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Melting Process of the Phase Change Material inside a Half-Cylindrical with Thermal Non-Equilibrium Copper Foam as a Porous Media: CFD Simulation

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ABSTRACT

Many thermal engineers employed latent thermal energy storage; however, the poor thermal conductivity of Phase-Change Material (PCM) severely hampered the storage efficiency. Because of its capacity to improve total heat conduction, filling metal foam has been a successful method of improving heat transmission. This research looked at the effect laws of porosity and pore density of copper foam to improve the thermal performance of the paraffin-metal foam composite PCM. The four parameters of the liquid fraction, temperature response rate, heat flow, and heat storage capacity were analyzed in a two-dimensional numerical model using the two-temperature non equilibrium equation, which was created and confirmed by published data.

The goal of this research is to evaluate quantitatively the impact of local thermal non-equilibrium porous media on the melting of paraffin at 33°C. The geometry of a paraffin-filled half cylinder with an insulating wall and a constant temperature. This simulation also takes into account the Darcy model and buoyant force owing to density variations. On the melting fraction of PCM, temperature and streamlines contours, and heat flux of the cylinder's surface, the impacts of the presence of copper foam with porosity = 0.8, and difference temperature T = 10, and 15 were investigated.

KEYWORDS: *Computational fluid dynamic, Phase change material, Local thermal non-equilibrium porous media, Buoyant force, Darcy model*

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I. INTRODUCTION

The use of phase transition materials to store energy is a fantastic innovation in energy storage. Researchers have praised these materials for their ability to receive and store heat as latent heat at a steady temperature. PCM has important uses in numerous industries such as culinary, clothes, textile, building, heating and cooling systems, desalination systems, and medical due to its ability to store energy in the form of heat at varied temperatures.

Although the latent heat of PCM is higher in the solid to vapor phase than in the solid to liquid phase, phase change solid-liquid is extensively employed due to the small transition volume. Latent heat and the temperature at which the solid to liquid phase transition occurs are two critical characteristics in PCMs.

Organic, inorganic, and eutectic mixes are the three categories of PCMs. PCMs, on the other hand, can be classed as follows in terms of melting temperature (Tm) and latent heat solid-liquid (hsl).

- Queues salt solution for -70 < Tm < 0◦C with 220 < hsl < 320 kj/kg.
- Paraffins for 0 < Tm < 130◦C with 180 < hsl < 220 kj/kg.
- Sugar alcohols for 60 < Tm < 210◦C with 210 < hsl < 430 kj/kg.

Paraffins are an organic PCM with additional benefits such as availability, high latent heat in the solid-liquid transition, auto nucleation capabilities, high nucleation rate, chemical stability, and low cost. The melting temperature range of 0–130°C, which is ideal for most industrial uses, is one of the most essential features of paraffin. However, paraffins have a low thermal conductivity, which has been used in studies for thermal energy storage systems, cooling photovoltaic panels, and controlling the temperature of medicine during delivery processes.

II. LITERATURE REVIEW

Porous metals are a distinct family of materials with low densities and unique physical, thermal, and other characteristics. Porous structures have been achieved by a variety of methods. The definition of porous metal, production processes, and thermal applications are all covered in the previous research. A thorough examination of fluid flow behavior through porous media is offered. The thermal characteristics of porous metals, such as thermal conductivity and heat transfer performance under natural and induced convection, are discussed in depth.

S. Mondal et al (2008) Phase change materials (PCM) take advantage of latent heat that can be stored or released from a material over a narrow temperature range. PCM possesses the ability to change their state with a certain temperature range. These materials absorb energy during the heating process as phase change takes place and release energy to the environment in the phase change range during a reverse cooling process. Insulation effect reached by the PCM depends on temperature and time. Recently, the incorporation of PCM in textiles by coating or encapsulation to make thermo-regulated smart textiles has grown interest to the researcher.

Dianaet al. (2015) the purpose of this paper is to provide a source of information on thermal energy use in buildings, its drivers, and their past, present and future trends on a global and regional basis. Energy use in buildings forms a large part of global and regional energy demand. The importance of heating and cooling in total building energy use is very diverse with this share varying between 18% and 73%. Biomass is still far the dominant fuel when a global picture is considered; the role of electricity is substantially growing, and the direct use of coal is disappearing from this sector, largely replaced by electricity and natural gas in the most developed regions.

Amrita et al. (2018) Glazed facades are being increasingly used in modern buildings in order to improve the daylight availability in the interiors, offer better external views and also add to the architectural beauty of the building. However this increased usage of glazed facades is leading to higher solar gain inside the building which is becoming a major issue in hot climatic regions. External shadings are thus used to protect the buildings from direct solar radiation which cause high solar gain as well as discomfort due to glare.

Saber Yekan et al. (2019) In the present paper, the modeling of the free convection of two-phase nanofluid inside the inclined porous semi-annulus enclosure is considered. The cavity is filled with Fe3O4-water magnetic nanofluid. Buongiorno and Darcy models are used for modeling two-phase and porous media, respectively. The governing equations are discretized by finite volume method and SIMPLE algorithm. The effect of parameters such as inclination angle of cavity ($0 \leq \theta \leq 90$), porous Rayleigh number ($10 \leq Rap \leq 103$), porosity number ($\varepsilon = 0.4$ *and* 0.7), and volume fraction of nanoparticles ($0 \leq \varphi Ave \leq 0.04$) on the flow pattern, temperature field, nanoparticle distribution, and Nusselt number are studied. In low porous Rayleigh numbers, Nusselt number is not the function of porosity number and the inclination angle of the enclosure.

C. Thirugnanam at al. (2020) In many parts of the world, direct solar radiation is considered to be one of the most prospective sources of energy. Among the different energy end uses, energy for cooking is one of the basic and dominant ends uses in developing countries. Thermal energy storage is essential whenever there is a mismatch between the supply and consumption of energy. Latent heat storage in a phase change material (PCM) is very attractive because of its high storage density with small temperature fluctuate.

Xi Meng et al. (2020) Latent thermal energy storage was widely used in many thermal engineering, but the low thermal conductivity of Phase-Change Material (PCM) limited the thermal storage efficiency seriously. Filling metal foam has been an effective way to enhance the heat transfer due to its capability to improve the overall heat conduction effectively. To optimize the thermal performance of the paraffin-metal foam composite PCM, this study analyzed the influence laws of porosity and pore density of copper foam. A two-dimensional numerical model considering two-temperature non-equilibrium equation was built and validated by published results, while the four parameters including the liquid fraction, the temperature response rate, the heat flux, and heat storage capacity were evaluated.

Yan Cao (2021) The aim of this study is numerically to investigate the effects of local thermal non-equilibrium porous media on the melting process of paraffin with the melting temperature33◦C. The geometry consists of a half-cylinder containing paraffin with a uniform constant temperature and an insulating wall. Also, Darcy model and buoyant force due to density changes are considered in this simulation. The effects of the presence of aluminum foam with porosity ε = 0.8, and 0.95 and difference temperature ΔT = 5, 10, and 15 have been studied on the melting fraction of PCM, temperature and streamlines contours and heat flux of cylinder's surface. The observations show that enhancement of porosity 0.8 to 0.9 increases the volume of PCM 11.7%, and reduces time of melting process 30.8% for ΔT = 15. Moreover, increment of ΔT = 5 to 15 leads to decrease time of melting process 71.8% when porosity is 0.95.

III. GEOMETRY SETUP AND MODELLING

The study uses the CFD model in this section to examine the effects of local thermal non-equilibrium porous media on the melting process of paraffin with the melting temperature 33◦C. CFD review involves three major steps: (a) pre-processing, (b) solver execution, and (c) post-processing. The first step includes the creation of the geometry and mesh generation of the desired model, while the results are seen as expected in the last step. In the execution of the solver (medium) stage, the boundary conditions are fed into the model.

The geometry for performing simulation analysis is taken from **Yan Cao** et al. (2021). Fig. 5.1 presents the A porous half-cylinder with a radius of R = 5 cm is filled with paraffin as the phase transition material, which has a melting temperature of Tm = 33°C (see Fig. 1). The porous medium's substance is copper foam, which is examined as local thermal non-equilibrium in this simulation. It's also worth noting that the geometry's top wall is exposed to a uniform constant temperature, while the bottom wall is insulated. As a result, the heated wall melts the paraffin, causing a natural convection flow inside the chamber, which aids in the melting of the paraffin. The gravitational acceleration in the y-direction is 9.8 ms^2.

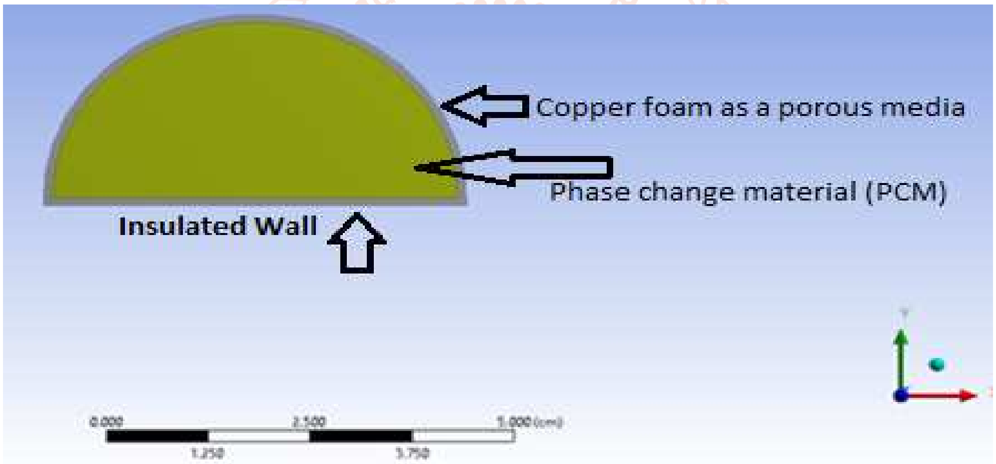


Fig 1 Created modal on the Ansys software of half-cylinder filled Copper foam as porous media

In the pre-processor phase of ANSYS FLUENT R 17.0, a three-dimensional discretized model was created. Despite the fact that the grid types are linked to simulation results, the structure as a whole must be discrete in the final volume; the ANSYS programmed generates a coarse mesh. Mesh is made up of unit-size mixed cells with triangular frontier faces (ICEM Tetrahedral cells). A mesh metric is employed in this research, along with a medium fluid curvature.

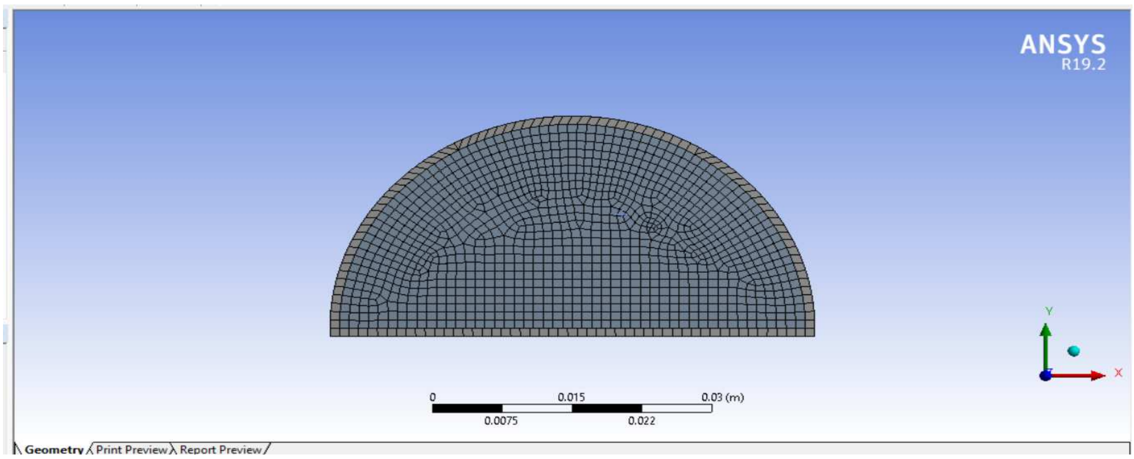


Fig 2 Meshing of heat exchanger

S. No.	Parameters	
1	Curvature	On
2	Smooth	Medium
3	Number of nodes	164979
4	Number of elements	141811
5	Mesh metric	None
6	Meshing type	Tetrahedral

Table 1 Meshing detail of model

The Fluent 19.2 was used to calculate computationally. In research, the approach used to differentiate the governing equations was a finite element. For this convective term, the researchers used a simpler algorithm, and for connecting calculations of the melting fraction and streamline & temperature for different temperature difference. (ΔT =5,10,15)

A local thermal non equilibrium porous Copper foam filled with the paraffin (Phase Change Material) in a half cylinder having 5 cm radius and 12cm length. We have crated this modal on the software and after that create mashing on the modal. A local thermal non equilibrium porous Copper foam & paraffin (Phase Change Material) having some property

S. No.	Parameters paraffin	Copper foam
1	Density (Kg/m^3) 800	8933
2	Thermal conductivity (W/mK) 0.2	400
3	Specific Heat (J/kgK) 1250	380
4	Viscosity (kg/ms) 0.008	-
5	Latent heat of fusion (J/kgK) 125000	-
6	Melting temperature(^{0}C) 30	-
7	Melting temperature range (^{0}C) 1	-
8	Thermal Expansion Coefficient (1/K) 0.002	-

Table 2 The thermophysical properties of used material

Detail	Value
Type	Pressure Based
Velocity formulation	Absolute
Temperature for hot wall	306^0
Temperature for insulating wall	291^0
Time	Transient
Gravitational Acceleration (Y m/s^2)	-9.81

Table 3 Details of boundary conditions

IV. RESULTS AND DISCUSSIONS

This section is aimed at evaluating the mass fraction rate & velocity with different temperature & different time (hour). Here we are considering two temperature difference 10^0 & 15^0. these temperature difference Between the Hot wall of the of the half cylinder& paraffin (Phase change material). First, we considering the thermal non-equilibrium porous media as a Copper foam & validate the result with the researcher **Yan Cao [1].**

4.1. Mathematical model

Two-dimensional flow, incompressible, unsteady, laminar flow, local thermal non-equilibrium in porous media, and constant characteristics are among the assumptions. Due to the existence of porous medium and varying density with temperature, the effects of Darcy and buoyant force are taken into account in the momentum equation. The data reduction of the measured results is summarized in the following procedures.

Momentum equation

$$\frac{\rho_f}{\varepsilon}\frac{dV}{dt}+\frac{\rho_f}{\varepsilon^2}(V.\nabla)V = -\nabla P+\frac{\mu_f}{\varepsilon}\nabla.(\nabla V)-\frac{\mu_f}{K}V+(\rho\beta)_f(T-T_{Ref})g-10^5\frac{(1-\lambda)^2}{\lambda^3+.001}V$$

Energy equation of fluid:

$$\varepsilon\rho_f\left(C_f+L\frac{d\lambda}{dT_f}\right)\frac{\partial T_f}{\partial t}+\rho_f C_f(V.\nabla T_f) = \varepsilon k_f\nabla.(\nabla T_f)-h_{sf}A_{sf}(T_f-T_{fs})$$

Energy equation of porous media:

$$(1-\varepsilon)\rho_s c_s\frac{\partial T_s}{\partial t} = (1-\varepsilon)k_s\nabla.(\nabla T_s)-h_{sf}A_{sf}(T_s-T_f)$$

The solid to fluid phase change is a function of the error function, which is calculated as follows:

$$\lambda = 0.5_{erf}\left(4\frac{T_s-T_m}{T_l-T_s}\right)+0.5$$

Where,

$A_{sf} = Surface\ area\ dansity\ [m^2]$

$C = Specific\ heat\ capacity[J\ kg^{-1}K^{-1}]$

$d_p = Pore\ diameter\ [m]$

$d_f = fiber\ diameter\ [m]$

$R = radius\ of\ cylinder\ [m]$

$g = Gravitational\ acceleration[ms^{-2}]$

$h_{sf} = Local\ heat\ transfer\ coefficient[Wm^{-2}K^{-1}$

$K = Permeability\ [m^{-2}]$

$k = Thermal\ conductivity[Wm^{-1}K^{-1}]$

$L = Latent\ Heat[J\ kg^{-1}]$

$P = pressure[Nm^{-2}]$

$T = Temperature\ [K]$

$T_m = Melting\ Temprature[K]$

$V = Velocity\ vector\ [ms^{-1}]$

Greek syomble

$\beta = Thermal\ expansion\ coefficient[K^{-1}]$

$\omega = pore\ density[-]$

$\mu = dynamic\ viscosity[kg\ m^{-1}s^{-1}]$

$\lambda = Melting\ fraction[-]$

$\rho = Density\ [kg\ m^{-3}]$

$\varepsilon = Porosity[-]$

$R_e = Reynolds\ number$

$P_r = Prandtl\ number$

Subscript

$Ave = Average$

$C = cold$

$pcm = phase\ change\ material$

$f = Fluid$

$s = Porous\ media$

4.2. Validation of numerical computations

By the researcher paper **Yan Cao [1],** we are finding that the Malting fraction, velocity streamline & temperature with the aluminum foam increase the rate of malting fraction with constant porosity.

When the temperature difference between the hot wall & paraffin (Phase change materials) is $\Delta T = 10^0$ & the porosity is considered 0.8. we are using the porous medium is aluminum foam, which is treated as a local thermal non-equilibrium. We observed that the malting fraction in this chart.

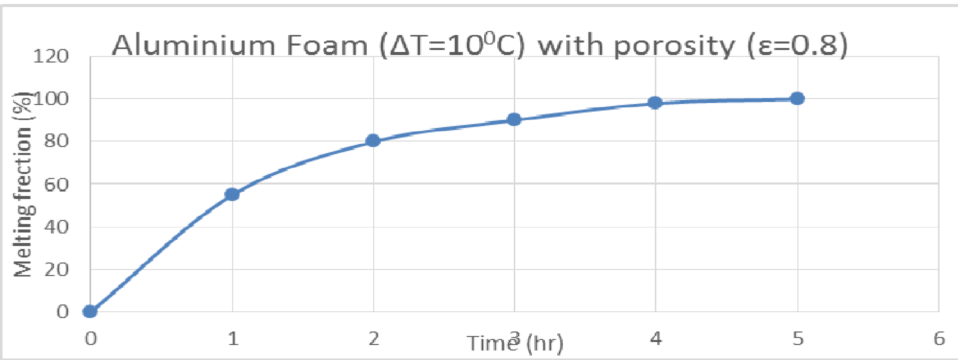


Fig 3 Malting fraction (%) for aluminum when porosity is 0.8 with ΔT = 10^{0}C

Now the temperature difference between the hot wall & paraffin (Phase change materials) is $\Delta T = 15^0$ & the porosity(ε) is considered 0.8.

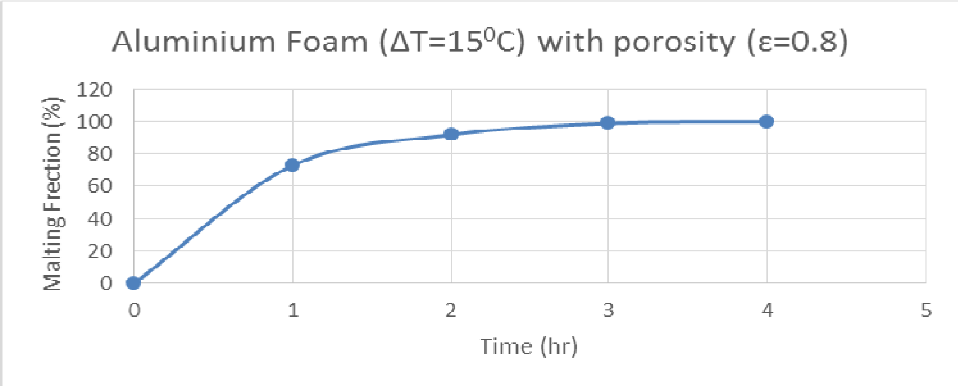


Fig 4 Malting fraction (%) for aluminum when porosity is 0.8 with ΔT = 15^0C

Now if we are putting the copper foam as a porous media instead of aluminum foam. & Validate the result. With the CFD Analysis, we found that the mass fraction rate, velocity stream line & temperature contour for thermal non-equilibrium porous media as a copper foam at a temperature difference T = 10^0 with porosity 0.8.

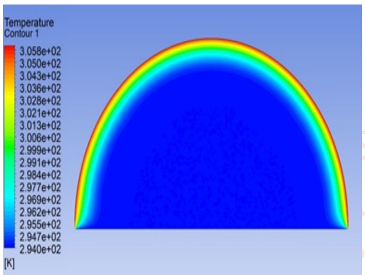
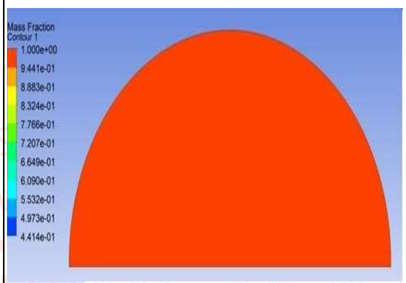
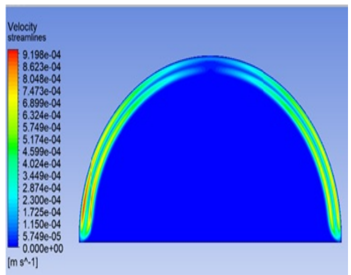
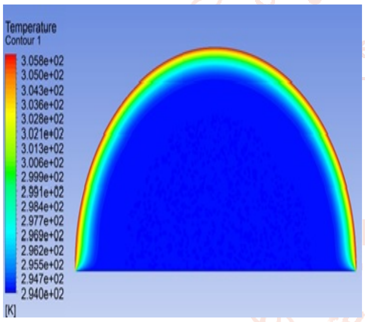
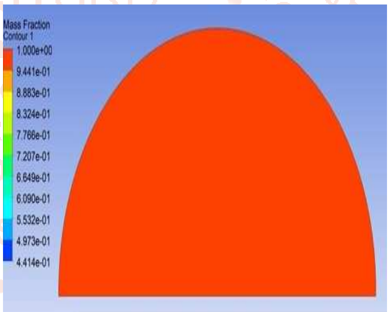
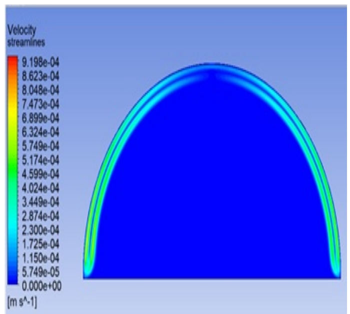
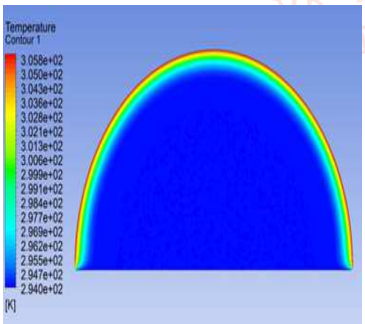
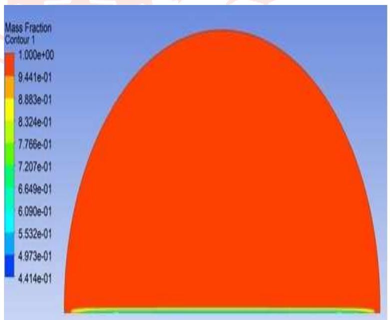
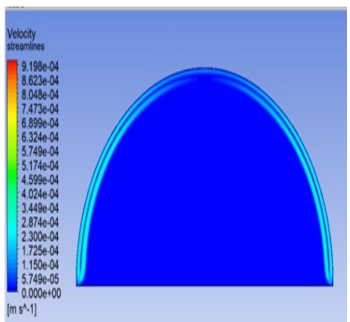
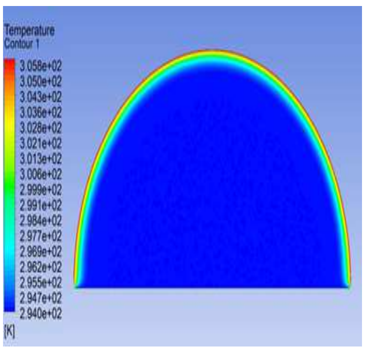
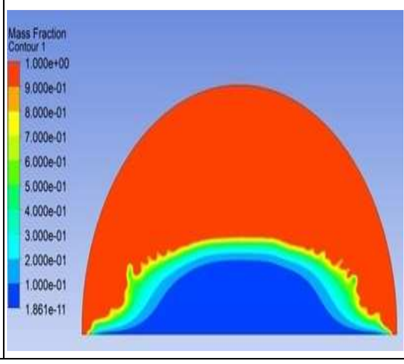
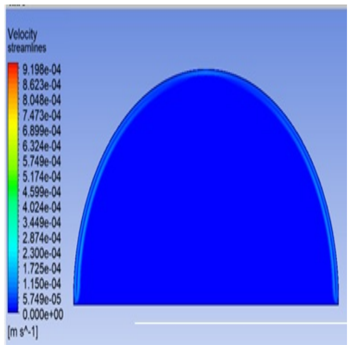
Time /contour	Temperature contour	liquid fraction	Velocity Streamline
4 hr			
3 hr			
2 hr			
1 hr			

Figure 5: Melting Fraction & velocity stream line for copper foam hot wall ΔT= 10^0

The mass fraction rate, velocity stream line & temperature contour for thermal non-equilibrium porous media as a Copper foam at a temperature difference T = 15^0 with porosity = 0.8.

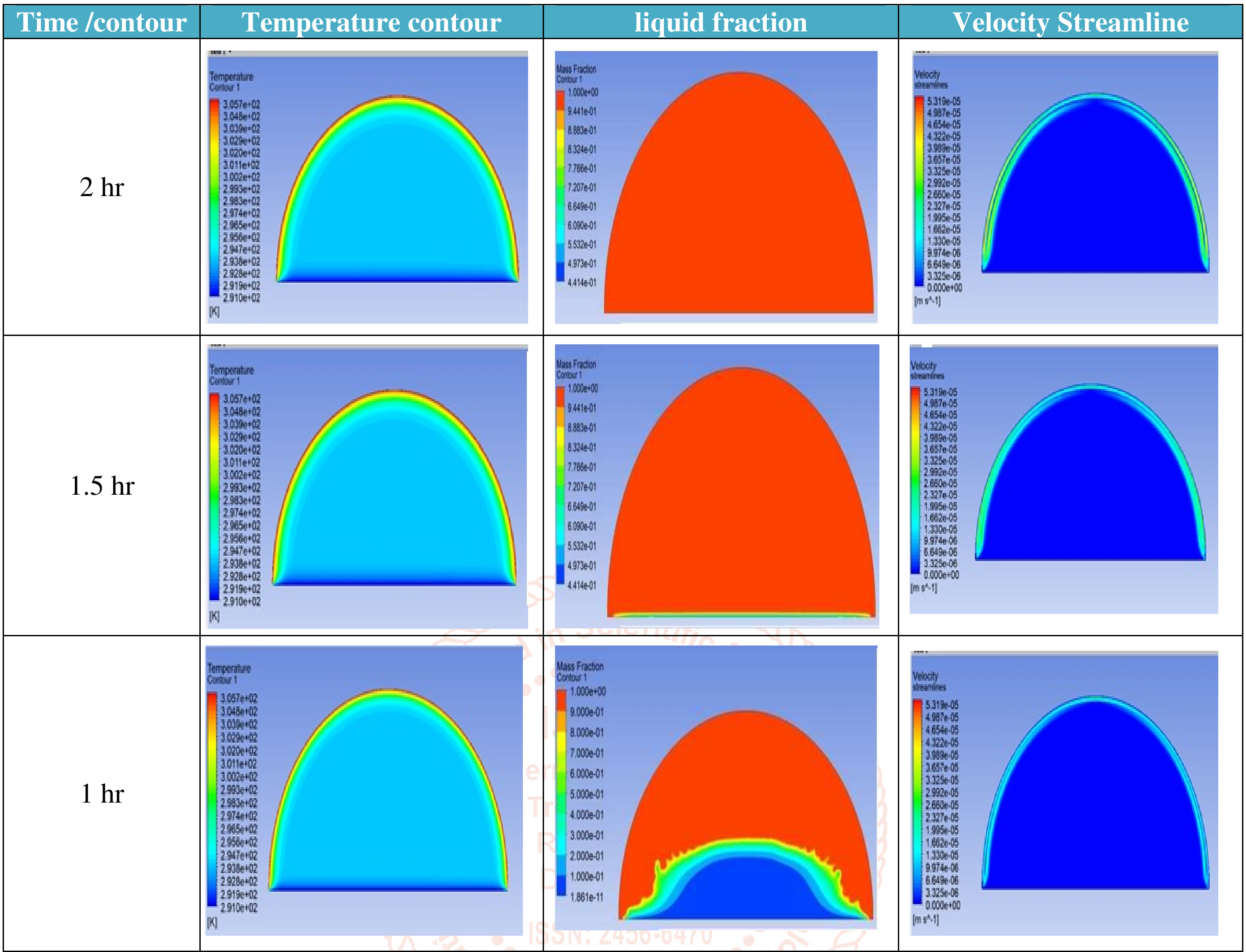


Figure 6: Melting Fraction & velocity stream line for copper foam hot wall ΔT= 15^0C

4.3. Melting Fraction Result At a different time schedule

With the help of CFD analysis, we are observed that the melting fraction, on the basis of volume weighted average (%) is measured

Time	Melting fraction (%) Δ T=10^oC
4 hr	1
3 hr	0.998762
2 hr	0.9430025
1 hr	0.7832433

Time	Melting fraction (%) Δ T=15^oC
3 hr	1
2 hr	0.994320
1.5 hr	0.9600231
1 hr	0.8200514

If we are comparing the result between the aluminum foam & copper foam melting fraction, so we find that the copper foam porous media taking less time than the aluminum Foam as a hot wall. If we are draw the graph value between them so we can find that the rate of melting fraction is increase in the copper foam hot wall.

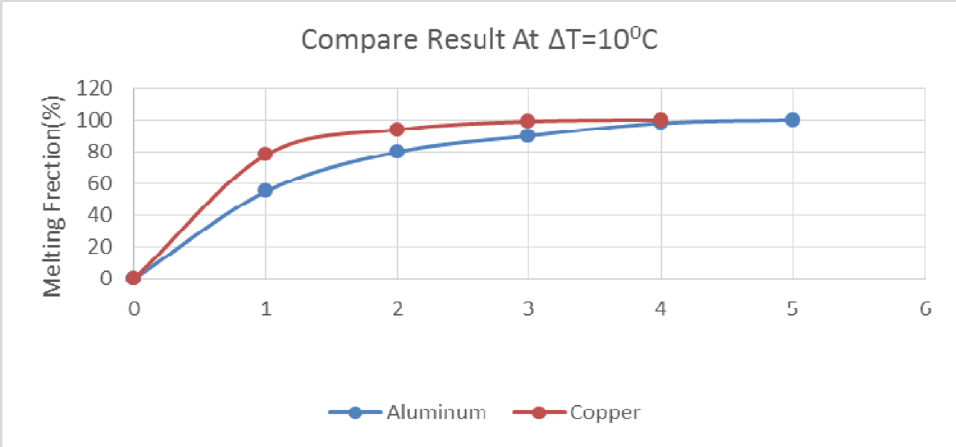


Fig. 7: Malting fraction (%) result between the aluminum foam & copper foam at temperature different ΔT=10^{0}C

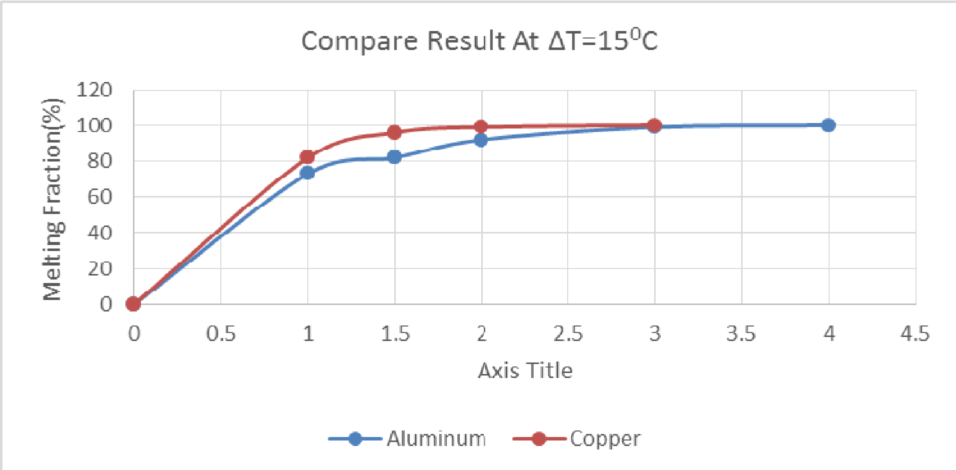


Fig. 8: Malting fraction (%) result between the aluminum foam & copper foam at temperature different ΔT=15^{0}C

V. CONCLUSIONS

This CFD study investigates the malting Fraction of the phase change materials is increase, when we are using the copper foam instead of aluminum foam. We are study about the percentage of melting fraction of paraffin with different temperature difference from ΔT = 10^{0}C & the ΔT =15^{0}C with the constant porosity(ε=0.8).

Now we'll look at how temperature differences affect the results. For two reasons, raising T induces an increase in melting fraction in both porosities and at fixed times.

- Temperature gradient and heat flow rise as ΔT is increased.
- The buoyant force and the strength of the vortices are increased by increment ΔT.

We have found some observation hare, which is studies by CFD Analysis.

- We found that if the PCM is malted at the same time (t=2 hour) at a temperature difference of T = 10^{0}C, the aluminum foam used as a porous media is around 80% and the copper foam as a porous media is about 94 %. Also, melting PCM for the same duration (t=2hr), the temperature difference for both aluminum foam and copper foam (T = 15^{0}C) is around 92 % for aluminum foam and about 96 % for copper foam. Observation shows that if we are using copper Foam as a porous media at a temperature difference ΔT = 10^{0}C, it will melt about 14% earlier at the same time. And at a temperature difference ΔT = 15^{0}C, it will melt about 2% earlier at the same time.
- It's also been discovered that malting the PCM using copper foam as a porous media takes less time than with aluminum foam.
- At the constant porosity 0.8, increment of ΔT = 10^{0}C to 15^{0}C leads to decrease time of melting process 49.7%.
- The melting process is always parabolic, with negative concavity in relation to time.

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