadecane, Lauryl Alcohol, Butyl stearate, n-hexadecane, Decanoic acid, n-docosane, Caprylic acid, Butyl palmitate, Methyl palmitate, Stearic acid, Palmitic acid, Dodecanol, Polyglycol E600, Polyglycol E1000, Polyglycol E2000, n-nonadecane, Paraffin wax, Myristic acid etc.

The availability of inorganic PCM materials available is $\text{LiClO}_3 \cdot 3\text{H}_2\text{O}$, $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, $\text{LiBO}_2 \cdot 8\text{H}_2\text{O}$, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, $\text{CaCl}_2 \cdot 12\text{H}_2\text{O}$, $\text{CaBr}_2 \cdot 6\text{H}_2\text{O}$, $\text{LiNO}_3 \cdot 3\text{H}_2\text{O}$, and $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$.

The availability of eutectic PCM materials in the market are. $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} - \text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O} - \text{SrCl}_2 \cdot 6\text{H}_2\text{O}$, Capric acid-Myristic acid, Capric Acid-Steric acid, Lauric acid-myristic acid-stearic acid, Capric acid-palmitic acid-stearic acid, Methyl stearate-Cetyl palmitate, Octadecane + docosane, Octadecane + heneicosane etc.

Eutectic PCM is created by blending two or more PCM substances, which can include combinations of organic-organic, organic-inorganic, and inorganic-inorganic materials. These PCM exhibit a distinct and precise melting temperature, resulting in high thermal energy storage density. They undergo melting and freezing without phase segregation, reducing the likelihood of component separation.

In conclusion, eutectic PCM possesses a range of advantageous properties that make them compatible with building materials, effectively enhancing the latent heat storage capacity of structures. These PCM are available in various forms and categories. To select the most suitable PCM for building applications, a

comprehensive analysis of thermal, physical, and chemical properties is essential. This thorough examination ensures the optimal choice of PCM to suit the specific needs and requirements.

The study explored three distinct phase change materials for space cooling purposes. Design calculations were conducted for the inline arrangement of tubes. These calculations aimed to determine the time required to achieve a specific room temperature. The selection of the material is crucial to ensure rapid cooling and reaching the desired temperature promptly. Unlike air coolers, this technology does not encounter issues related to excessive humidity. It is essential to analyze the temperature profile in specific locations to identify the most suitable material. This technology proves particularly effective in areas with high pollution levels. Moreover, significant temperature variations between day and night further enhance its efficiency.

The provided table presents data related to three different phase change materials (PCMs): Paraffin wax, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, and Polyethylene glycol E600. The table 1 includes various parameters and their corresponding values for each PCM. These data provide information about the mass, heat transfer, melting behavior, and time taken for melting for each PCM. It gives insights into the energy storage capacity, melting characteristics, and phase change properties of the different PCMs under consideration.

Table 1: Three different phase change materials (PCMs): Paraffin wax, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, and Polyethylene glycol E600

S.No		Paraffin wax	$\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	Polyethylene glycol E600
1	Mass	2kg	6.079kg	4.425kg
2	Heat Transfer	255.757kJ	139.6KJ	266.413KJ
3	PCM Melted	1.2415 kg	0.773 kg	1.95 kg
4	Fraction	0.602	0.127	0.44
5	Time taken for melting	146.2 min	202.25	131.39 min

These thermo-physical properties shown in table 2 provide crucial information about the behavior and performance of the paraffin wax PCM, including its phase change temperature, energy storage capacity, density, thermal conductivity, and specific heat capacity. Understanding these properties is essential for designing and utilizing the PCM effectively in various thermal energy storage applications.

Table 2: The phase-change material is paraffin wax (RT-27 by Rubitherm).

Phase change material	Properties	Value
Paraffin wax (RT-25 by Rubitherm).	Melting temperature (T_m)	23°C (22 to 24°C)
	Specific enthalpy of melting (hm)	206 kJ/kg
	Density in liquid state	1, 750 kg/m ³
	Density in solid states	800 kg/m ³
	Thermal conductivity (k)	0.2 W/m K
	Specific heat capacity (cp)	2500 J/kg K

The provided data in table 3 represents a set of readings for the temperature of a phase change material (PCM) made of paraffin over a period.

Table 3: Readings for PCM material (paraffin)

S.No	Time (Sec)	Temperature (°C)
1	0	34.2
2	5	34.1
3	10	33.8
4	15	33.4
5	20	33.1
6	25	32.9
7	30	32.5
8	35	32.3
9	40	32.1
10	45	31.8
11	50	31.5
12	55	31.3
13	60	31.1

Each reading includes the time in seconds and the corresponding temperature in degrees Celsius. Based on these readings, it appears that the paraffin PCM material is undergoing a phase change from a higher temperature phase to a lower temperature phase, releasing heat energy in the process. This behavior is typical for PCM materials, as they absorb or release thermal energy during phase transitions, providing effective thermal energy storage capabilities.

IV. CONCLUSIONS

Three different phase change materials (PCMs) were investigated for cooling the space. Design calculations were conducted for the inline arrangement of tubes to determine the time required to reach a specific temperature in the room. The selection of the material is crucial to ensure a rapid attainment of the desired temperature. The duration of cooler operation was examined for various materials, with a focus on achieving prolonged cooling of the space. Additionally, the relationship between time and melt fraction was investigated for three different mammalian species. The following conclusions were drawn after experimental validation.

1. The experiment recorded the temperature at regular time intervals and it gradually decreases over time, from 34 °C to 31 °C in a period of 1 minute which indicated a cooling process.
2. **Heat Transfer:** The amount of heat transferred during the phase change is highest for Paraffin wax at 255.757kJ, followed by Polyethylene glycol E600 at 266.413kJ, and the lowest is for CaCl₂·6H₂O at 139.6kJ.
3. **PCM Melted:** During the phase change process, the amount of PCM that melts is the highest for Paraffin wax, where 1.2415kg of PCM melts. For CaCl₂·6H₂O, 0.773kg of PCM melts, and for Polyethylene glycol E600, 1.95kg of PCM melts.
4. **Fraction:** The fraction of PCM that undergoes phase change (melts) relative to the initial mass is highest for Paraffin wax at 0.602, followed by Polyethylene glycol E600 at 0.44, and the lowest is for CaCl₂·6H₂O at 0.127.
5. **Time taken for melting:** Paraffin wax takes the shortest time to melt, with a duration of 146.2 minutes. CaCl₂·6H₂O takes the longest time at 202.25 minutes, and Polyethylene glycol E600 takes 131.39 minutes to melt completely.
6. **Vonmises stress:** The stress variation is minimum as 4.7 Mpa and 10 MPa is maximum and the 100 number of iterations are taken to get the converged solution.

These conclusions provide valuable insights into the behavior and performance of each PCM during the phase change process. They also highlight the varying thermal properties and characteristics of the different PCMs, which are crucial considerations when choosing a suitable PCM for specific applications.

SCOPE FOR FUTURE WORK

1. **PCM Selection and Optimization:** Further research can focus on identifying and optimizing the selection of suitable PCMs for specific air cooling applications, considering factors such as phase change temperature, thermal conductivity, and stability.
2. **Integration with Renewable Energy Sources:** The integration of PCM-based air coolers with renewable energy sources, such as solar energy, has gained attention. Researchers have been exploring ways to utilize solar energy for charging the PCM during the day and releasing stored energy for cooling during the night, resulting in reduced energy consumption and increased sustainability.
3. **Experimental and Numerical Studies:** More experimental and numerical studies can be conducted to assess the performance of PCM-based air coolers under different operating conditions, including varying ambient temperatures and humidity levels.

The scope for future work in PCM-based air coolers is broad, encompassing various aspects such as PCM optimization, system design, encapsulation techniques, performance evaluation, and economic analysis. By addressing these areas, researchers can further enhance the effectiveness and practical implementation of PCM-based air cooling systems, leading to more energy-efficient and sustainable cooling solutions for different applications.

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