

Buoyancy Driven Turbulent Heat Transfer Characteristics in Enclosure Filled with Phase Change Materials



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Abstract: *The exponentially growing computing capabilities of electronic circuits require effective and efficient heat sink designs to control the temperature inside the system. To achieve the desired temperature for efficient working of electronic devices, phase change materials are widely used. In the present study we discuss the complex flow physics of a phase change material filled in a cubical enclosure in the turbulent flow regime with a local heater mounted on the enclosure bottom wall. The thermal properties of local heat source are that of silicon at a working temperature of 330 K. The walls of the enclosure other than the heat source are considered as adiabatic. The turbulent natural convection flow is modeled by the computational fluid dynamics (CFD) approach using Reynolds averaged Navier-stokes equation (RANS) with Lambremhorst $k-\epsilon$ turbulence model. A finite difference method is used to discretize the governing equations and an in-house CFD code is developed for simulating the turbulent characteristics. The flow physics of three different phase change materials (n-Octadecane, PEG900, Paraffin (RT60)) has been analyzed with Grashof number being fixed for all three phase change materials. The transient flow characteristics are investigated by plotting the stream function, velocity and temperature contours of the phase change materials..*

Keywords: *Phase change material, Convective heat transfer, mixed convection.*

I. INTRODUCTION

Use of Phase Change materials in power electronics, Thermal battery management systems and aerospace applications [1] has been a major source of interest for researchers in recent years. These substances have a low melting temperature with high latent heat energy of melting and high heat capacity. The electrical non-conductivity of these materials (n-Octadecane, paraffin RT60 and PEG (900)) make them a competing candidates for use in

electronic circuit and components' cooling. Apart from applications in electronic cooling they also find great applications in thermal regulation systems of building and solar power storage devices, such varied engineering applications can be explained by their property to absorb and release large amount of heat energy without any changes in temperatures during the phase change regime. After the phase change is complete, the material continues sensible heating or cooling.

Few studies and works have been published which have shed some light on the flow physics of Phase Change materials in the natural convection regime.[1-4]. Most of them have been majorly focused of cooling of telecommunication and hand-held devices while the application in electric vehicle cooling systems (Battery thermal management and motor controller cooling) has been totally devoid and requires extensive investigation resources. For instance, the results of an experimental study of pure gallium melting inside a parallelepiped with adiabatic walls and remaining isothermal vertically opposite faces are presented in the study [2]. This model has frequently been used for the development of computer codes by [3-9] for modeling the convective heat transfer for the phase change material. Numerical and mathematical modeling was carried out for a PCM melting in a square enclosure to study the transient effects of high values of Rayleighs number [3]. Similarly another study which studied the same flow physics inside a rectangular cavity also illustrated the influence of the Rayleigh number on the thermal and the hydrodynamic structures. Furthermore an interesting study was conducted by varying the Stefan number, Ostrogradsky number and the Rayleigh number for a PCM (n-octadecane) inside a square enclosure with a silicon heat source mounted in the bottom wall similar to this study [4]. The evolution of temperature fields and stream function was examined.

In all the above mentioned studies what they lacked was the use of a phase change material other than n-octadecane. Hence a different phase change material (Polyethyl glycol 900) study was conducted [10], for the melting process inside an enclosed parallelepiped, heated with copper plate installed on one side and cooled by water on the opposite vertical side. The properties for PEG900 have been computed using the thermo-physical properties given in [10]. [11] Numerically and experimentally have studied the flow physics of low-melting-point-alloy (LMPA) based heat sink in a cylindrical container.

Manuscript received on April 02, 2020.

Revised Manuscript received on April 15, 2020.

Manuscript published on May 30, 2020.

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It has been shown that LMPA can extend the effective protection time to 1.5 times longer and maintain the temperature in comparison with traditionally used praffinRT60.[12] have used RT60 as the phase change material to design a finned plate latent heat thermal energy storage system for domestic applications. The obtained design was one half of the conventional (500 l) water tank used, resulting in a more compact configuration which can be easily integrated in a tight space like residential flats.

In the all above mentioned studies it can be seen that studies lack an illustration with a heat generating source for different phase change materials and how these material behave for different parametric values like (Stefan number and Grashof number). A similar study can be seen in [4] but only with n-octadecane as a phase change material. Furthermore there has been no prominent illustration with Lambremhorst k-ε turbulence model for the PCM flow physics during free natural convection. To design an optimal cooling system for electronic devices it is required that all possible phase change materials with different thermo-physical properties are studied. Therefore, in the present paper the buoyancy driven turbulent heat transfer characteristics are studied for three different phase change materials in a square enclosure. Based on the above literature survey and the authors' best knowledge the study presented in this paper i.e, buoyancy driven turbulent heat transfer for different phase change materials is being discussed for the first time. The materials that are being used are selected based on their varied Prandtl number values ranging from 0.433 to 118.

II. MATHEMATICAL MODELLING AND NUMERICAL METHOD

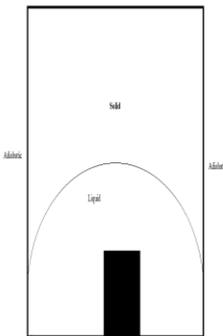


Fig.1 Cavity with boundary conditions

The natural convection turbulent heat transfer inside a square enclosure with heat source mounted at the bottom and all other walls assumed as adiabatic. The boundary conditions has been represented in fig.1. The enclosure is filled with different phase change materials. The material for the heat source is considered as silicon at 330K [4].

The melted material is supposed to be a viscous Newtonian fluid, satisfying the Reynolds averaged Navier-stokes equation (RANS) with Lambremhorst k-ε turbulence model.

The system of energy transfer and momentum is described by the system of unsteady two dimensional Boussinesq-Oberbeck equations using variables “velocity-pressure-enthalpy” in the following form [4, 13, 14]

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\rho_m \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu_m \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)$$

ρ_m is the density of the phase change material and u and v are the velocities in x and y direction respectively. μ_m is the viscosity of the phase change material at the melting phase

$$\rho_m \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \mu_m \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + (\rho\beta)_m g(T - T_F) \quad (3)$$

β is the coefficient of thermal expansion at the melting phase and T_F is the melting temperature of the phase change material

$$\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = k_m \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (4)$$

$$\frac{\partial h}{\partial t} = k_s \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (5)$$

$$(\rho c)_{hs} \frac{\partial T}{\partial t} = k_{hs} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + Q \quad (6)$$

k_m, k_s and k_{hs} are the thermal conductivity of the melt (liquid PCMs), solid PCMs and heat source material.

III. RESULTS AND DISCUSSION

In this paper we have discussed the effects of convective heat transfer for different phase change materials. The phase change materials used were n-octadecane, PEG900 and Paraffin (RT60) with the following characteristics were considered. Thermo-physical properties of Phase change materials used-

Table-I: Thermo-physical properties of PCMs used.

PCM	Density(kgm ⁻³)	μ(kgm ⁻¹ s ⁻¹)	T _m (K)	Pr	Ste
n-Octadecane	746	1.81	301.3	48.3	3.84
			5	6	
PEG(900)	1100	9.9	305	118	2.65
Paraffin(RT60)	770	3.75	326.1	0.43	13.1
			5	3	9

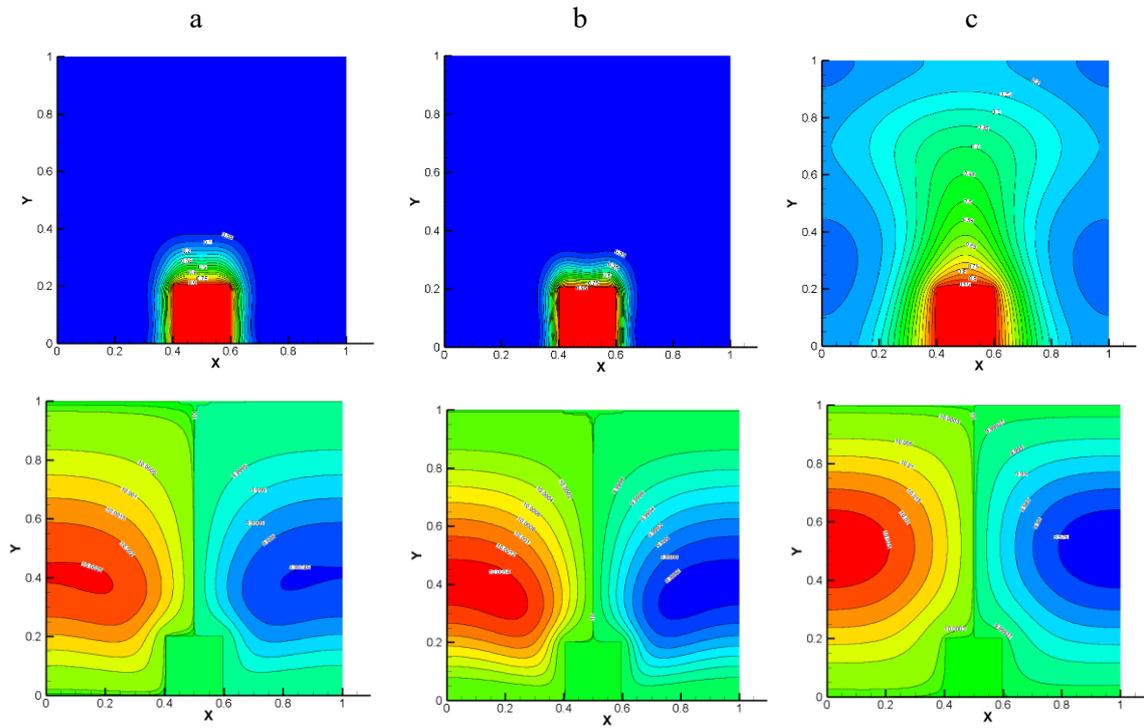


Fig 2. Temperature contours and Stream function for n-Octadecane (a), PEG (900) (b) and Paraffin (RT60) (c) at $T=12$

In fig.2 the temperature contours and stream function of three different phase change material is shown at $T=12$. The Grashof number is fixed at 10^3 . The ascending thermal plumes can be seen rising towards the top surface due to convection in Paraffin (RT60) i.e, fig 2(c). While in temperature contour graphs of n-Octadecane and PEG900 conduction regime is

Predominant and the convective flux is yet to be formed. It can also be noted that the rate of melting is more in n-octadecane than in PEG900. The stream function for all the materials is symmetric around the central axis.

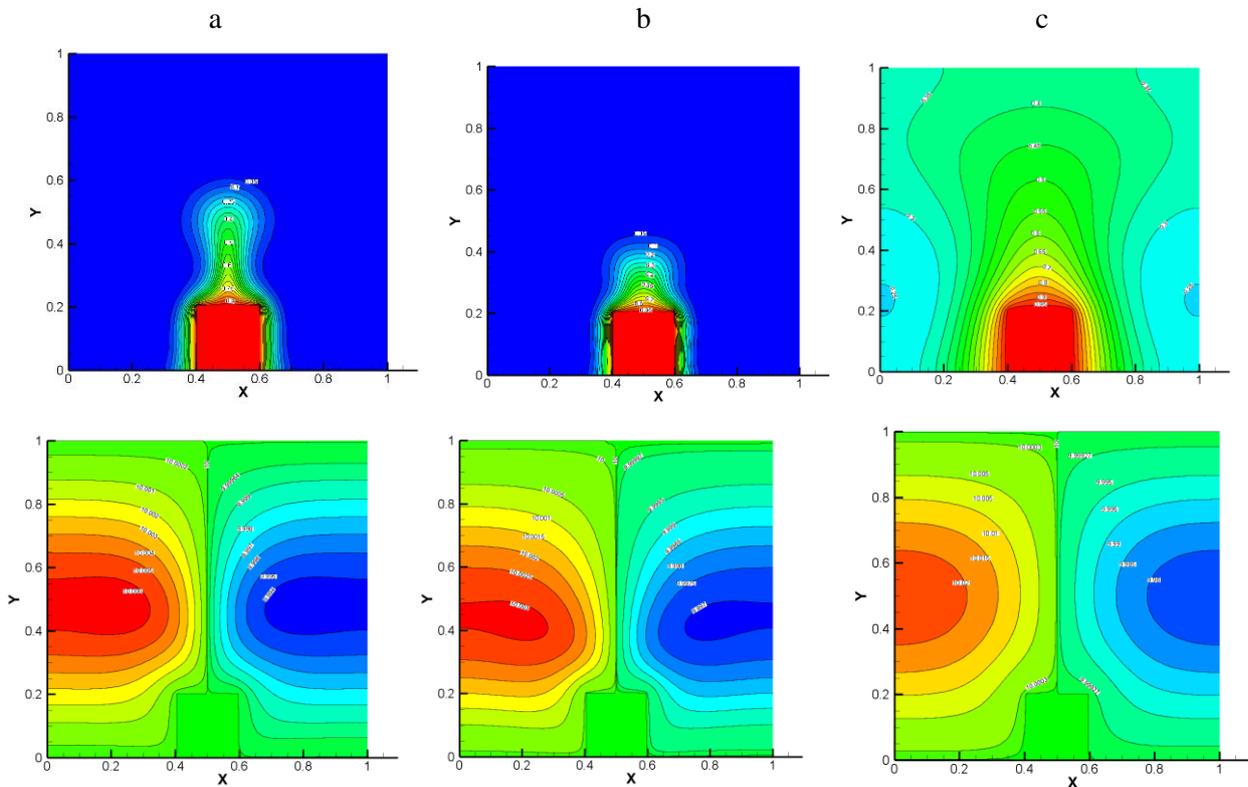


Fig 3. Temperature contours and Stream function for n-Octadecane (a), PEG (900) (b) and Paraffin (RT60) (c) at $T=20$

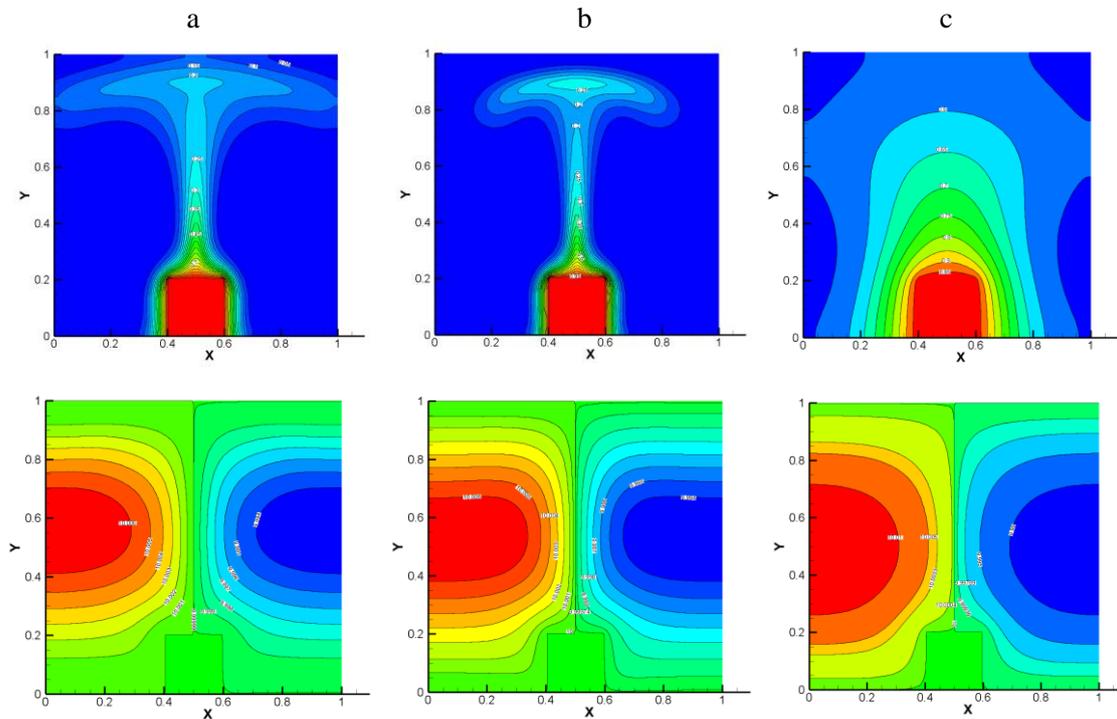


Fig.4 Temperature contours and Stream function for n-Octadecane (a), PEG (900) (b) and Paraffin (RT60) (c) at $T=40$

In fig.3 the temperature contours and stream functions are shown at $T=20$. The ascending convective thermal plumes are now evidently observed in all three PCMs.

While the convective regime for n-octadecane is more when compared to that of PEG900. The rate of convective heat transfer is higher for n-octadecane than PEG900. While a curved thermal plume is visible in the case of n-octadecane, the curvature of thermal plume for PEG900 has not formed visibly. The enclosure with paraffin (RT60) is now completely influenced by the convection heat transfer of the material and the rising plumes have now started moving horizontally and have reached the side wall too, while in the enclosure of other two materials the side walls still remain uninfluenced by the ascending thermal plumes. It is also observed that the thermal plumes reach the upper walls much faster than the side walls for n-Octadecane and PEG900. The stream functions for all the three materials are symmetric along the central axis but the complexity in patterns is far less in Paraffin (RT60) than n-Octadecane and PEG900.

In fig.4 the temperature contours and stream functions are shown at $T=40$. The ascending thermal convective plumes for n-octadecane and PEG900 have now started moving horizontally also which means that the side walls of the upper domain are now also influenced by the convective heat transfer. In the upper domain the melting is also observed to be non-uniform due to dissimilarities between horizontal and vertical velocities

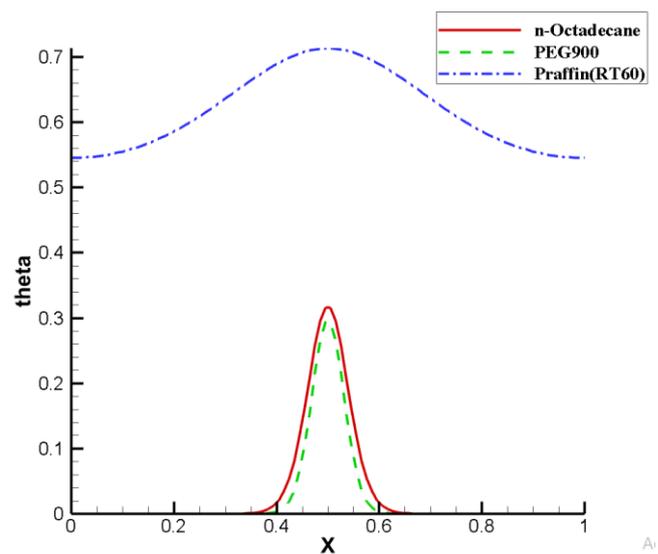


Fig.5 Temperature transition at section at $y=0.5$ at $T=40$

In Fig.5 the temperature variation between the three PCMs is shown at a sectional cut of $y=0.5$. The temperature range along x- axis for n-Octadecane and PEG900 is high, while the region is less influenced by the convective heat transfer. Sharp rises can be seen for temperature gradients. For Paraffin (RT60) the temperature gradient is smooth but the influenced region is more. Also the temperature is much higher than n-Octadecane and PEG900. This shows that Paraffin is reaching its stable phase of convective heat transfer while PEG900 and n-Octadecane will take more time to reach a stable or smooth temperature gradient across x-axis. The maximum temperature of n-Octadecane at $y=0.5$ sectional cut is 6.89% higher than PEG900 while maximum temperature of Paraffin (RT60) is 145.86% higher than that of PEG900.

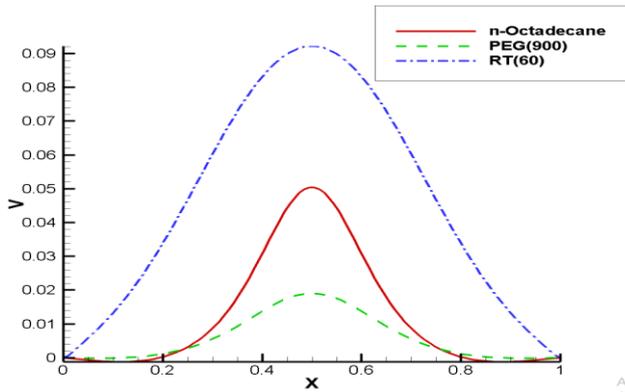


Fig.6 (a)

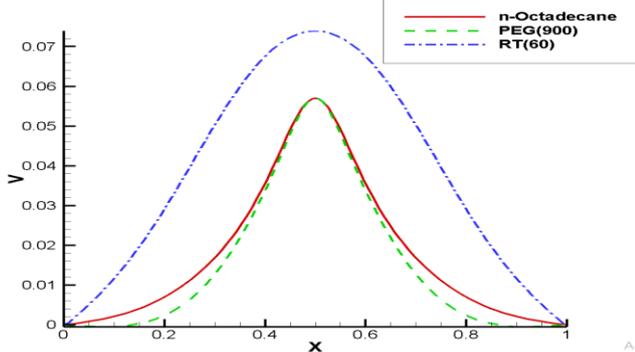


Fig.6 (b)

Fig.6 Velocity at $y=0.5$ at (a) $T=20$ and (b) $T=30$

In Fig.6 (a) and (b) the velocity variation at section $y=0.5$ has been shown at $T=20$ and $T=30$ respectively. The maximum velocities at both the $T=20$ and $T=30$ is attained by Paraffin(RT60) which is 80% more than velocity of n-Octadecane but what interests one more is the sudden rise in the velocity of PEG900 at $T=20$ and at $T=30$. The velocity which was 80% less than the velocity of n-Octadecane becomes almost equal at $T=30$ with a rise of 470% of its value at $T=20$. This indicates the conductive to more dominant convective heat transfer transition for this period.

IV. CONCLUSION

The convection flow characteristics inside a cubical enclosure with an internal heat source mounted at the bottom surface are numerically investigated for various phase change material with varied thermo-physical properties. The turbulent flow is modeled by the computational fluid dynamics (CFD) approach using Lambremhorst $k-\epsilon$ turbulence model and the governing equations are discretized using finite difference method. The stream line patterns and temperature contours are analyzed for three different phase change materials across various time. A comparison is made between the temperature variations of these materials at a sectional cut of $y=0.5$. It was found that Praffin (RT60) reaches the convective regime faster when compared to n-Octadecane and PEG900. Also the heat transfer is better in cases of Paraffin (RT60) followed by n-Octadecane. It is also observed that there is sudden increase in velocity of PEG900 at $T=30$ when compared to $T=20$, which almost 4.5 times more. There are also varied temperature differences between n-Octadecane, PEG900 and Paraffin (RT60) at $T=40$ which is almost 1.5 times more than temperatures of n-Octadecane and PEG900. The results from the present study will be suitable for selecting suitable Phase

change materials for designing effective thermal management systems for cooling of electronic devices and battery thermal managment systems.

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