EXPERIMENTAL AND NUMERICAL ANALYSIS OF PHASE CHANGE MATERIAL BASED AIRCOOLER

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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, $CaCl_2H_2O$, 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 Air Cooler, cooling effectiveness, Ansys

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. According to the International Energy Agency (IEA), the energy consumption and consequent carbon dioxide emissions for all sectors are listed below

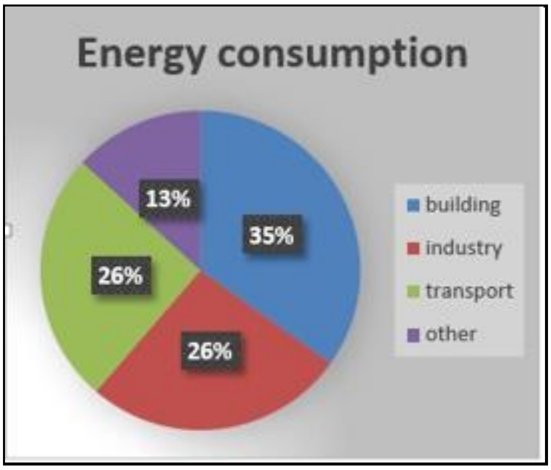

Figure 1 Energy Consumption in all Sectors

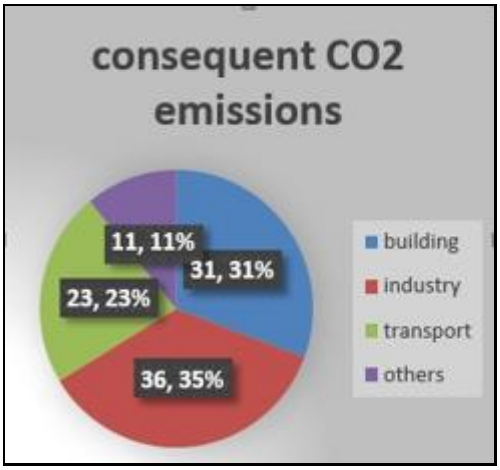

Figure 2 CO_2 Emission in all Sectors

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) (even though when indirect building emissions from power generation are included, buildings and construction represent nearly 40% percent of energy-related CO_2 emissions). Air conditioning is another source of greenhouse gas emissions in the construction industry. Air conditioning is described as the act of eliminating heat andmanaging the humidity of air in an enclosed area using electric power to create a more pleasant indoorspace for humans.

The problem with air conditioning systems is that the utilization of electricity is higher and greenhouse gas emissions, such as chlorofluorocarbons, are emitted if they are not effectivelymanaged, so that global warming is increasing rapidly. Not only the environment, but it will also show some effect on human beings like Dry eyes, skin problems, allergies, and illnesses are all side effects of using an air conditioner.

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.

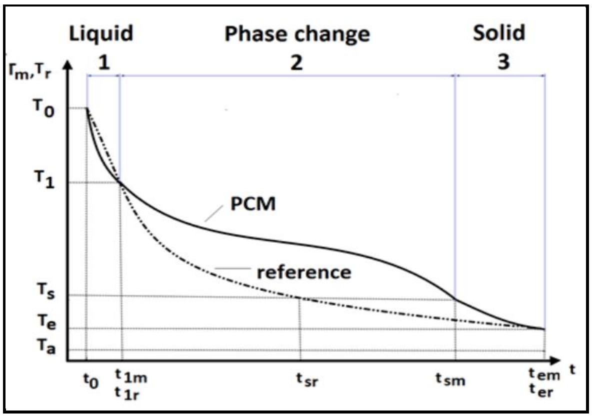

Figure 3 PCM materials conversion at different temperatures against time

Objective of the proposed research methodology and motivation:

1. **Energy Efficiency:** PCM-based air coolers have the potential to improve energy efficiency in cooling systems by reducing electricity consumption and reliance on conventional air conditioning methods.

2. **Thermal Comfort:** PCM-based air coolers can provide enhanced thermal comfort by maintaining a more stable and comfortable indoor temperature.

3. **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.

4. **Cost Savings:** By reducing energy consumption, PCM-based air coolers can lead to cost savings for building owners and users.

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. Electronics cooling and thermal management.
vi. Automotive cooling and waste heat recovery
vii. Solar energy storage and utilization
viii. Food and cold chain preservation

II. ITERATURE 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] , three-dimensional transient simulations were conducted in both a real-size room and a portable storage unit. Various cooling elements with different shapes were placed within the enclosure, including vertical plates, horizontal plates, horizontal square tubes in both in-line and staggered configurations, as well as vertical square tubes in an in-line configuration. Additionally, Arye and Guedj (2004) conducted experiments using a shell-and-tube unit where the tubes, filled with PCM, were oriented vertically.

Mozhevelov et al. (2005) [2] focused on investigating thin vertical storage units positioned parallel to the walls of a room. Furthermore, Letan and Ziskind (2005) presented a case study involving a real-size room being cooled during daytime using 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] validates a numerical model for analyzing the thermal performance of a window shutter containing 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] study provides a numerical investigation of heat transfer enhancement in a multitube thermal energy storage heat exchanger using fins. 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] demonstrates the enhancement of free cooling potential through a PCM based storage system integrated with a DEC unit. 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 an experimental analysis of the effective thermal conductivity enhancement of PCM using fined tubes in high-temperature bulk tanks. The results highlight the significant improvement in thermal performance achieved through the incorporation of fined tubes. The research contributes to the understanding of heat transfer enhancement techniques for PCM-based thermal energy storage systems and provides valuable insights for optimizing energy storage.

M. Frigione, 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 in the built environment.

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.

Considering the uses of pcm materials, which is used to estimate the aspects of heat transfer under ambient conditions. The best justifiable solution can be obtained when experimentation is done for varied pcm materials at different locations and at different atmospheric temperatures.

Nomenclature:

Nn	Number of tubes in a row normal to flow	5
Np	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
ρl	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 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 efficient heat transfer 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: Define 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 = $W = Nn*Sn = Nn*(3 \times d)$
Length of the configuration is $L = Np*Sp = Np*(3 \times d)$
Total number of tubes in the cooler is $N = Nn*Np$
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 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:

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

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

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

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

Umax is the air velocity at the minimum frontal area. In an in-linearrangement, this is.

$$V_{max} = u_\infty \cdot (S_n / S_n - d)$$

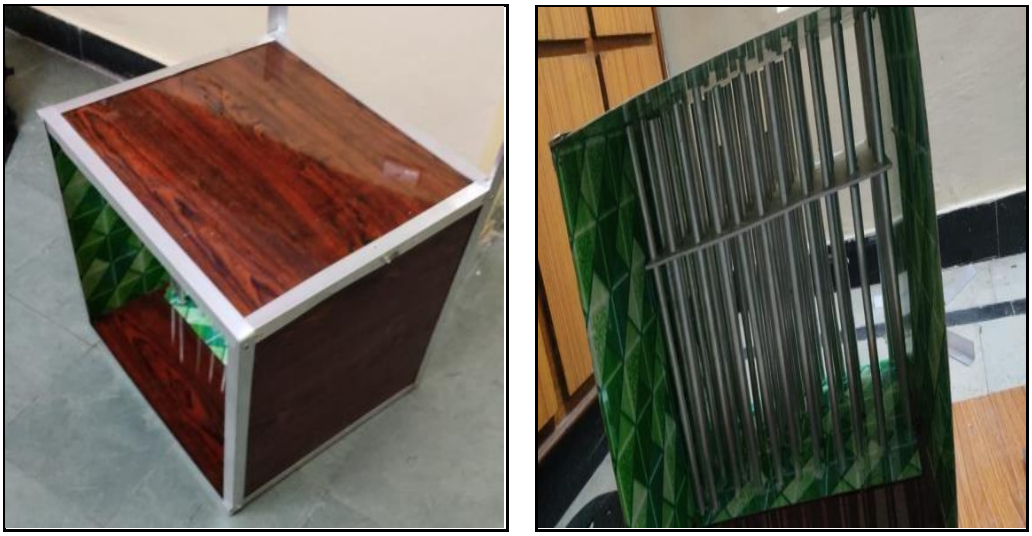

Figure 4 PCM based air cooler in different orientations.

A. **Design of phase change material air cooler using CATIA V5**

The base frame for phase change material is designed on the Catia v5 software. The CATIAV5 Software is used to design the Arm. 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 is designed on the Catia v5 software. The CATIA V5

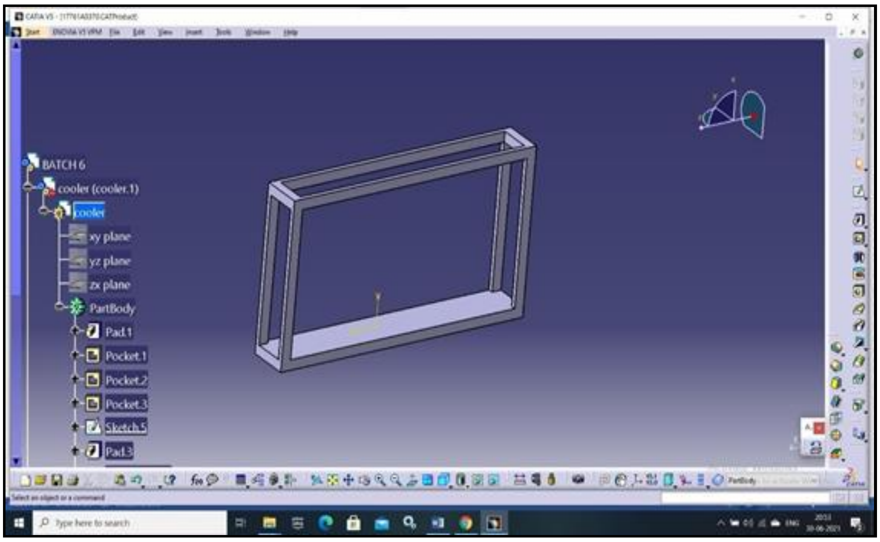

Figure (5a)

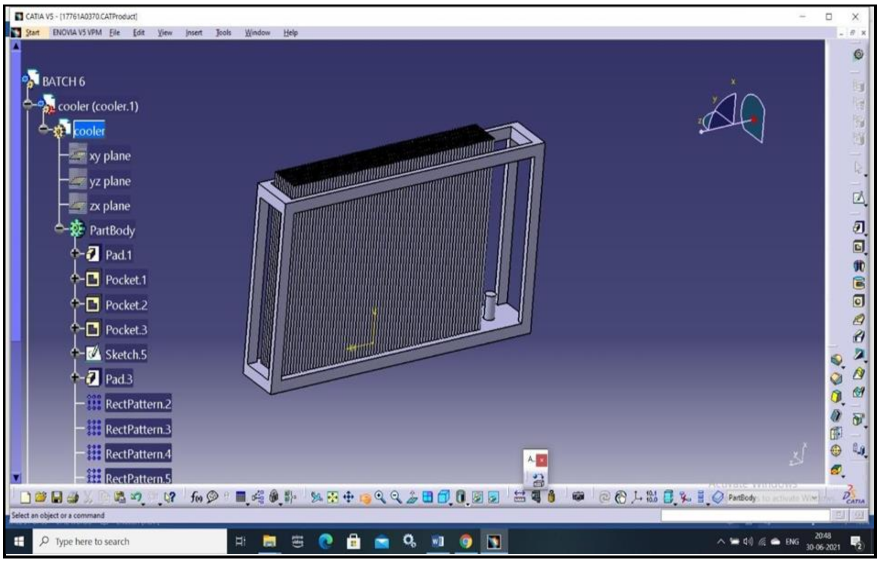

Figure (5b)

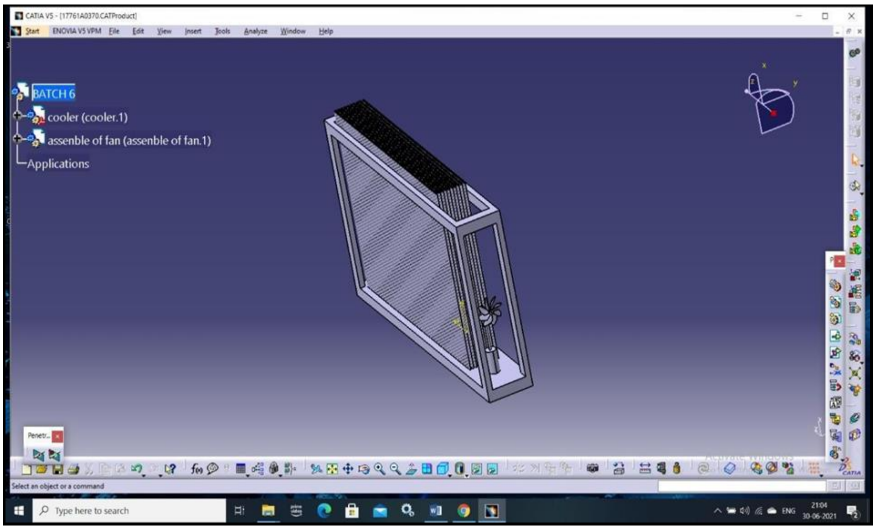

Figure (5c)

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 to 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.

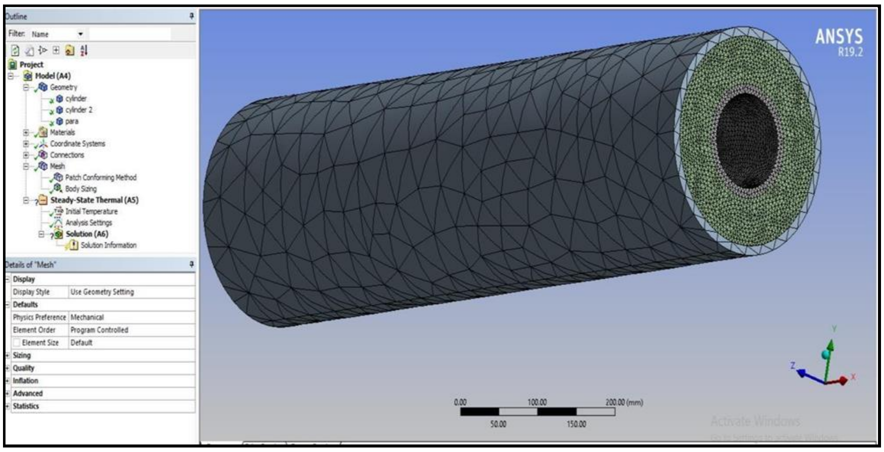

Figure (6a)

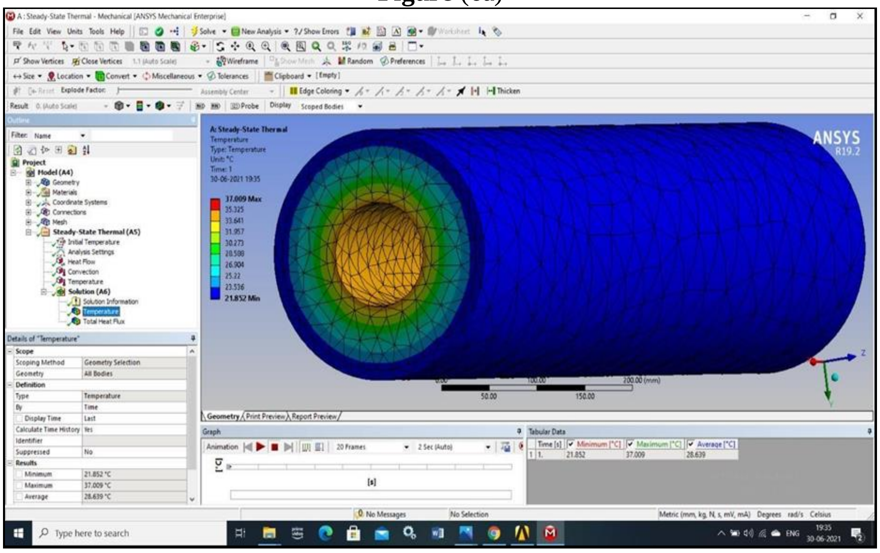

Figure (6b)

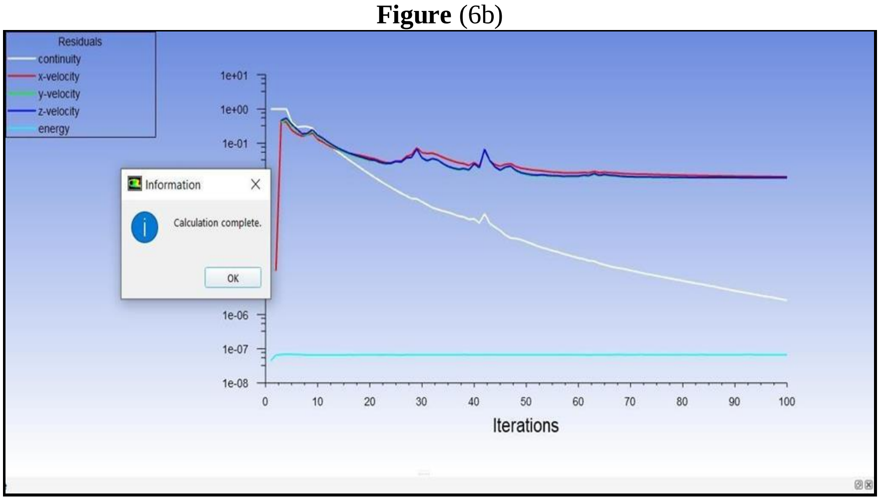

Figure (6c)

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

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, Cacl26H2O, 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, Cacl26H2O, and Polyethylene glycol E600

S.No		Paraffin wax	CaCl26H2O	Polyethylene glycolE600
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 takenfor 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-25 by Rubitherm).

Phase change material	Properties	Value
Paraffin wax (RT-25 byRubitherm).	Melting temperature (Tm)	23◦C (22 to 24◦C)
	Specific enthalpy of melting (hm)	206 kJ/kg
	Density in liquid state	l, 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. 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.

Table 3: Readings for PCM material (paraffin)

S.No	Time (Sec)	Temperature (0C)
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**

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.

Unlike air coolers, this technology does not face issues related to excessive humidity. It is essential to analyze the temperature profile in a specific location to choose the appropriate PCM. This technology proves particularly effective in areas with high pollution levels. Furthermore, the significant temperature difference between day and night further highlights the potential benefits of this cooling approach.

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.
4. **Smart Control and Monitoring Systems:** Advancements in control and monitoring systems have enabled more precise and efficient operation of PCM-based air coolers. This includes the integration of sensors, actuators, and intelligent algorithms for optimal temperature regulation, energy management, and user comfort.
5. **Economic Analysis:** Future studies can include comprehensive economic analyses, considering factors such as lifecycle costs, payback periods, and return on investment to assess the economic viability of PCM-based air cooling systems.

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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