

Computational Fluid Dynamic Analysis of Enhancing Passenger Cabin Comfort Using PCM

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Abstract. The main purpose of this study is to determine a cost effective way to enhance passenger cabin comfort by analyzing the effect of solar radiation of a open parked vehicle, which is exposed to constant solar radiation on a hot and sunny day. Maximum heat accumulation occurs in the car cabin due to the solar radiation. By means of computational fluid dynamics (CFD) analysis, a simulation process is conducted for the thermal regulation of the passenger cabin using a layer of phase change material (PCM) on the roof structure of a stationary car when exposed to ambient temperature on a hot sunny day. The heat energy accumulated in the passenger cabin is absorbed by a layer of PCM for phase change process. The installation of a ventilation system which uses an exhaust fan to create a natural convection scenario in the cabin is also considered to enhance passenger comfort along with PCM.

1. Introduction

A common issue faced by the car drivers in Chennai is the hot suffocating interior of the car after hours of constant solar radiation when parked in an un-shaded area. The heat build-up in the cabin due to solar radiation can elevate up to 80°C average. The undesired rise in cabin temperature will affect the human comfort and interior aesthetics of the cabin [3]. Such conditions can affect the life span of the components in the passenger cabin adversely. To bring down the hot cabin temperature to ambient temperature the driver has to operate the air-conditioning system in full load, thus consuming excess fuel. The concept helps in reducing the usage of air conditioner unit to reduce the interior temperature and thus the usage of fuel and power consumption. Thermal comfort of passengers in an automotive cabin is a challenging and mandatory requirement in today's world as they have an accountable role on passenger safety, pleasurable drive.

Thermal energy storage via phase change materials (PCMs) is one of the most promising candidates as zero power usage method to maintain ambient temperature profile during both the winter and summer seasons. PCMs are substances that use latent heat energy for the changing of phase from solid to liquid or



vice versa. The phase change process of a PCM from solid to liquid and liquid to solid occurs at nearly constant temperature. The phase change process of the PCM is directly proportional to the solar load [2].

2. Work Terminology

2.1 Passenger Cabin Modeling

A 3-D model has been prepared using the SOLIDWORKS software shown in figure 1. Here the front dashboard and rear passenger seats are not considered for simplification of the simulation process. The data for the Computational cabin dimensions were based upon the Mercedes Factory Diagram Car Dimensions [8]. Unwanted CAD surfaces were removed and the necessary surfaces that make the cabin volume were retained. The discontinuities in the Cabin design have been connected and the misalignments corrected. A volume is composed out of the surfaces stitched together. The domain is symmetrical and only half cabin is considered to reduce mesh count and computational cost. The solar load gets accumulated in the passenger cabin and thus causes the increase in temperature. The thermal variation of the passenger cabin have been understood through this study either by forced or free convection, a fan slot is assigned in the cabin design at the rear wind shield. The fan is placed at the top corner of the wind shield so that it does not affect any other aesthetics in the interior of the cabin. The fan outlet slot is shown in figure 1.

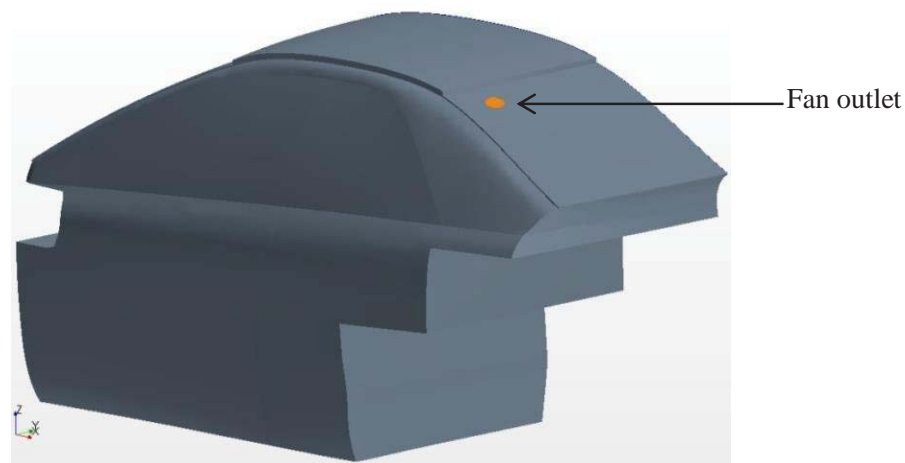


Figure 1. Cabin Model with Exhaust fan outlet.

2.2 Roof Structure

A normal car roof which is exposed to solar radiation on a sunny day maybe under a solar flux of 1000W/m^2 [1]. The various approaches on reducing the solar irradiation on the car roof is either by using photovoltaic systems to produce electric power or by reflecting it away using a coating. The application of PCM in the roof structure has a wide range of scope. In this study, a layer of PCM below the insulation layer and above the holder layer, as shown in figure 2, so that the PCM absorbs heat from the inner cabin for its phase change process as the temperature inside the cabin will be higher than the ambient temperature.

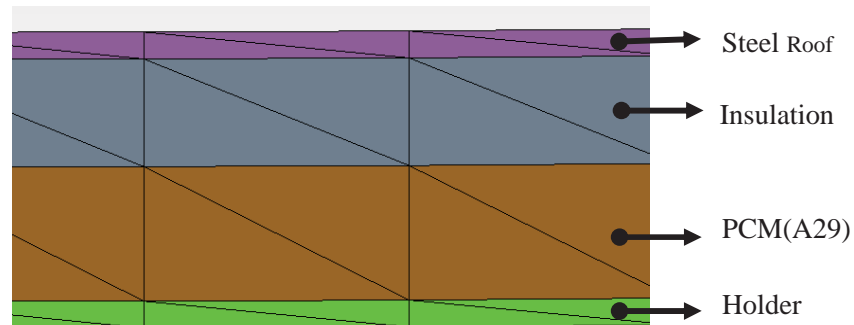


Figure 2. Roof Structure with PCM(A29).

2.3 Surface Meshing

To obtain accurate conditional values of the simulation process the surface has been meshed with triangular elements as it suits the proposed car design the most. The software analyzes the triangles that are grouped into meshes than on a similar number of triangles that are presented individually. The roof has been distinguished into four layers to access different conditions. The total number of mesh elements are 2,37,042 elements as shown in figure 3. The wind shield ends have been meshed with prismatic elements to analyze the properties at the holder layer precisely [5]. The roof structure with surface meshing is shown in figure 4.

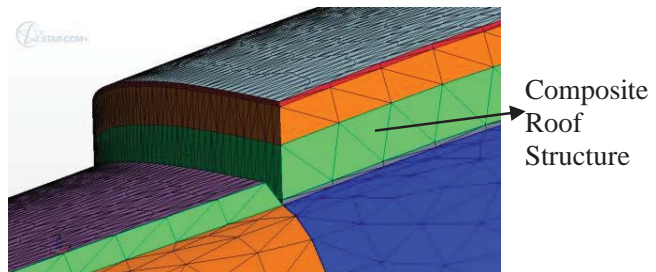
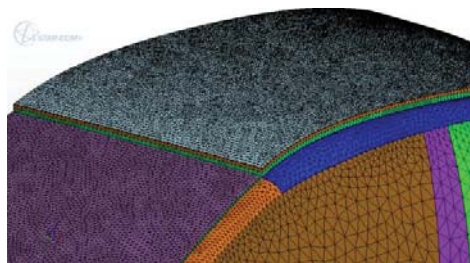
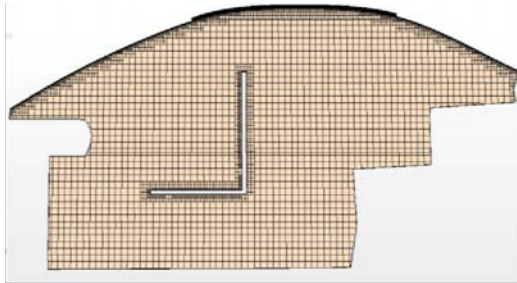
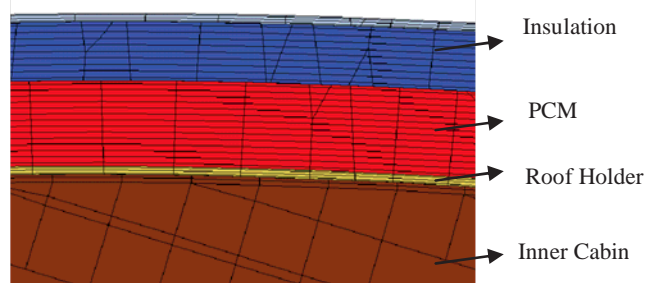


Figure 3. Triangular Surface Meshed Cabin. **Figure 4.** Roof Structure with Surface Mesh.

2.4 Volume Meshing

Volume mesh is used to analyze the variation in temperature or air flow in the interior of the cabin. Prism layers are given to form the meshes near the wall to obtain accurate results. The cross-sectional view of the volume mesh generated in the Star CCM+ is shown in the figure 5. The borders of the windshield and the roof top are meshed with prismatic layers. The inner volume of the cabin is made with thin and trimmer mesh elements. The L shaped region is left in the volume mesh to understand the thermal variation on the passenger seat. Volume meshing of roof structure is shown in figure 6.

**Figure 5.** Volume Mesh Of Cabin Interior.**Figure 6.** Volume Mesh Of Roof Structure.

2.5 Selection of PCM

PCMs are mainly divided into two categories; organic and inorganic materials. There are more than over 500 types of PCMs including salt hydrates, metals, alloys, poly-alcohols, eutectics and paraffin [4]. The selections of PCMs are done on the basis of the comparing the important properties such as melting temperature, heat of fusion, thermal conductivity and density.

Table 1. Properties of PCM.

| Properties | Values |
|-----------------------|-----------------------|
| PCM Name | A29 |
| Melting Temperature | 29°C |
| Latent heat of fusion | 225 KJ/Kg |
| Density | 810 Kg/m ³ |
| Thermal conductivity | 0.18 W/m-k |
| Specific Heat | 2.15 KJ/Kg-K |

The most commonly used PCM are Paraffin's as their melting temperature is in the human comfort condition. These are crystalline derivatives of alkyl hydrocarbons with variable chain lengths. The main criterion for the selection of PCM has been based on the melting temperature. As the ambient temperature in the passenger cabin has been considered to be 27°C, the melting temperature of the PCM was set as 29°C. The various phase change materials have been studied and the PCM with the most satisfying condition has been found to be A29 and the properties are listed in table 1.

3. Result and discussion

In this study, to reduce the temperature inside a car cabin which is exposed to continuous sunlight, CFD analysis have been carried out with normal roof, with PCM layer, fan without PCM layer and a fan along with PCM layer.

3.1 Analysis result of car cabin with normal roof

In this case, the car cabin is analyzed for the temperature variation for 1 hour when parked in an un-shaded region with normal roof structure. As shown in figure 7. It is observed that there is a gradual decrease of temperature towards the passenger cabin. But the cabin temperature has elevated from 27°C to about

96.6°C due to heat accumulation of the solar radiation in the cabin. The heat is transmitted and conducted through the roof and the windshields. Cabin inner temperature will be higher than the outside environment as the heat gets accumulated inside the cabin creating greenhouse effect. Since the cabin is considered to be air-tight, there is no circulation of air in the cabin. Cabin volume temperatures can rise up to 120°C on exposure to direct solar load [7]. The roof top has the highest temperature rise as the solar radiation is incident there. The top and bottom holder layers are observed to have temperatures higher than the roof temperature as the cabin temperature has risen to 96°C, as shown in figure 8. The insulation layer has the temperature rise similar to that of the roof.

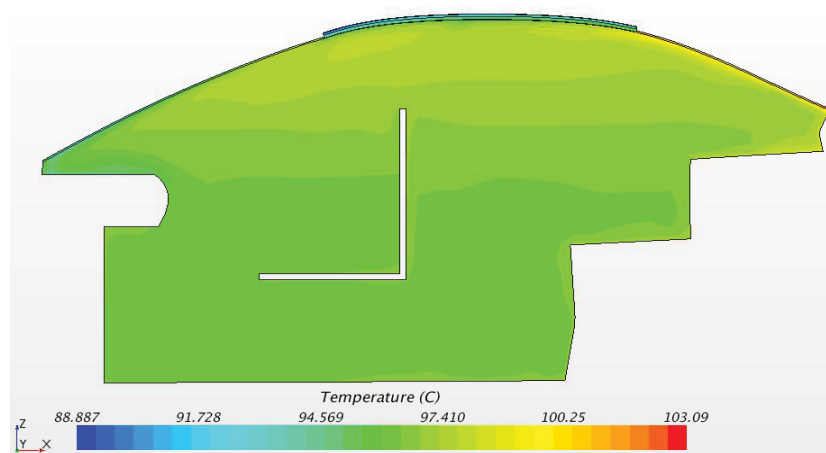


Figure 7. Temperature contour of cabin with normal roof.

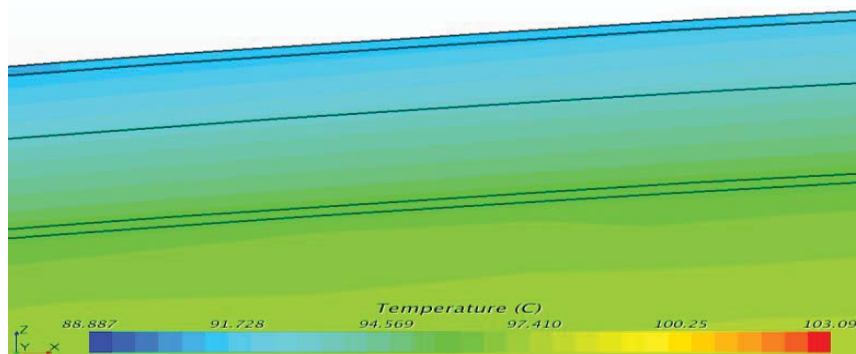


Figure 8. Enlarged view of normal roof.

3.2 Analysis result of car cabin with PCM layer on roof

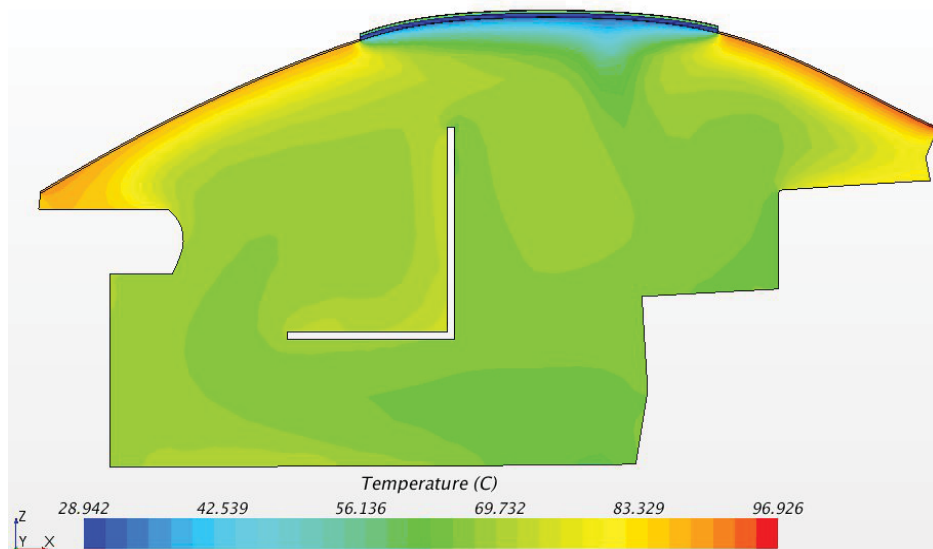


Figure 9. Temperature contour of cabin with PCM layer.

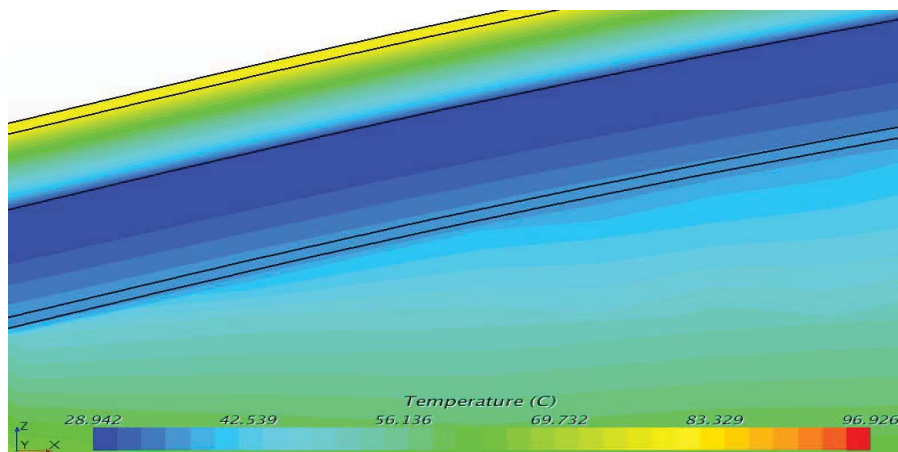


Fig 10. Enlarged view of roof with PCM.

The figure 9 depicts the temperature contour in the passenger cabin after 1 hour of soaking with a layer of PCM in the roof structure. The temperature in the cabin is observed to rise from 27°C to 67.96°C. The heat build in the cabin is less compared to the previous case as the PCM absorbs the heat from the passenger cabin and the above layers for its phase changing process. It is seen that the temperature of the PCM layer is very low compared to the surrounding as PCM undergoes phase changing process at constant

temperature. The PCM layer and the holder layer is observed to have approximately similar temperatures, whereas, the insulation layer has the temperature closer to the roof top, as shown in figure 10.

3.3 Analysis result of car cabin with fan and without PCM layer

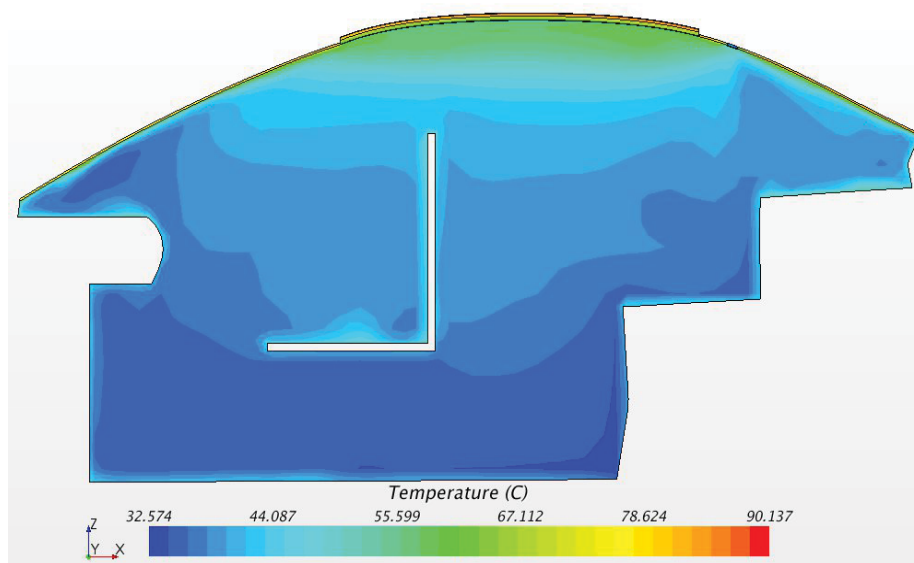


Figure 11. Temperature contour of cabin with fan and without PCM layer.

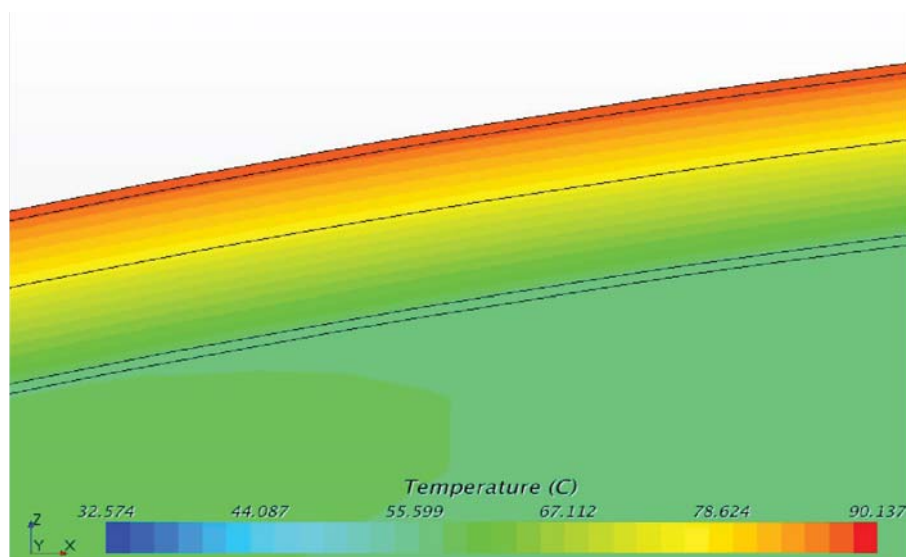


Figure 12. Enlarged view of roof with fan.

The car cabin is analyzed for one hour to understand the temperature contour in the cabin with a blower to facilitate forced convection when parked in an open area as shown in figure 11. Drastic reduction in temperature is noticed as we go down the layers to the cabin. The temperature has elevated from 27°C to 38.73°C. The circulation of fresh air in the cabin avoids heat accumulation due to solar radiation. The temperature at the bottom of the cabin seems to be very less as the leakage is provided beneath the dash board. The drastic drop in the cabin temperature is due to the forced convection in the cabin which avoids heat accumulation in the cabin. The temperature decreases as we go down the layers of roof as shown in figure 12.

3.4 Analysis result of car cabin with fan and with PCM layer on roof

In this case, the temperature variation in the passenger cabin with a PCM layer on the roof and a fan, to provide forced convection is analyzed and studied. It is observed that the cabin temperature is very low compared to all previous cases as shown in figure 13. The fan plays a major role in enhancing the solar load reduction by avoiding accumulation of solar radiation. The remaining heat build-up is absorbed by the PCM for phase change process.

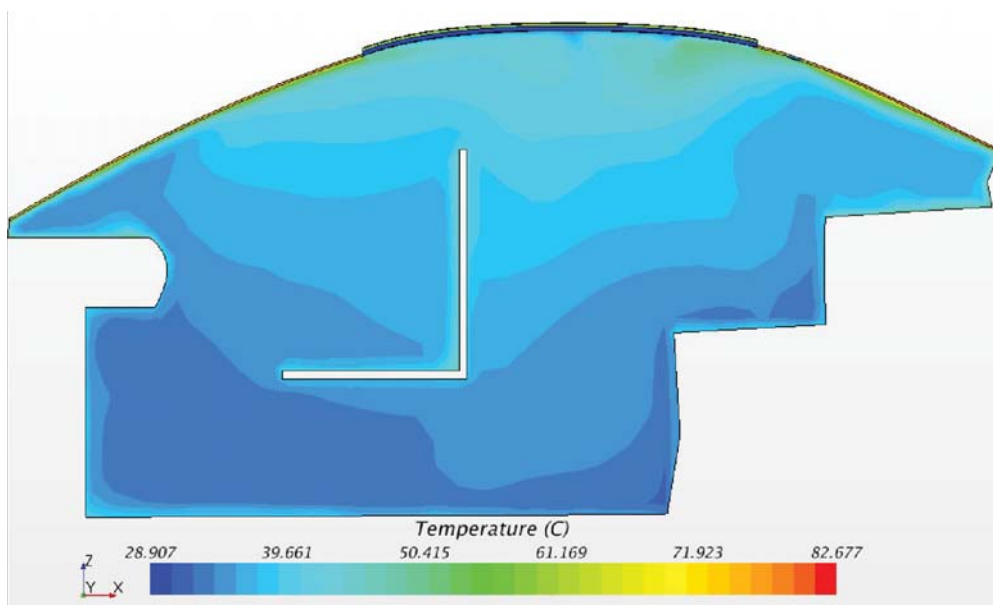


Figure 13. Temperature contour of cabin with fan and with PCM layer.

The fan plays a major role in enhancing the solar load reduction by avoiding accumulation of solar radiation. The remaining heat build-up is absorbed by the PCM for phase change process. The cabin temperature is observed to be 36.41°C. The roof is observed to have a very high temperature as shown in Figure 14, because it is under constant solar radiation.

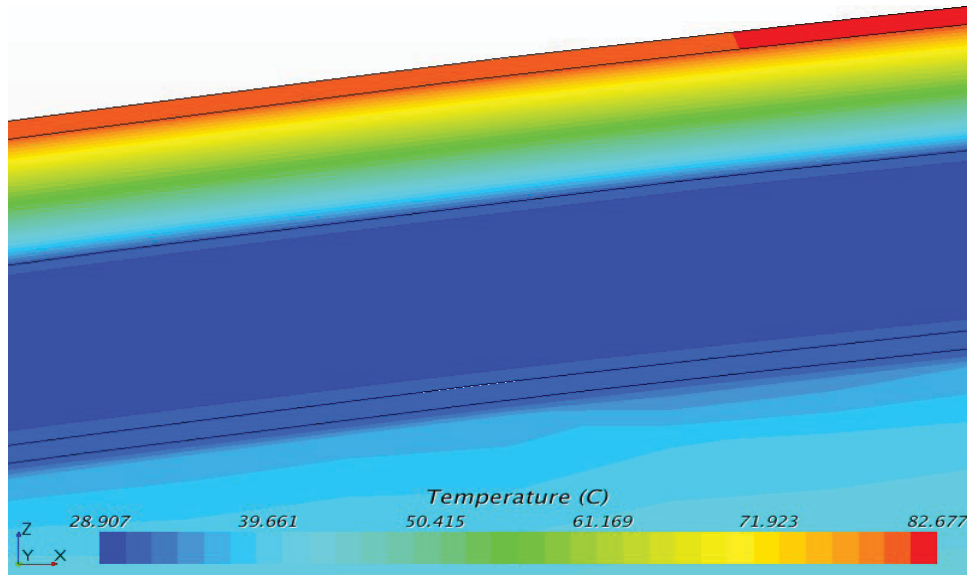


Figure 14. Enlarged view of roof with PCM and fan.

The PCM, the holder top and bottom has nearly same temperatures as they are close to the inner cabin which has less temperature than the outside atmosphere. All the results are tabulated in table 2.

Table 2 . Results comparison.

| Analysis | Initial Temperature | Final Temperature |
|--------------------------|---------------------|----------------------|
| With normal roof | 27 ⁰ C | 96.6 ⁰ C |
| With PCM layer | 27 ⁰ C | 67.96 ⁰ C |
| Fan without PCM layer | 27 ⁰ C | 38.73 ⁰ C |
| Fan along with PCM layer | 27 ⁰ C | 36.41 ⁰ C |

4. Conclusion

The solar Radiation transmitted and conducted into the cabin is observed to be through windshield and roof respectively. The top roof surface gains a temperature of more than 80°C in all the cases as it is under constant solar radiation. As the heat flows in it gets accumulated in the cabin and increases the temperature. The PCM layer absorbs the heat from the cabin and thus the temperature of the layer increases resulting in melting of A29 PCM layer. As such the sensible heat is very less which gets conducted to the next layer in the roof structure. The heat conducted to the next layer in with PCM case is very less compared to without PCM case. As a result, the Cabin temperature stays about 30C lower with the use of a PCM layer in the roof structure. In General, the Cabin inner temperature will be higher than the outside environment as the heat gets accumulated inside the cabin creating greenhouse effect. The fan helps in continuous air exchange with the outside atmosphere which has a lesser temperature than the cabin. The reducing the Cabin inner temperature which is even more enhanced by using PCM. As a result, the Cabin temperature is reduced by about 60°C with the combined action of the fan and the PCM layer.

References

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