EXPERIMENTAL AND NUMERICAL ANALYSIS OF AN AUTOMOBILE CABIN THERMAL MANAGEMENT USING PHASE CHANGE MATERIAL (PCM)

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Abstract - *In the modern world, everybody is looking for comfort and comfort mainly is associated with the perfect ambient temperature and perfect humidity which helps to reduce the stress to a certain extent. Today, the temperature is rising day by day and the same in the case of vehicles. Vehicles are primarily meant for a space that provides comfort to the occupants. Considering the comfort factor vehicles are installed with air conditioning systems. But these air conditioning systems act as a parasite on the vehicle consuming a part of the energy produced by the engine. This paper presents a numerical analysis and modelling results for an innovative system which helps in reducing the temperature inside the vehicle on sunny days. A PCM named Calcium Chloride Hexahydrate is used for the numerical and experimental analysis*

Key Words: Phase change materials (PCM), computational Fluid Dynamics, Automobile cabin, thermal management, automobiles, heat transfer, HVAC

1. INTRODUCTION

The temperature during the summer days is increasing gradually. When vehicles are parked facing the sun a large amount of heat energy emitted by the sun enters the cabin through the greenhouse of cars. The heat gets accumulated inside the cabin. The dashboard and other parts of most automobiles are made of plastic, which when in the presence of heat from the sun emits harmful gases which can cause harmful effects to the occupants. This increased heat in the car cabin can also result in damage to the dashboard plastics. To reduce the temperature inside the vehicle cabin air conditioning systems are used but to reduce this high temperature inside the cabin to low levels the work done by the air conditioning system of the vehicle is very high and also the power required for the working of the air conditioning systems are from the work produced by the engine. Air conditioning systems are a parasite to the automobile engine. The user has to wait for a long time for the interior temperature of the car to cool down by either rolling down the window or switching on the a/c. The rise in the temperature inside the cabin may make the users uncomfortable. Moreover, the vehicle cabin may face an aging problem and may damage the dashboard plastics and materials kept in the vehicle. Various findings say that every year has recorded many children die due to heatstroke due to being left inside the vehicles. When the vehicle is parked in direct heat and sun the temperature rise in the parked vehicle is mainly due to the solar radiation that enters the car through the glasses and is partially trapped within the car. The temperature inside the car on a summer day could reach up to 110ºC whereas the outside temperature ranges from 35ºC to 45ºC. so, to reduce thermal heat inside a vehicle we have proposed an innovative method to stop the heat entering the cabin by arresting the heat on the roof itself. For that PCM has been used which has the ability to absorb the heat and store it within the material itself. Phase change materials have the ability to change their phase from solid to liquid and vice versa. Phase-changing materials have the ability to absorb heat and convert it into liquids. And when it releases heat, it changes into a solid-state. In this paper, a numerical analysis is performed on a two-conditioned roof system with PCM and a Roof other than PCM. The PCM analysed in the present study is Calcium Chloride Hexahydrate ($CaCl_2.6H_2O$). A test model was also developed to show how the system works. The roof is made of 5086 series aluminium. The phase switches are inserted between the insulator layers and the top sheet metal layers The inserted roof contains PCM in it. Phase Change Material (PCM) is a composite material that melts and hardens at a certain temperature and is able to store and release a large amount of heat energy. PCM is in a solid-state at first. As the natural temperature rises, it absorbs energy in the form of heat. When the ambient temperature reaches the melting point, PCM absorbs most of the heat energy at an almost constant temperature. This continues until all the material is converted into a liquid phase. In this way, the heat is stored in the PCM and the temperature is maintained at a very good level. When the temperature around an object decreases, it hardens as it releases the heat back into space. The purpose is to design and build a vehicle roof that is resistant to heat entering the car cabin to maintain a central temperature in the car park where the car is parked in a shady area. The main feature of the design is to make the cabin temperature more comfortable for passengers as they enter the parked car. Installation of this roof design will reduce the internal temperature of the car house. Due to this roof structure, the deterioration of plastic parts can be reduced. The driver does not have to keep the car windows low to vent. When children and pets are left in the car cabin, they will not be affected by the increase in car room temperature.

Varieties of PCMs have been shown to have a wide range of melting points. However, for their involvement as subtropical heat-retaining materials, a certain desirable thermodynamic (high-temperature low temperature, good heat transfer), kinetic and chemical properties (non-toxic, long-term stability, heat) is required. Additionally, economic considerations and the availability of PCM also need to be explored. As PCMs are defined by their melting points, specific to a specific application, i.e., each application may require a specific PCM or PCM set based on operating temperature. Therefore, the thermal condition of the vehicle and the availability of appropriate PCM is very important.

1.1 METHODOLOGY

The 3D model of the car has been designed in Solidworks, The PCM layer is incorporated into the roof of the car. PCM helps in maintaining the desired temperature by absorbing the excess heat. When the engine is turned off, say, at a traffic signal, PCM restricts the increase in cabin temperature by absorbing the excess heat to some extent depending upon its thermophysical properties. The heat absorbed by the PCM is released either during the vehicle movement or at night when the outside temperature is lower than the melting temperature of the PCM. The PCM added to the vehicle body should not considerably affect the weight of the body. The analysis is done using ANSYS Fluent. Both steady-state and transient state thermal analyses were performed

1.2 BOUNDARY CONDITIONS

The inside surfaces of the vehicle are provided with a temperature similar to room temperature i.e., 26°c simulations. The external free stream temperature is considered to be 309 K, i.e., 36°C, and the properties of air are taken into consideration. The conditions inside the vehicle cabin are considered as the ideal room temperature condition of 299K i.e., 26°C For solving the above problem, a pressure-based solver and both steady-state and a transient time-based approach is being used. In the case of PCM, the melting and solidification model along with the energy model is used. The thermal mixed model is used to solve the problem. Double precision mode with dual processor usage is preferred for smooth working and lower CPU demand. The model has been analysed for the location of Kerala for the month of June. The latitude and longitude of Kerala are 10.8505° N, 76.2711° E.

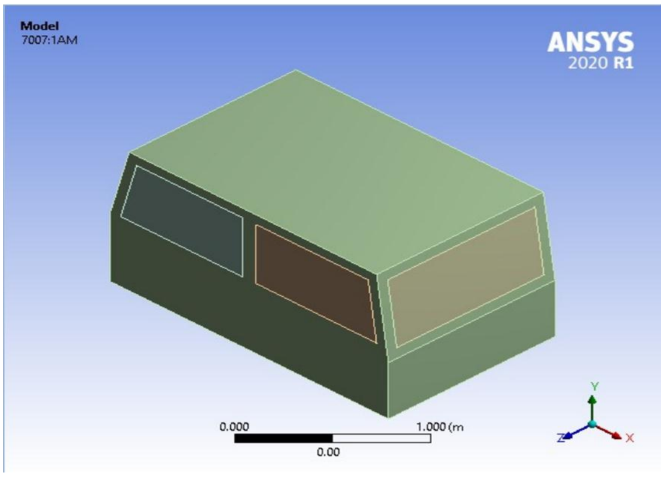

Fig -1: 3D model of a Car

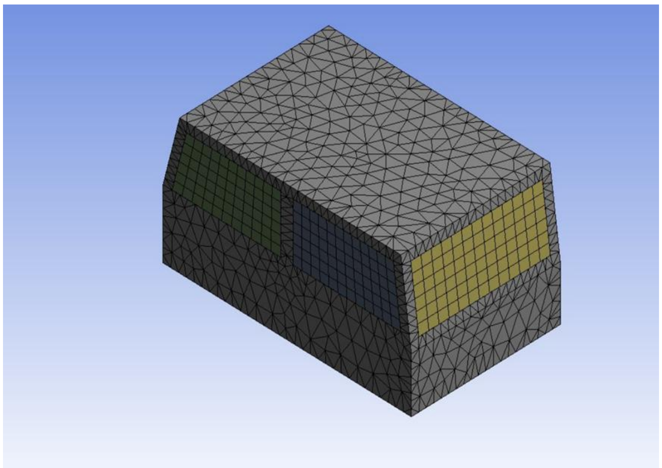

Fig -2: Mesh model

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	Default
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Use Adaptive Sizing	Yes
Resolution	Default (2)
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Slow
Span Angle Center	Fine
Initial Size Seed	Assembly
Bounding Box Diagonal	2.5417 m
Average Surface Area	0.42561 m²
Minimum Edge Length	3.0295e-003 m
Quality	
Check Mesh Quality	Yes, Errors
Target Skewness	Default (0.900000)
Smoothing	Medium
Mesh Metric	None
Inflation	
Assembly Meshing	
Advanced	
Statistics	
Nodes	8740
Elements	16246

Fig -3: Mesh setup for 3D model incorporated with PCM

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	Default
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Use Adaptive Sizing	Yes
Resolution	Default (2)
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Slow
Span Angle Center	Fine
Initial Size Seed	Assembly
Bounding Box Diagonal	2.5417 m
Average Surface Area	0.38587 m²
Minimum Edge Length	1.e-002 m
Quality	
Check Mesh Quality	Yes, Errors
Target Skewness	Default (0.900000)
Smoothing	Medium
Mesh Metric	None
Inflation	
Assembly Meshing	
Advanced	
Statistics	
Nodes	7910
Elements	15856

Fig -4: Mesh setup for 3D model without PCM

1.3 EXPERIMENTAL MODEL

1.3.1 Materials used

- PCM – Calcium Chloride Hexahydrate
- Roof – 5086 series Aluminium
- Side glass – Window glass with 4mm thickness
- Temperature sensor – TPM-10 Digital Thermometer
- Base – Wood
- Side panel – Aluminium Composite Panel (ACP) Sheet

1.4 CALCIUM CHLORIDE HEXAHYDRATE (CaCl2. 6H2O)

Calcium chloride hexahydrate is a low inorganic hydrated salt, non-toxic at 29 ° C, compliant with the optimal operating temperature of solar photovoltaic panels and has an ambient temperature of phase change (190 kJ / kg).

Strong odorless, colourless. The formation has the stability of a high switching phase, passing 3,000 cold and hot rotation tests, and can maintain the same distribution of the nucleating agent in a short time. Some of the features of PCM are shown in Table -1

Fig -5: Calcium Chloride Hexahydrate

Melting Temperature (°C)	24-27
Latent Heat (kJ kg-1)	190
Specific Heat (J kg-1K-1)	1800
Thermal Conductivity (W m-1 K-1	0.81
Density (kg m-3)	1805
Non-toxic	Yes
Flammability	No

Table -1: Properties of $CaCl_2.6H_2O$

1.5 FABRICATION OF EXPERIMENTAL SETUP

The test set is built on the items listed above. Plane glass is sealed together with the help of a liquid sealant so that the heat of the cab does not come out of the setup. Roofs are made from 5086 series of aluminum one sheet metal sheet is cut and made in the form of a roof and the PCM material is filled into the cavity provided between the aluminum roof. similarly, a roof is constructed without placing the PCM. so that the difference is reflected in the temperature. The automotive cabinet is represented by a set of tests performed on exactly the same components present in the car. Initially, a square pipe frame is constructed. The side panels are made of ACP sheet. The ACP sheets are considered because it resembles the structure of a vehicle door. It consists of glass, a metal roof, and a wooden base. The glass is glued onto the frame provided for the glass to fit in the glass is then fixed into the aluminum channel area by using silicon glue the top of the car is made of Aluminum. Insulation material used by PCM. PCM is a transition phase capable of absorbing heat and transforming a phase from its solid state to a liquid state. And when the material releases the heat, it converts its phase back into solid-state. PCM is stored in a metal bottom plate made of the same material as the roof.

The analysis was performed in the case of a vehicle parked under the sun in the month of June 2022, when the ambient temperature was 309 K. The study was performed at 1000 s; a situation where the car is outside the traffic where the vehicle has occurred in direct sunlight. Both conditions are considered (i) roof without PCM and (ii) Roof where PCM material is installed.

When the car is standing for 1000s under the sun the engine is turned off, with an ambient temperature of 309 K and direct sunlight, heat transfer occurs from the surrounding area to the car room. Considering the surrounding conditions and the total thermal load on the vehicle, simulations were performed showing that the passengers were exposed to high temperatures of 301K, acting as the basis for analysis, i.e., the case where PCM was not incorporated to the roof of the vehicle.

Length	2.00 ft
Breadth	2.00 ft
Height	2.00 ft
Glass area	4.65 sq. ft

Table -2: Dimensions of the experiment model

Fig -6: Fabricated setup of PCM

Fig -7: Roof without PCM

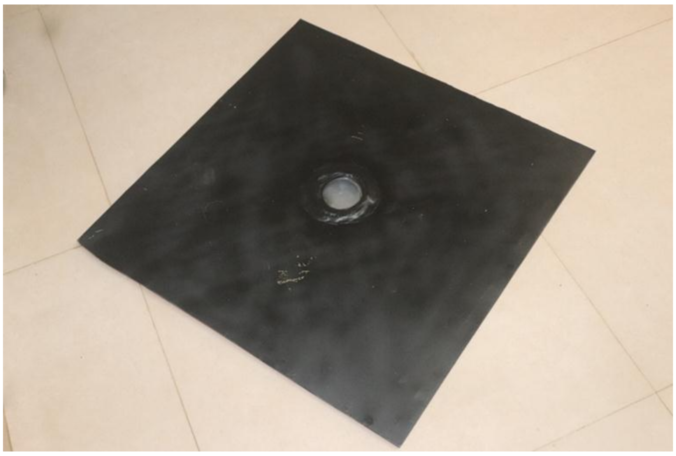

Fig -8: Roof with PCM

2. RESULT AND ANALYSIS

2.1 Steady State Thermal Analysis

The steady state thermal analysis is conducted to determine whether there is any difference in temperature when the PCM is incorporated into the cavity provided in the roof. For the analysis, the roof which is not insulated with PCM is considered and then the PCM insulated roof is considered. The surrounding temperature is assumed to be 36° C i.e. 309K. from the results obtained from the steady state thermal analysis, a slight variation in the temperature can be seen when comparing both the condition. The results of the analysis are given

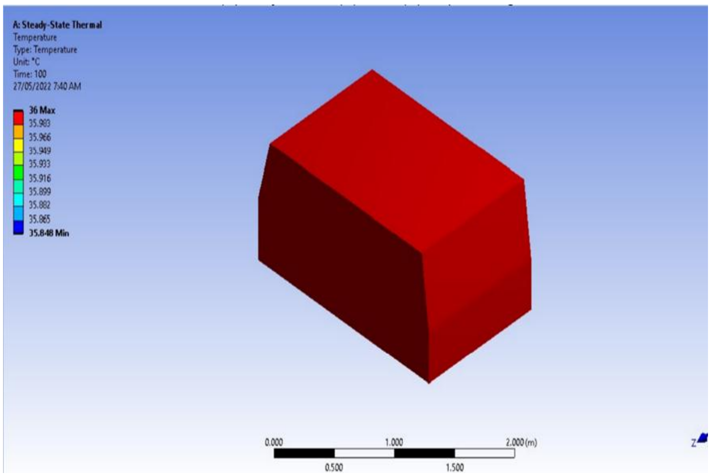

Fig -9: Boundary condition

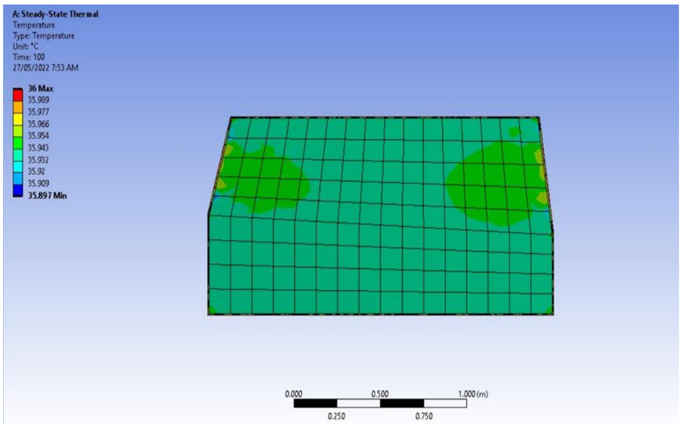

Fig -10: Results of Steady state thermal analysis on cabin without PCM on roof

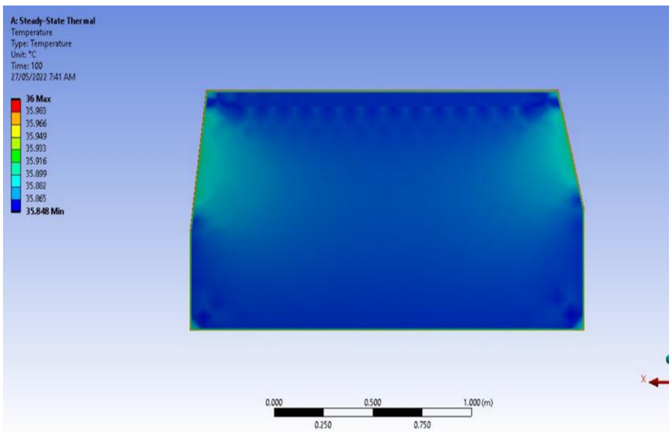

Fig -11: Results of Steady state thermal analysis on cabin with PCM on roof

TEMPERATURE	WITH PCM [°C]	WITHOUT PCM[°C]
MAXIMUM	36	36.
MINIMUM	35.915	35.962
AVERAGE	35.848	35.897

Table -3: Results of Steady state thermal analysis on different conditions

2.2 Transient State Thermal Analysis

The initial temperature inside the cabinet is estimated at 295 K as maintained by the air-conditioner. This increase in temperature is caused by excessive sunlight emitting through the wind window and side glass windows due to high cracking and low glass absorption and due to the car's hot roof.

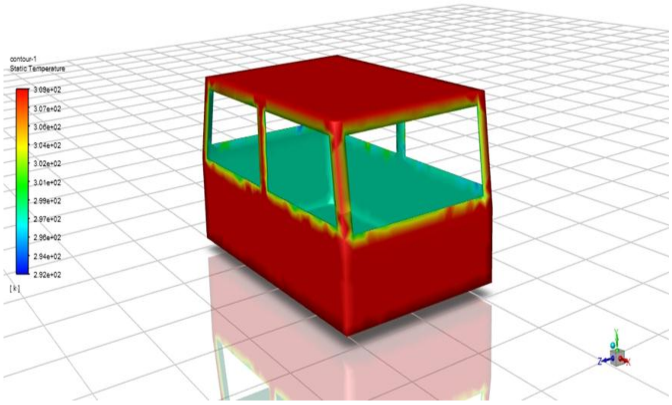

Fig -12: Temperature distribution on the vehicle surface

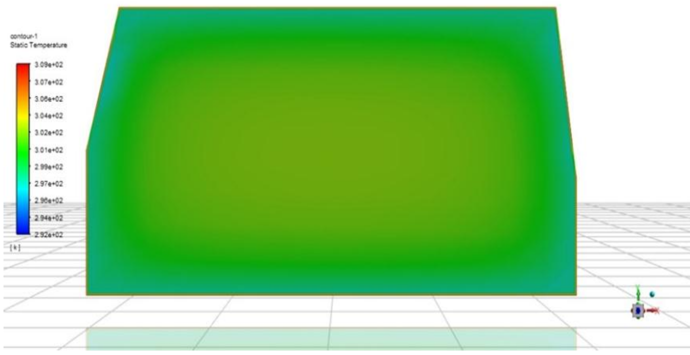

Fig -13: Temperature contours inside the cabin without PCM on roof for 1000sec

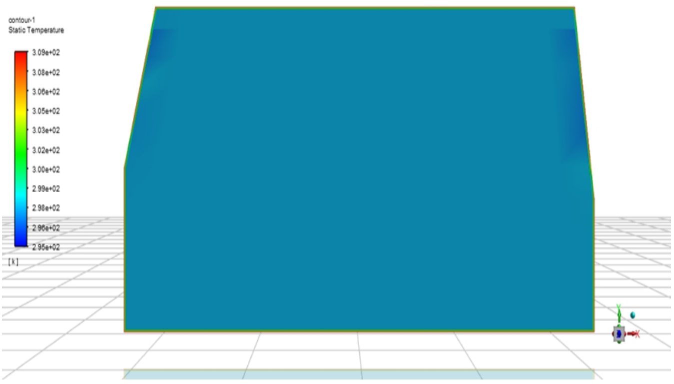

Fig -14: Temperature contours inside the cabin with PCM on roof for 1000sec

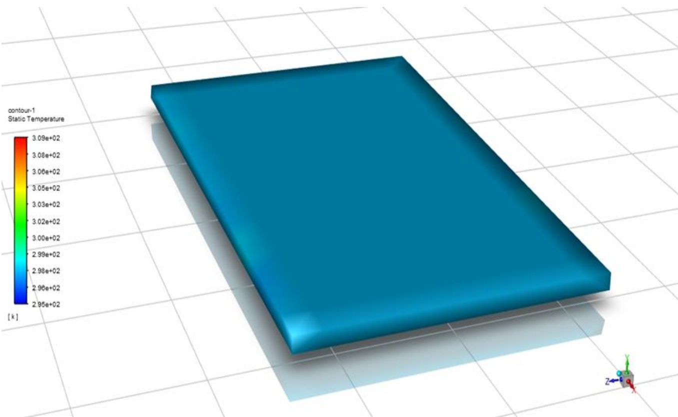

Fig -15: Temperature distribution in PCM

TEMPERATURE	WITH PCM [°C]	WITHOUT PCM[°C]
MAXIMUM	36	36
MINIMUM	25	30

Table -4: Results of Transient state thermal analysis

The initial temperature inside the cabinet is estimated at 295 K as maintained by the air-conditioner. This increase in temperature is caused by excessive sunlight emitting through the wind window and side glass windows due to high cracking and low glass absorption and due to the car's hot roof. The effect of the greenhouse also plays a role in increasing the temperature as the incoming sunlight has a relatively short height, which is easily penetrated through the glass windows. When it enters, it loses energy and converts into long-wavelength rays, which have difficulty passing through the glass, thus, being trapped inside, leading to a rise in temperature. This unfavorable situation will cause passengers to turn on the engine and turn on the AC to get a comfortable temperature near the set point. To analyze the effect of PCM on cabinet heating, four selected PCMs are used individually and are investigated for the effect of temperature reduction due to various sizes. In this case, a 50 mm thick $CaCl_2.6H_2O$ is installed inside the car roof.

The simulation results showed that there is a decrease in temperature at which riders are exposed, from 303 K to 298 K, i.e., about 5 K. In PCM applications, there is a slight increase in temperature. compared to the base case because the heat is absorbed by the PCM. It can be noted that the temperature inside the room does not exceed 298 K after 1000 seconds. This subtle temperature maintains a continuous temperature in the PCM during the phase conversion process, thus, helping to reduce the heat accumulation inside the car compartment.

To assess the impact of the installation of PCM inside the roof on car thermo-regulation, further studies have been performed comparing the base case (roof without PCM) with a case with PCM installation and comfort temperature. The Bureau of Energy Efficiency (BEE) guidelines suggest that based on the comfort chart, the ideal temperature can be maintained at about 24 ° C - 25 ° C According to the new guidelines for COVID-19 also, the temperature of comfort is measured between 24 ° C - 30 ° C. Therefore, keeping in mind these two factors, taking into account the comfort level of residents as 25 ° C, further analysis was done by studying the difference in comfort temperature and base case and the case of PCM installation. PCMs retain heat by changing their phase, thus, maintaining a continuous temperature in the PCM during the process and preventing an increase in temperature inside the cabinet. $CaCl_2.6H_2O$ has a high melting point of 24 ° C. Thus, based on the considered ambient state, $CaCl_2.6H_2O$ will take longer to melt and thus, will retain heat longer, and therefore, maintain a lower temperature inside the cabin. The results mean that $CaCl_2.6H_2O$ has shown better results with a lower melting point. Based on PCM's analysis of the temperatures reached, the difference between the normal comfort temperature and the ambient temperatures reached, it can be concluded that PCM Calcium Chloride Hexahydrate has an excellent thermal storage capacity and can hold low temperatures for a long time.

2.2 EXPERIMENTAL RESULTS

When the roof filled with the PCM material was installed in the setup, the range of temperature inside the cabin was noted much low than in the experiment with the roof, in which the PCM material was not filled and the results were much better than it could decrease the temperature by at least 10ºC. The temperature sensors were kept at two different locations one at the bottom corner and one at the top corner. The temperature range of the complete cabin setup can be measured with the help of this arrangement. The temperature at different locations is noted.

	TEMPERATURE (°C)	
TIME	WITHOUT PCM	WITH PCM
9.00 AM	43.1	34.9
10.00 AM	47.1	35.4
11.00 AM	50.4	35.9
12.00 PM	51.8	36.3
1.00 PM	53	36.8
2.00 PM	45.4	36.2

Table -5: Temperature at different time

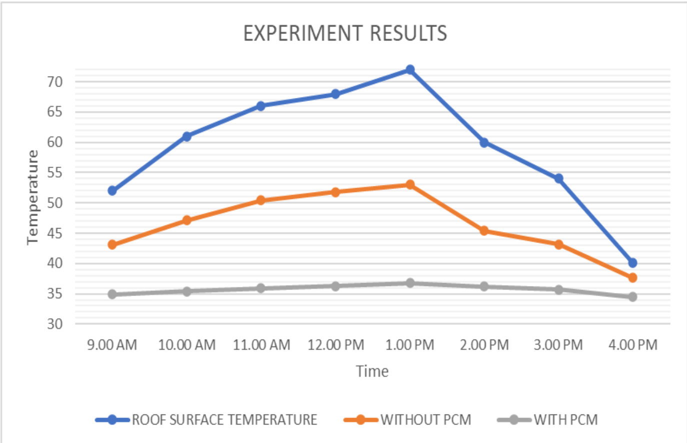

Fig -16: Temperature variation with time

Table 3.2 shows the different types of reading of the vehicle cabin on two particular days and of two different roof types. The readings were taken for a day with the two roof conditions i.e., the insulated and non-insulated roof. the amount of heat and temperature present inside the cabin was noted and recorded. It was noted that the temperature was comparatively low during the early hours of the day and it increases as the time increases. The cabin temperature is very high during peak hours and decreases gradually as the outside is reduced. And the next day the study noted the temperature of the cabin with the insulated roof. Temperature is noted in two different areas of the car cabinet. Temperature sensors were kept in the upper corner on one side and the lower corner on the other end to determine the full temperature setting of the car cabinet test. It was observed that the temperature variation gradually increased and decreased, but the temperature inside the cabinet was much lower than before. The efficiency of the roof was shown in high hours PCM can hold high temperatures during peak hours. This demonstrates the ability of the selected PCM to bind excess heat in most cases without allowing heat to enter the vehicle compartment.

3. CONCLUSIONS

- When a car engine is turned off and parked in direct sunlight, it is thought that, for a maximum of 1000 seconds, the temperature inside the chamber rises from 297 K to 303 K, that is, the temperature rises by 6 K in 1000. s. The main reasons for the increase in temperature inside the car cabinet is the occurrence of solar radiation, as well as metabolic load due to passengers sitting inside the car.

- To reduce this temperature, PCM Calcium Chloride Hexahydrate ($CaCl_2.6H_2O$) was selected based on their melting point and individual comfortable temperatures adopted by ASHRAE. After PCM use, the reduction in temperature found inside the cabinet is approximately 6 K. This is because PCM begins to absorb excess heat that reaches the inside of the cabinet after the engine is turned off.

- After simulation was performed on the ANSYS Fluent, it was noted that the PCM, $CaCl_2.6H_2O$ proved to be the best advantage in its application. Thus, it is used on the roof of a car.

- This project presents a new design for a car roof structure, made by adding a layer of PCM to the car roof. The result shows a decent decrease in the temperature of the car house when the PCM roof is installed on the car roof.

- The test fully fulfilled the purpose of lowering the car's cabinet temperature when the car is parked in a sunny or shady place. The results obtained favor the test.

- When the temperature was measured in both non-insulated and insulated cabin, the insulated cabin had a much lower internal temperature than the non-insulated cabins.

- Test results have shown that the new design has better thermal performance than the standard roof design of available cars.

- The new design can help reduce by up to 30% of the amount of energy needed to cool the heat entering the cabinet from the roof. The level of savings can be very high if there is natural air and movement in the vehicle used.

- PCM insulated roof test cabin had a much lower cabin temperature compared to the conventional cabin, PCM had resolved the purpose of binding external heat to the entry of the car adding to the cabin temperature increase when all vehicles were insulated. PCM cabinet temperature will be very low and can reduce the deterioration of the plastic parts of the car. This is a promising design that can be very productive due to its simple structure and reasonable price.

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