

CFD Analysis of Application of Phase Change Material in Automotive Climate Control Systems

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Abstract: In this research study the heat absorbing and removing capability of PCM is used to control the heat generated inside a car cabin due to solar radiation. A thin layer of PCM coating over the car outer surface, particularly on the top and on the wind-shield has been made. As a result the temperature inside the car cabin is maintained in comfort condition without using the airconditioner. CFD is found to be a better alternate in modern industries and has the ability of solving such complex problems. With the help of CFD, a comparative analysis are executed to study the following cases such as,

- Case 1: car with AC off without PCM
- Case 2: car with AC on without PCM
- Case 3: PCM coated where AC off.

The comparative temperature pattern inside the cabin is used to understand the thermal comfort in the cabin and the advantages of using PCM.

Keywords: PCM, cabin, windshield, CFD.

I. INTRODUCTION

Climate control in automobile is becoming a critical factor for modern day automobile engineers. Application of HVAC is found to be the available methodology till date while some may believe aerodynamic cooling just by keeping the windows open would be an alternate choice, in fact driving by keeping window open not only increases the aerodynamic drag also keep the domain noise level undesirable and the inner environment cannot be assured to be clean while HVAC technique is used, it consumes too much of energy that makes the vehicle fuel inefficient. During parking of the vehicle when relative wind velocity is almost the absolute velocity of wind which is around 2-4 m/s, solar heating of inner cabin is found to be so sensitive. When HVAC system is put in off mode the cabin temperature raises very drastically. Particularly during summer when the ambient temperature is very high at peak hours say 12 PM to 3 PM it is absolutely a critical challenge to keep the cabin temperature low. Phase changing materials (PCM) which are capable of storing huge amount heat during the phase change extends its application in many areas.

II. IMPACTS ON FUEL CONSUMPTION

Air Conditioning and Climate Control both provide ways of controlling the air temperature inside your vehicle to deliver passenger and driver comfort. During the winter months, our vehicles use the waste heat from the engine to warm up the cabin air. However, during the summer, air conditioning is often needed to reduce the temperature of the cabin to a comfortable level. It also helps to de-humidify and de-mist the vehicle. Air conditioning just cools and dries the air, whereas climate control can provide both hot and cold air, allowing you to choose a specific temperature (usually between 15° and 26°). The use of air conditioning and climate control units will increase your fuel consumption by as much as 20% in cars and vans. This is because they take power from the engine and add to the weight of the vehicle.

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III. PHASE CHANGE MATERIALS

A phase-change material (PCM) is a substance with a high heat of fusion which melts and solidifies at a certain temperature and has the capacity of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage (LHS) units.

IV. THERMAL ENERGY STORAGE IN PCM

Generally, phase change processes occur at nearly constant temperatures. This makes them attractive for use in a variety of applications. Theoretically, the processes might be employed in three different methods as follows,

- Solid-liquid (melting and solidification)
- Liquid-gas (evaporation and condensation)
- Solid-gas (sublimation and re-sublimation)
- Solid-solid transformations.

Processes including gas, involves considerable volume changes of the working material or changes of the operating pressure also affecting the phase-change temperature which implies specific design issues, while solid-solid transformations usually mean relatively low latent heat values. Thus, solid-liquid transformations seem to be the most attractive and best choice of application. Initially, the solid-liquid PCMs behave like sensible heat storage (SHS) materials; their temperature rises as they absorb heat. Unlike conventional SHS, however, when PCMs reach the temperature at which they change phase (their melting temperature) they continue to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. When the ambient temperature around a liquid material falls, the PCM solidifies, releasing its stored latent heat. A large number of PCMs are available in any required temperature range from -5 to 190 °C [1], within the human comfort range between 20 – 30 °C. They store 5 to 14 times more heat per unit volume than conventional storage materials such as water, masonry or rock.

A. Advanced Phase Change Materials

- Market Paraffin
- fatty acids
- Salt hydrates

B. Advanced Phase Change Material Application

- Building and construction
- HVAC
- Energy storage
- Shipping and transportation
- Others (Textiles, Protective clothing)

V. COMPUTATIONAL FLUID DYNAMICS

In the recent past CFD has become an integral part of the modern industry and it extends its support to many researchers to understand and analyze the problem more vividly. Even experiments play a vital role in design process CFD techniques will decrease the dependence on the more expensive, time consuming experimental procedures. Still CFD has a lot of variables in it such as mesh count, mesh type, turbulence models, order of discretisation, numerical schemes etc. In recent studies the applications of PCM in thermal energy storage system and about various PCM

materials were explained experimentally and numerically using CFD [2]. A. Jamekhorshid, S. M. Sadrameli presented a paper in which they studied the amount of PCM to be used inside the car for absorbing the thermal energy [3]. LOKESH JAIN¹, S.D. SHARMA have experimentally studied the effects of ambient temperature, solar radiation and thickness on transmittance of PCM material [4].

A. Cad Modelling Of Car Cabin

The car interior has been designed three dimensionally using CATIA software. Fig 1, Fig 2, Fig 3 shows the geometrical descriptions of various parts.

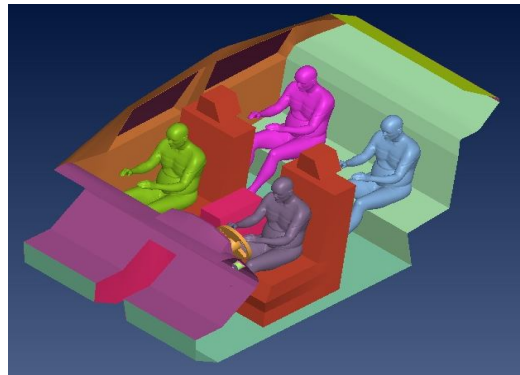


Fig.1. Car interior details

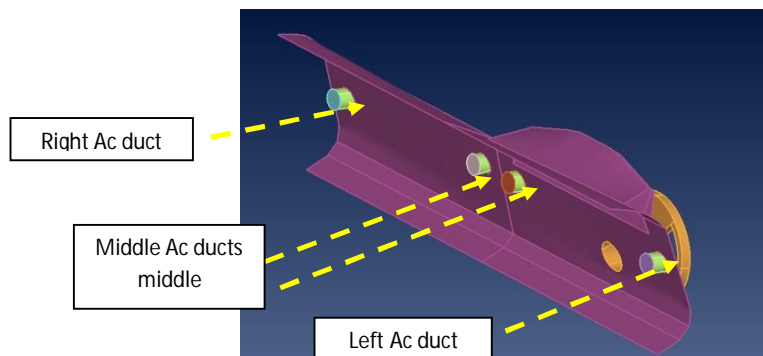


Fig.2. AC ducts in dashboard

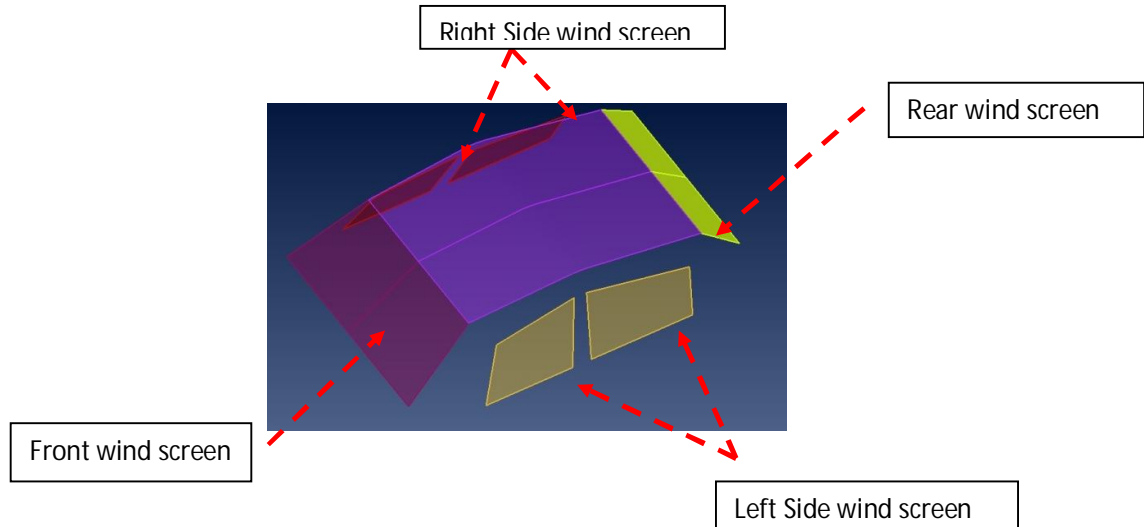


Fig.3. wind screen

VI. NUMERICAL METHODOLOGY

To perform a numerical simulation the developed cad model is imported to CFD modelling software ANSA where the fluid domain has been extracted and surface meshes were created. By using ANSYS-TGRID the volume mesh has been generated. Finally the boundary conditions were applied in FLUENT solver and results were simulated. Figure 4 shows the complete CFD process.

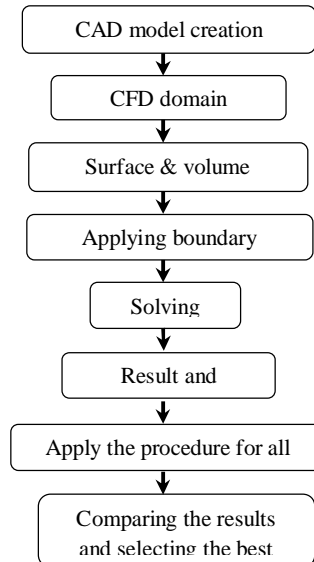


Fig.4. Flow Chart

A. Mesh elements and quality criteria

TABLE I

Mesh Details

Type of mesh	Elements	Quality criteria
Surface mesh	Triangular	Equiangular skewness (0.6)
Volume mesh	Tetrahedral	Equivolume skewness (0.85)

Triangular and tetrahedral elements were preferred because of their ease of creation compared to other type of elements such as quad and hexahedral which are real complex to create since they can only be created manually. PRISM elements are used to create thin layers in order to define the PCM zone. The below figures shows the surface meshes and volume meshes in various regions.

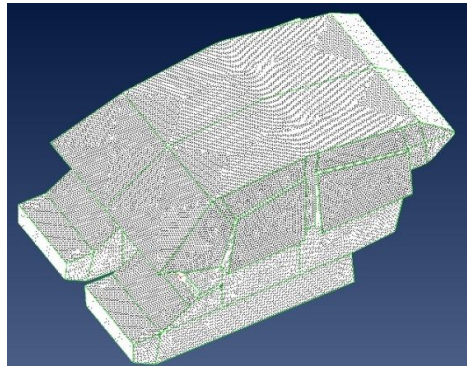


Fig.5. Surface meshes over the cabin

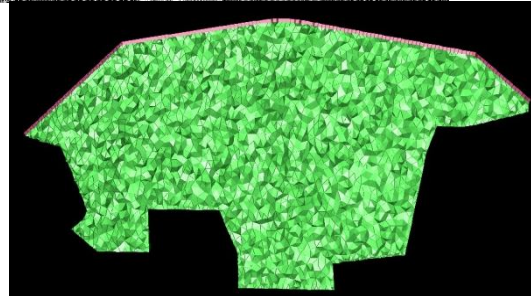
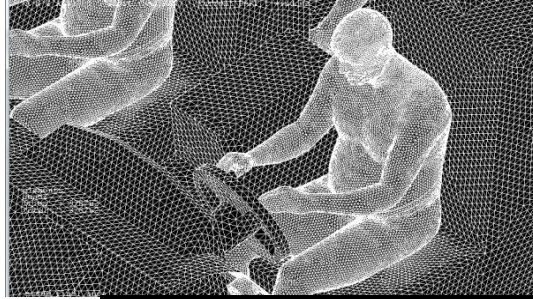


Fig.6. surface meshes near the driver cabin

Fig.7. volume mesh shown in Z-axis cut plane

TABLE 2

Fluid and Solid Properties:

Material	Density kg/m ³	Specific heat J/kg-k	Thermal conductivity W/m-K	Heat of fusion kj/kg ⁰ C	T _{mel} (K)
Air	1.225	1006.43	0.0242	-	-
Steel	8050	490	50.2	-	-
PCM	1800	3400	1.088	236.17	304.98

B. Boundary Conditions

- **AC ducts:** Velocity inlet at 2 m/s, 300 K.
- Car ceiling and wind screen outer surface are modeled as wall with convective and radiation heat transfer (effective temperature (T_{eff} from 6th floor model [5]).
- **Other walls:** modeled as adiabatic wall
- **Outlet:** pressure outlet

C. Calculations

The convective heat transfer co-efficient and the effective temperature has been calculated using below expressions (1), (2) with respect to the wind velocity at various time periods,

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$$h = 18.63 * V^{(0.605)} \quad (1)$$

$$V = 0.25 * v \quad \text{if } v > 2 \text{ m/sec} \quad V = 0.5 * v \quad \text{if } v < 2 \text{ m/sec}$$

$$T_{\text{eff}} = T_{\text{amb}} + \frac{I * \alpha}{h} \quad (2)$$

Where, v - Wind velocity

V -calculated velocity (m/s)

T_{eff} = effective temperature (k)

T_{amb} = ambient temperature (k)

I -solar intensity (W/m²),

α -external emissivity

h = heat transfer co-efficient (W/m-K)

TABLE 3

Calculated Values

Time (min) 12-12.30PM	v	h	T_{amb}	I	α	T_{eff}
5	4.10	43.74	312.50	1130	0.6	328
10	4.15	44.06	312.80	1130	0.6	328.18
15	4.25	44.70	313.15	1130	0.6	328.31
20	4.36	45.40	313.55	1130	0.6	328.48
25	4.65	47.21	313.90	1130	0.6	328.26
30	4.65	47.21	314.15	1130	0.6	328.51

VII. GOVERNING EQUATIONS

The following equations are used to mathematically model the flow and the energy transfer of a fluid.

A. Conservation of mass:

$$\text{Mass: } \frac{\partial \rho}{\partial t} + \text{div}(\rho u) = 0$$

B. Conservation of x momentum:

$$X\text{-momentum: } \frac{\partial(\rho u)}{\partial t} + \text{div}(\rho u u) = -\frac{\partial(p)}{\partial x} + \text{div}(\mu \text{ grad } u) + S_{Mx} \quad (1)$$

$$Y\text{-momentum: } \frac{\partial(\rho v)}{\partial t} + \text{div}(\rho v u) = -\frac{\partial(p)}{\partial y} + \text{div}(\mu \text{ grad } v) + S_{My} \quad (2)$$

$$Z\text{-momentum: } \frac{\partial(\rho w)}{\partial t} + \text{div}(\rho w u) = -\frac{\partial(p)}{\partial z} + \text{div}(\mu \text{ grad } w) + S_{Mz} \quad (3)$$

VIII. MODELING SOLIDIFICATION/MELTING

To model the solidification /melting ANSYS-Fluent uses Enthalpy-porosity formulation, in which the liquid-solid mushy zone is treated as PSEUDO POROUS zone where the liquid fraction lies between 0 and 1. The porosity decreases from 1 to 0 as the material solidifies. Thus the liquid fraction represents the melt-interface and also proportional to the porosity value to find the velocity drop associated with solid zone.

Liquid fraction is computed at each iteration based on an enthalpy balance and added to the energy equation.

C. Conservation of energy:

$$\text{Internal energy: } \frac{\partial(\rho H)}{\partial t} + \text{div}(\rho H u) = \text{div}(k \text{ grad } T) + \mathcal{E} \quad (4)$$

$$H = h + \Delta H \quad (5)$$

$$h = h_{\text{ref}} + \int_{T_{\text{ref}}}^T C_p dT \quad (6)$$

$$\Delta H = \beta L \quad (7)$$

$$\beta = 0 \quad \text{if } T < T_{\text{Solidus}}$$

$$\beta = 1 \quad \text{if } T > T_{\text{liquidus}}$$

Where,

H-Enthalpy

h- Sensible enthalpy, h_{ref} – reference enthalpy

T_{ref} – reference temperature (K)

T-domain temperature (K)

β - Liquid fraction, L-latent heat content

C_p – Specific heat capacity (j/kg-k)

ρ - Fluid density (kg/m³), p- Pressure (Pa)

u, v, w – fluid velocity (m/s)

μ - Dynamic viscosity (Ns/m²)

S_{Mx}, S_{My}, S_{Mz} – momentum source / momentum sink term

S- Source term

IX. SOLVER SETUP

ANSYS-FLUENT was used as the Solver. The following assumptions and methodologies were used to model this problem.

- Flow was assumed to be three dimensional, un-steady and compressible.
- Flow was assumed to be turbulent and turbulence was modeled by k-e standard.
- Energy equation was used.
- Conductive, convective heat transfer modes were considered.
- **Solidification/melting model was used to model Phase change phenomenon.**
- Segregated Scheme was used with simple algorithms for initial study.
- First order discretisation scheme was used for initial study.

X. CFD RESULTS

The velocity and temperature contour plots are taken for all three cases at 30th minute and shown below.

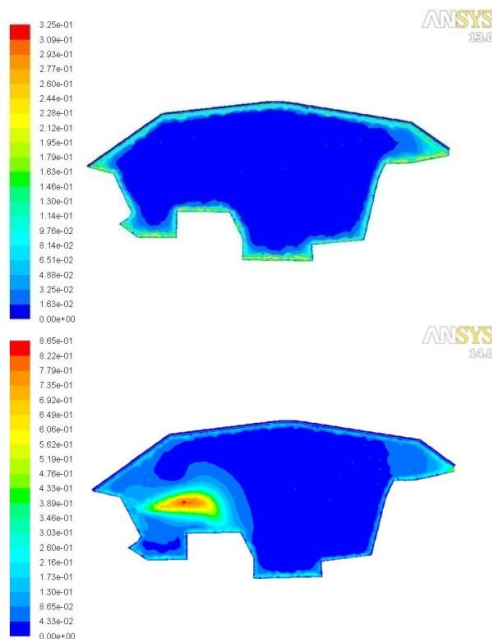


Fig.8. velocity contour (m/s) for case 1

Fig.9. velocity contour (m/s) case 2

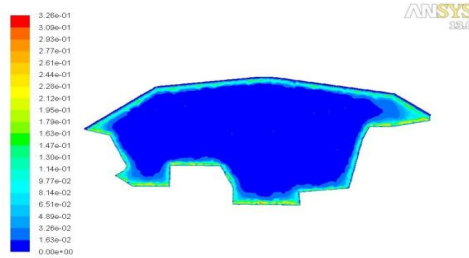


Fig.10. velocity contour (m/s) for case 3

The following figures compares the temperature distribution over the passengers for different cases and shows the minimum temperature (fig.13) in the case where PCM is coated on the car surface.

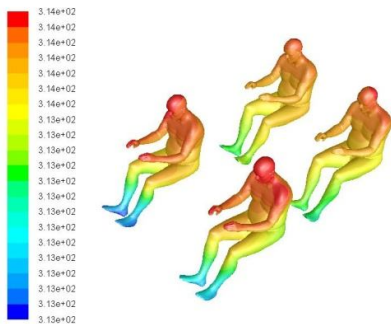


Fig.11. temperature contour (k) for case 1

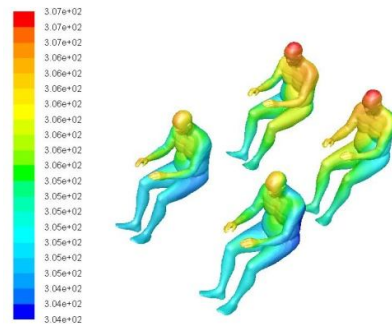


Fig.12. temperature contour (k) for case 2

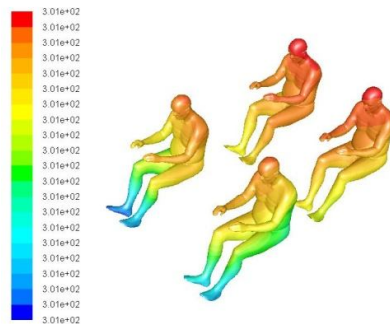


Fig.13. temperature contour (k) for case 3

A. Observation from the Results:

By comparing the temperature plots of all three cases the maximum temperature over the passengers vary from 314 to 301. And the findings are listed below,

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- ✓ Max Cabin temperature when AC is in OFF mode and no PCM is coated = 314 K (fig.11.)
- ✓ Max Cabin temperature when AC is in ON mode and no PCM is coated = 307 K (fig.12.)
- ✓ Max Cabin temperature when AC is in OFF mode and PCM is coated = 301 K (fig.13.)

XI. CONCLUSION

Thus a novel approach using Computational Fluid dynamics technique is attempt to compare the advantages of PCM coating over the car's outer surface for climate control application.

In future this work can be extended to analyze the cost effective and high thermal storage capacity phase change materials for various climate control applications.

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