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Analysis and Optimisation of Melting Rate of Solids PCM for Various Shapes and Configurations

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Abstract: *Analyses the melting chacractrtics of a phase change material (PCM) in different geometry and configurations. The paraffin wax is selected as the phase change material. The different geometries studied are rectangular block, sphere and cylinder. Also the effect of configuration on melting rate is studied. A simplified 3-dimentional pressure-based CFD model is used in Fluent to simulate the Melting process. Pre-processing is the first step in building and analyzing a flow model. It includes building the model, applying the mesh, and entering the data. The Gambit as the pre-processing tool in this work. GAMBIT is a software package designed to help analysts and designers build and mesh models for computational fluid dynamics (CFD) and other scientific applications. FLUENT is a computer program for modeling fluid flow and heat transfer in complex geometries FLUENT provides complete mesh flexibility, including the ability to solve flow problems using unstructured meshes that can be generated about complex geometries.*

Keywords: *Melting rate; Phase Change Material; Melt fraction; Geometries configuration; CFD analysis*

1. INTRODUCTION

Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems. Thermal energy can be stored in the form of sensible heat in which the energy is stored by raising the temperature of the storage material solid or liquid. Rock or water is the best example. Alternatively, thermal energy can be stored as latent heat in which energy is stored when a substance changes from one phase to another by either melting or freezing. The temperature of the substance remains constant during phase change. Of the two, latent heat thermal energy storage technique has proved to be a better engineering option primarily due to its advantage of providing higher energy storage density with a smaller temperature difference between storage and retrieval. Phase change materials (PCM) they are materials that use chemical bonds to store and release heat energy in the process of changing the state from solid to liquid. Among the variety of PCM proposed, paraffin wax has been considered most prospective, because of its desirable characteristics, including significant latent heat of fusion, negligible super cooling, low vapor pressure in melt, chemical stability and 100% recyclable. However, the inherent low thermal conductivity of paraffin could result in lower heat transfer rates during melting/freezing processes. In order to enhance the effective thermal conductivity usually highly conducting materials are added to the paraffin wax.

Spherical geometry represent an interesting case for heat storage application, since spheres are often used in packed beds as those described in subsection D. Due to the complexity of such systems, it is often more efficient to first model the behavior of an individual sphere, to then describe it with a simple parametric model to be used in the packed bed modeling.

Roy and Sengupta [1] have examined the melting process with the solid phase initially uniformly super cooled. The presence of super cooling, forced them to modify the heat transfer equation to include the effects of temperature gradient in the solid core. As a result, a closed-form solution could not be obtained. At every time step, the unsteady conduction equation has been solved numerically using a steroidal coordinate system, which has been suitably transformed to immobilize the moving boundary and to transform the infinite domain into a finite one. In a subsequent paper [2], they have examined the impact of convection on the melting process. They demonstrated that the fluid flow in the upper liquid region is essentially quasi-steady, since the liquid velocity in both the film and the upper zone are much greater than the rate of movement of the interface. They also demonstrated the importance of the ratio of the buoyancy force due to density variation of the liquid with temperature, and the density difference between the two phases, which reduces the melt rate and places an upper bound for the range over which the film solution is valid.

Ettouney et al. [3] experimentally evaluated the heat transfer in paraffin inside spherical shell. Their calculation shows that the Nusselt number in the phase change material during melting is one order of magnitude higher than during solidification and is strongly dependent on the sphere diameter. In consequence, the melting was about a factor two slower than the freezing. This counter-intuitive behaviour is caused by the convection, which brings a large fraction of the heat to the upper part of the sphere, where it heats the melt fraction instead of the solid phase. In the freezing process, conduction dominates and the freezing occurs around the entire surface. As the melt volume decreases and the role of natural convection diminishes rapidly. This result contrasts with the work of Barba and Spriga [4] on the behaviour of encapsulated salt hydrates, used as latent energy storage in a heat transfer system of a domestic hot water tank, who found that the shortest time for complete solidification is provided by small spherical capsules, with high Jacob numbers and thermal conductivities. On the impact of convection, Khodadadi and Zhang [5] also noted that it created an asymmetry: melting in the upper region of the sphere much faster than in the lower region due to the enhancement. Their computational findings were verified through qualitative constrained melting experiments using a high-Prandtl number wax as the phase change material.

Oztop and Dagtekin [6] studied steady state two-dimensional mixed convection problem in a vertical two-sided lid driven differentially heated square cavity. The left and right moving walls were maintained at different constant temperatures while upper and bottom walls were thermally insulated. Three cases were considered depending on the direction of moving walls and Richardson number, Ri. They observed that both Richardson number and direction of moving walls affect the fluid flow and heat transfer in the cavity. For $Ri \leq 1$, the influence of moving walls on the heat transfer is the same when the walls move in opposite direction regardless of which side moving upwards and the influence is less when both sides move upwards. For the case of opposing buoyancy and shear forces and for $Ri \geq 1$, the heat transfer rate is larger due to formation of secondary cells on the walls and a counter rotating cell at the centre.

Ismail and Henrique [6] created a parametric model for the study of the solidification of a PCM in a spherical shell. This model was based on pure conduction in the PCM subject to boundary conditions of constant temperature or convection heat transfer on the external surface of the spherical shell.. Like other groups, they found that the increase of the size of the sphere leads to increasing the time for freezing. The same team performed a specific numerical and experimental study on water solidification. The governing equations of the problem and associated boundary conditions were formulated and solved using a finite difference approach and a moving grid scheme. A shortcoming of the model was its incapacity of adequately handling super cooling. Nevertheless, they conclude that shell material affects the solidification time. Freezing was faster for metallic material (Cu, Al) followed by polyethylene, acrylic and PVC. However, the time difference was rather small, which still makes non metallic capsules attractive.

Anica Trp [7, 8] analyzed the transient heat-transfer phenomenon during technical grade paraffin melting and solidification in a cylindrical shell. The mathematical model, formulated to represent the physical problem, has been proved suitable to treat both melting and solidification processes. It can be concluded that the selection of the operating conditions and geometric parameters dimensions depends on the required heat transfer rate and the time in which the energy has to be stored or delivered. In consequence, these parameters must be chosen carefully to optimize thermal performances of the storage unit.

Gong and Mujumdar [9] developed a finite-element model for an exchanger consisting of a tube surrounded by an external co-axial cylinder made up of PCM. This model compares characteristics of two operations in mode 2, hot and cold fluids are introduced from different ends. Analyses show that the energy charged or discharged in a cycle using mode 1 is 5.0% higher than when using mode 2. The charge/discharge rate is also faster when using mode 1 because the temperature difference between the fluid and the PCM is higher in the fluid inlet than in the outlet. The larger the temperature difference is the more deeply the phase-change interface penetrates into the PCM and the more heat is stocked. In the discharge process, symmetrical phenomena occur.

Jones et al. [10] performed well-controlled and well-characterized experimental measurements of melting of a moderate Prandtl number material (n-eicosane) in a cylindrical enclosure heated from the side. The melt front was captured photographically and numerically digitized. A numerical comparison exercise was undertaken using a multi-block finite volume method and the enthalpy method for a range of Stefan numbers. Very good agreement was obtained between the predictions and the experiments for Stefan numbers up to 0.1807.

Esen and Ayhan [11] developed a model to investigate the performance of a cylindrical energy storage tank. In the tank, the PCM was packed in cylinders and HTF flowed parallel to it. The PCMs considered were calcium chloride hex-hydrate (CaCl2-6H2O), paraffin wax (P-116), Na2SO4-10H2O and paraffin. The performance of cylindrical energy storage tank was determined by computer simulations and backed by experimental data. The results show that the stored energy becomes higher at a given time as the mass flow rate or inlet HTF temperature increases and for more energy storage appropriate cylinder wall materials and dimensions should be selected, such as higher thermal conductivity and small radius.

Various numerical methods applied to the solutions of heat transfer problems involving phase change materials for thermal energy storage are identified.. The review is a model collection of fundamental and most recent works published on the subject. This survey is organized according to the problem geometry (Cartesian, spherical, and cylindrical) and specific configurations or applications. The authors do not claim anything about the completeness of the review as some papers may have been unfortunately neglected. This guideline is used for International Journal of Emerging Engineering Research and Technology (IJEERT). These are the manuscript preparation guidelines used as a standard template for all paper submissions of IJEERT. Author must follow these instructions while preparing/modifying these guidelines.

2. MATHEMATICAL FORMULATION

The model for the numerical study was created using pre-processor software GAMBIT 2.3.16. The GAMBIT model is then exported to FLUENT for problem solving. The pressure based method within version 6.3.26 of the commercial code FLUENT was utilized for solving the governing equations. The first order upwind differencing scheme was used for solving the energy equations.

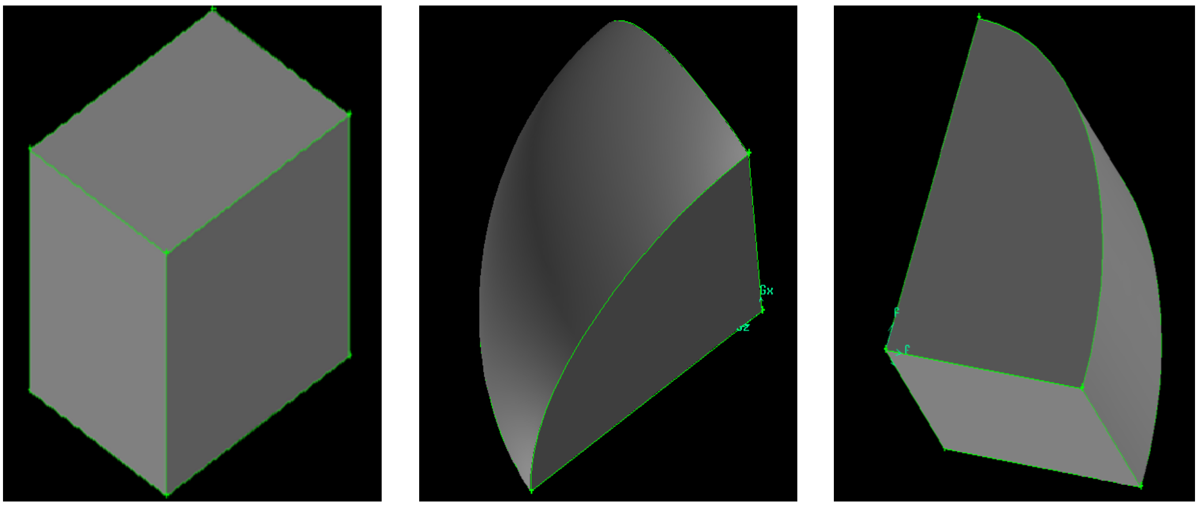

Fig1(a) *Rectangular block* **Fig1(b)** *sphere* **Fig1(c)** *Cylinder*

Fig1. *Geometry of the models*

The governing energy equations for the melting problems are

In Cartesian co-ordinate

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right)=\rho C\frac{\partial T}{\partial t}$$

In Cylindrical co-ordinate

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \emptyset^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

In Spherical co-ordinate

$$\frac{1}{r^2\sin^2\theta}\frac{\partial^2 T}{\partial \varphi^2}+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial T}{\partial \theta}\right)+\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)=\frac{1}{\propto}\cdot\frac{\partial T}{\partial t}$$

The one eighth of the view of the physical model is shown in Fig1 rectangular block, sphere and cylinder respectively. Heat is applied on the wall of the geometry. And the initial temperature of the whole system was maintained at 300 K and the temperature of the wall is changed in to 340 K.

The FLUENT code is validated by doing experiment, where ice is taken as the phase change material. Initial temperature is taken as 268K and wall temperature is taken as 300K.The experiment is done on different geometries such as rectangular block, sphere, and cylinder keeping same volume used in the FLUENT analysis.

Table1. *properties of the PCM (paraffin wax) used for computation*

Property	Paraffin wax
Density (kg/m^3)	750
Specific heat (J/kgk)	2890
Thermal conductivity (w/mk)	0.21 if T < $T_{SSolidus}$ 0.12 if T > $T_{liquidus}$
Viscosity (Ns/m^2)	3.833×10^{-3}
Latent heat (J/kg)	173400
Solidus temperature (k)	319
Liquids temperature(K)	321

It is seen from Fig 2 that the present numerical model of cylinder is in agreement with experimental results. In experiment, we get melting time as 50 min and by numerically get melting time as 55 min. Fig 3 shows the validation of rectangle in this case numerically we get melting time as 65 min and by experimentally we get melting time as 60 min and Fig 4 shows the validation of sphere in this case we get numerically the melting time as 95 min and by experiment 90 min.

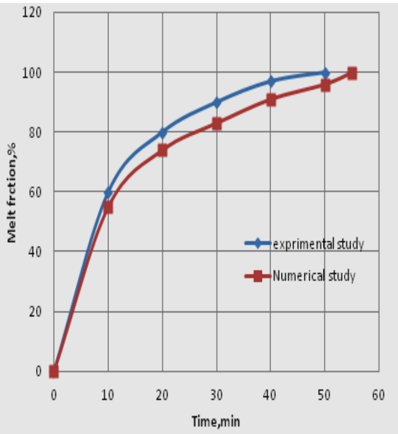

Fig2. *melts fraction Vs time, cylindrical geometry*

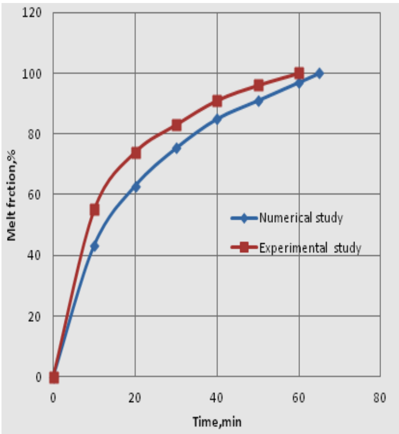

Fig3. *melt fraction Vs time, Rectangular block*

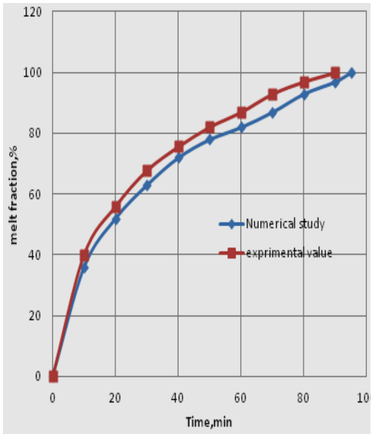

Fig4. *melts fraction Vs time, spherical geometry*

There is difference between the numerical and experimental results. This is because in the case of numerical studies we neglect the effects of convection. But there is effect of convection in the experimental case.

3. Result And Discussion

3.1 Sphere

The Distribution of solid and liquid phases and melt fraction of PCM at various times are discussed below

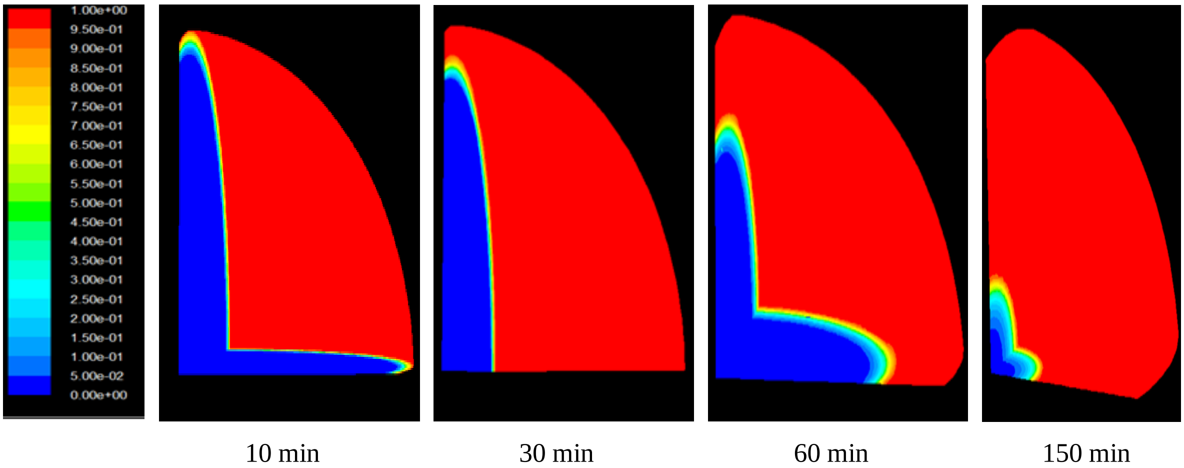

Fig5. *Distribution of solid and liquid phases at various times*

Fig 5 shows the results of melting simulations in the form of a phase distributions in spherical shape. The different colour represents different temperature range of PCM. Solid pcm is gradually changes in to liquid pcm according to time in Fig6 shows the graphical repsentation of melt fraction with respect time at different wall temperature .as expected the melt fraction increases more rapidly when the temperature difference is higher. And also the melt fraction is almost lineally increases as a function of time. When wall temperature is changes melting time is also decreases. When temperature difference is 19^{o}C That is wall temperature is maintained at 340 K, then melting time is 170 min .when wall temperature is increases in to 350 K then melting time is decreases in to140min is because by Fourier law of heat conduction.

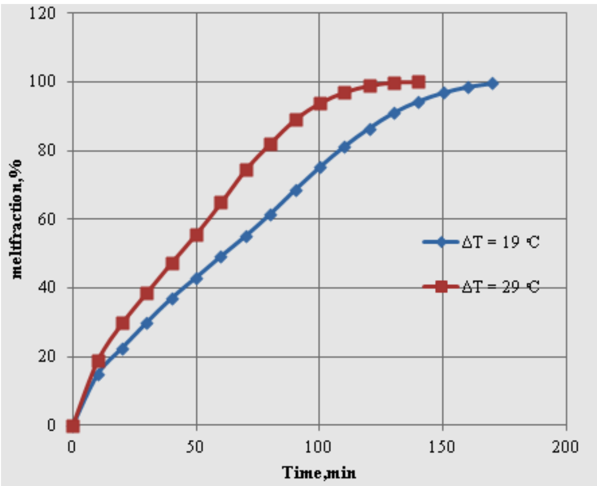

Fig6. *Spherical geometry melting*

3.2 Cylinder

Fig7(a) shows the melt fraction of phase change material in aspect ratio 0.5 .it is clear that when temperature difference changes melting time also changes at ΔT is 19^{0}C PCM takes 60 min to melt. Otherwise when ΔT is changes in to 29^{0}C melting time is decreases in to50 min.

Fig7 (b) shows the melt fraction of phase change material at aspect ratio 0.75, when ΔT is 19^{0}C PCM takes 100min to melt. And when ΔT is changes in to 29^{0}C PCM takes 70 min to melt it is clear that in this case also when temperature difference is increases melting time is decreases and also it is clear that when aspect ratio is changes from 0.5 into to 0.75 melting time is increases.

Fig7 (c) shows the melt fraction of PCM in aspect ratio 1. In this graph it is clear that at ΔT is 19^{0}C PCM takes 130 min to melt. And when ΔT is changes in to 29^{0}C melting time is decreases in to 90min and also when aspect ratio is changed from 0.75 in to 1 melting time increases

Fig7 (d) shows the melt fraction of PCM in aspect ratio 1.5.it is clear that when ΔT is 19^{0}C melting time is 160 min and when temperature difference is changed in to 29^{0}C melting time is decreases in to 110 min and also when aspect ratio is changes from 1 to 1.5 melting time also increases.

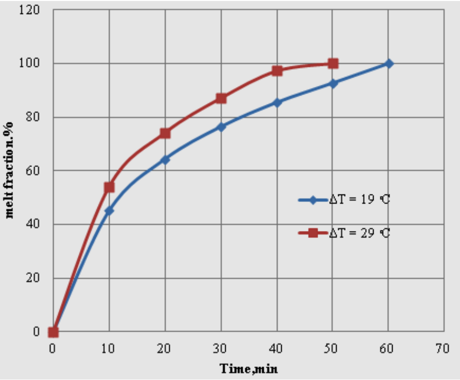

Fig7(a). *Aspect ratio 0.5*

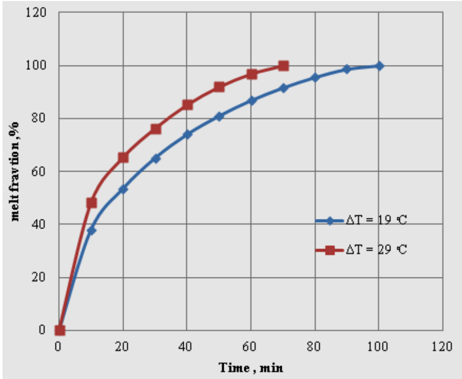

Fig7(b). *Aspect ratio 0.75*

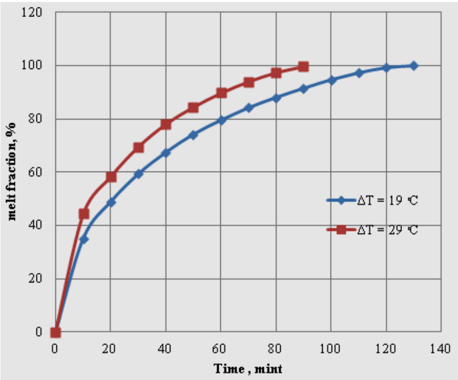

Fig7(c). *Aspect ratio 1*

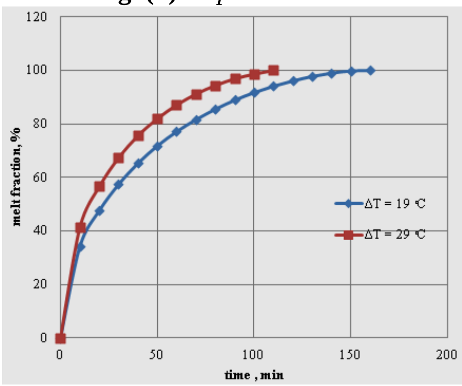

Fig7(d). *Aspect ratio 1.5*

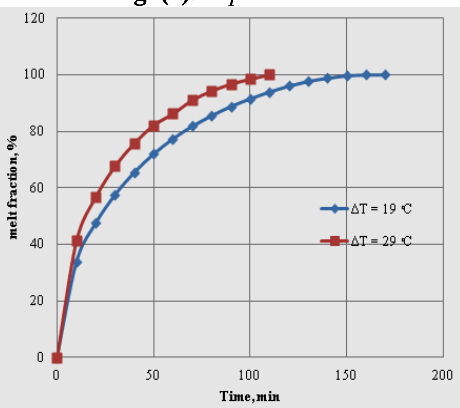

Fig7(e). *Aspect ratio 2*

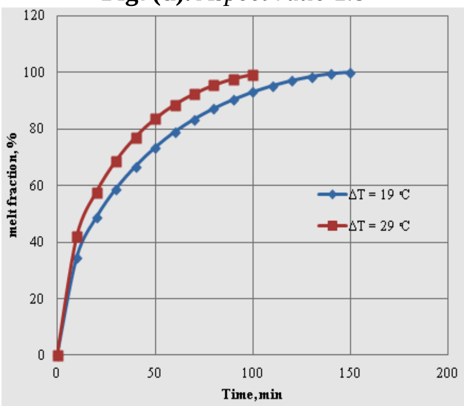

Fig7(f). *Aspect ratio 2.5*

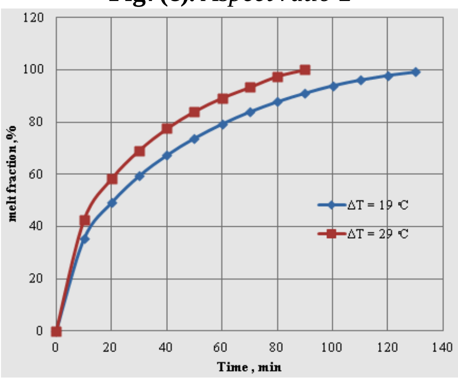

Fig7(g). *Aspect ratio 3*

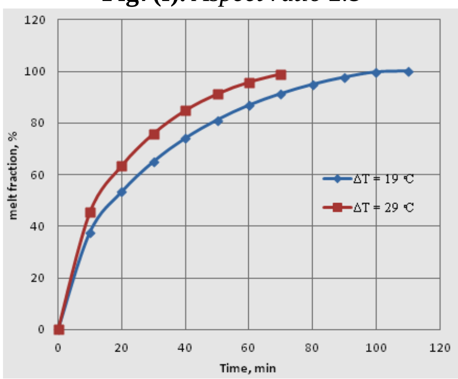

Fig7(h). *Aspect ratio 5*

Fig7. *Cylindrical geometry melting*

Fig7 (e) shows the melt fraction of PCM at aspect ratio 2 in this case at temperature difference is 19^0C melting time is 170 min and when temperature difference is changes in to 29^0C melting time is decreases in to 110 min .and also when aspect ratio is changes from 1.5 into 2 melting time is increases from 160 min to 170min.

Fig7(f) shows the melt fraction of PCM in aspect ratio 2.5 .When temperature difference is 19^0C melting time is 150 min and when temperature difference is changed in to 29^0C melting time is also changed in to 100 min similarly when aspect ratio is changes from 2 to 2.5 melting time decreases from 170 min to 150 min.

Fig7 (g) shows the melt fraction of PCM at aspect ratio 3.in this case at temperature difference 19^{0}C melting time is 130 min and when temperature difference is changed in to29^{0}C melting time is also changed in to 90 min.hen aspect ratio is changed from 2.5 to 3 melting time is also changed from 150 min to 130 min at temperature difference is 19^{0}C.

Fig7 (h) shows the melt fraction of PCM at aspect ratio 5 it is clear that at temperature difference 19^{0}C melting time is 110 min when temperature difference is changed in to 29^{0}C melting time is changed in to 70 min. and also when. Aspect ratio is changed from 3 to 5 melting time also decreases.

Fig8. shows the comparison of melt fraction at various aspect ratios. From figures it is clear that aspect ratio 0.5 takes least time to melt. It takes 60 min to melt. And aspect ratio 2 takes 170 min to melt the PCM. And also when temperature difference (ΔT) changes melting time also changes. That is when temperature difference increases melting time decreases.

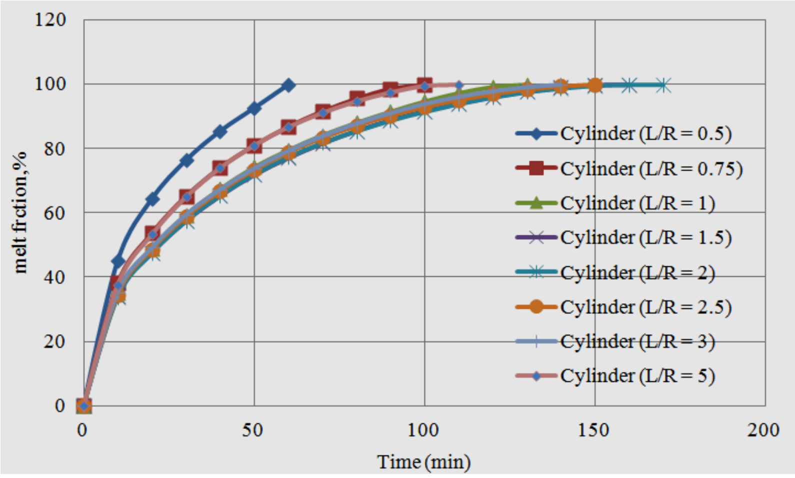

Fig8. *Comparison of melt fraction for various aspect ratios*

Fig9. shows the melting time Vs Aspect ratio graph .from figure it is clear that aspect ratio strongly depended the melting time. That is when aspect ratio changes melting time also changes .at aspect ratio 2 PCM takes more time to melt .and aspect ratio 2 is the maximum value.

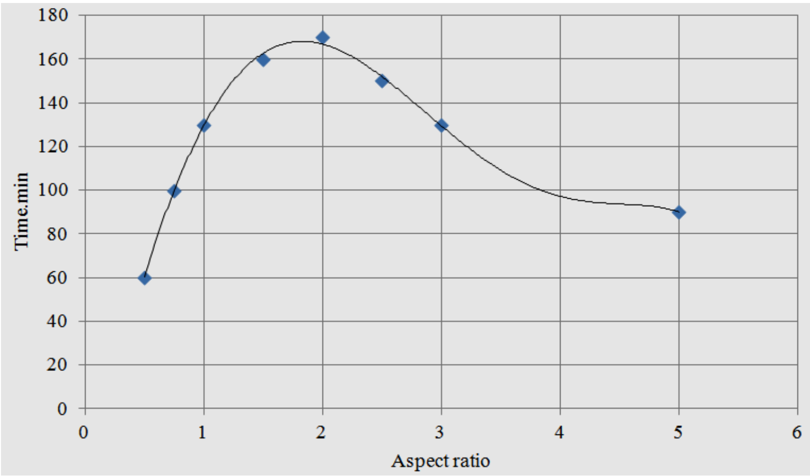

Fig9. *Melting time Vs Aspect ratio*

3.3 Rectangular block

Fig10 (a) shows the melt fraction of PCM in aspect ratio 0.5. In this graph it is clear that at ΔT is 19^{o}C PCM takes 120 min to melt. And when ΔT are changes in to 29^{o}C melting time are decreases in to 90 min. Fig10 (b) shows the melt fraction of PCM in aspect ratio 1. In this graph it is clear that at ΔT is 19^{o}C PCM takes 140min to melt and when ΔT is changes in to 29^{o}C melting time is decreases in to 100min.and also when Aspect Ratio changes from 0.5 to 1 melting time is increases from 120 min to 150 min.

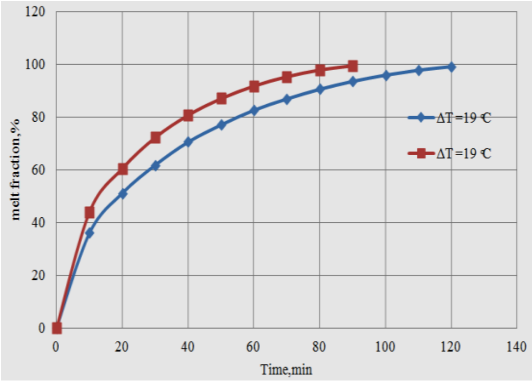

Fig10 (a). *Aspect ratio 0.5*

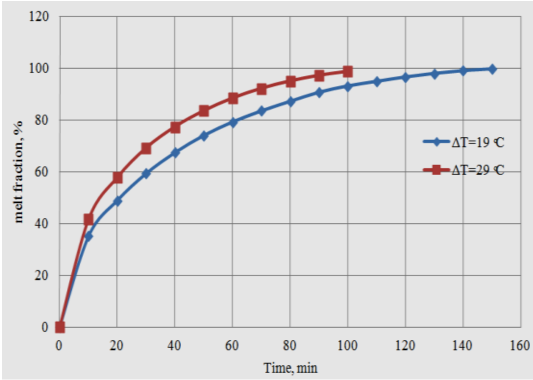

Fig10 (b). *Aspect ratio 1*

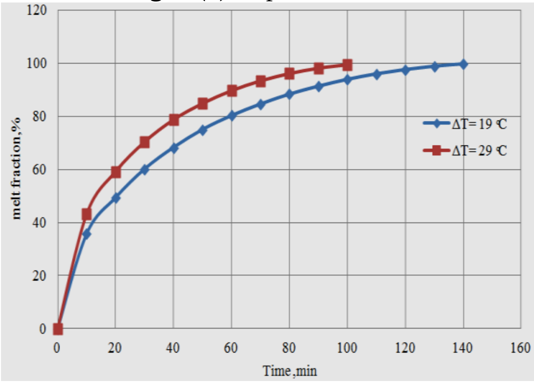

Fig10(c). *Aspect ratio 1.5*

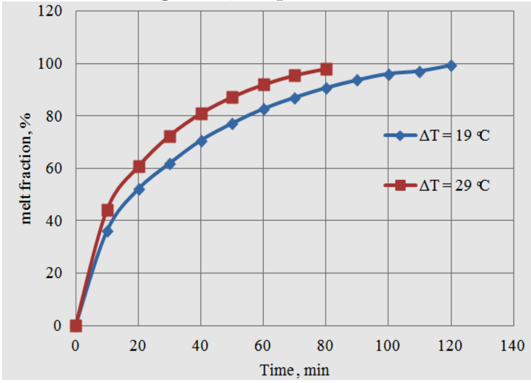

Fig10 (d). *Aspect ratio 2*

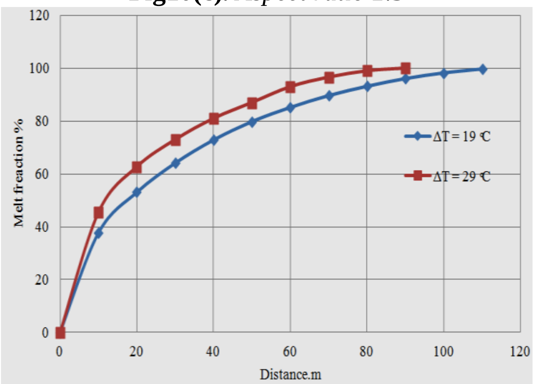

Fig10 (e). *Aspect ratio 2.5*

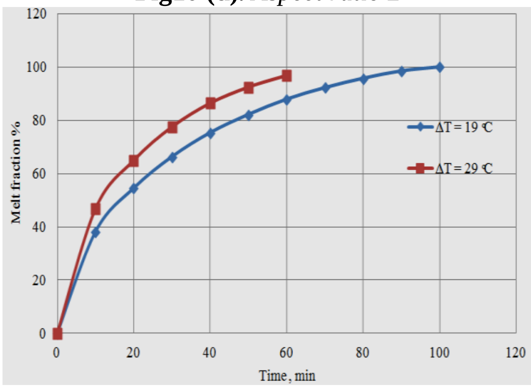

Fig10 (f). *Aspect ratio 3*

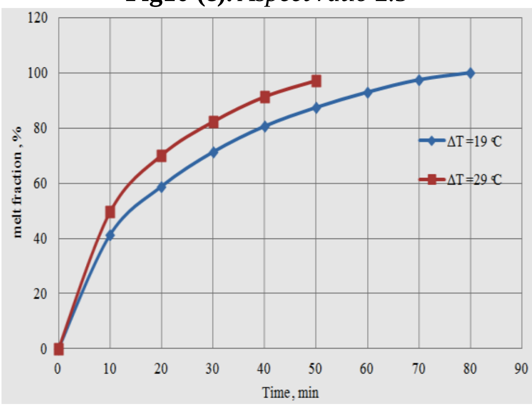

Fig10 (g). *Aspect ratio 4*

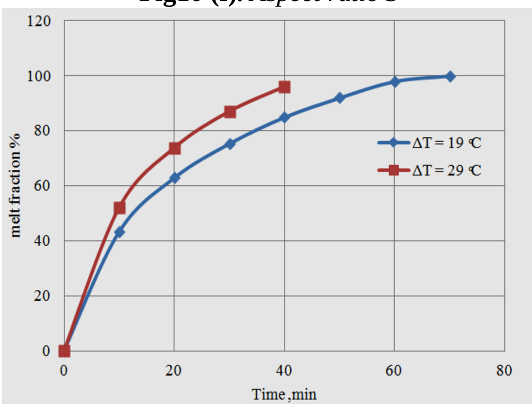

Fig10 (h). *Aspect ratio 5*

Fig10. *Rectangular geometry melting*

Fig10(c) shows the melt fraction of PCM in aspect ratio 1.5 in this graph it is clear that at ΔT is 19°C PCM takes 140 min to melt. And when ΔT is changes in to 29°C melting time is decreases in to 100min and also when Aspect Ratio changes from 1 to 1.5 melting time is degreases from 150 min to 140 min.

Fig10 (d) shows the melt fraction of PCM in aspect ratio 2 in this graph it is clear that at ΔT is 19°C PCM takes 120 min to melt. And when ΔT is changes in to 29°C melting time is decreases in to 80 min and also when Aspect Ratio changes from 1.5 to 2 melting time is degreases from 140 min to 120 min.

Fig10 (e) shows the melt fraction of PCM in aspect ratio 2.5 in this graph it is clear that at ΔT is 19°C PCM takes 110 min to melt and when ΔT are changes in to 29°C melting time are decreases in to 90 min and also when Aspect Ratio changes from 2 to 2.5 melting time is decreases from 120 min to 110 min.

Fig10 (f) shows the melt fraction of PCM in aspect ratio 3 in this graph it is clear that at ΔT is 19°C PCM takes 100 min to melt And when ΔT is changes in to 29°C melting time is decreases in to 60 min and also when Aspect Ratio changes from 2.5 to 3 melting time is degreases from 120 min to 100 min.

Fig10 (g) shows the melt fraction of PCM in aspect ratio 4 in this graph it is clear that at ΔT is 19°C PCM takes 80 min to melt and when ΔT is changes in to 29°C melting time is decreases in to 50 min and also when Aspect Ratio changes from 3 to 4 melting time decreases from 100 min to 80 min.

Fig10 (h) shows the melt fraction of PCM in aspect ratio 5 in this graph it is clear that at ΔT is 19°C PCM takes 70 min to melt and when ΔT is changes in to 29°C melting time is decreases in to 40 min and also when Aspect Ratio changes from 3 to 4 melting time is degreases from 80 min to 70 min.

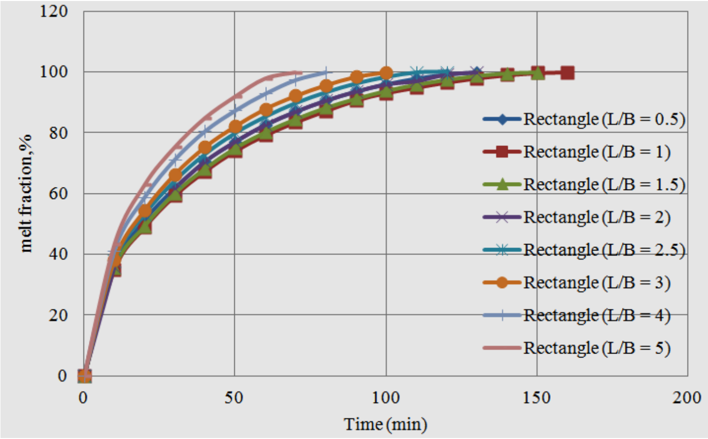

Fig11. *Comparison of melt fraction in various aspect ratios*

Fig11 shows the melting rate of rectangle shape PCM in various aspect ratios in this case also melting rate also depends on the aspect ratio. Melting time is a change according with changing in aspect ratio at aspect ratio 0.5 to 1 melting time are increases from 120 min to 150 min .and at aspect ratio 1 PCM takes more time to melt .that is it takes 150 min to melt. And from 1 to 1.5 melting time are decreases. That is in aspect ratio 1 to 5 melting time is decreases. Aspect ratio 5 takes least time to melt that is 70 min.

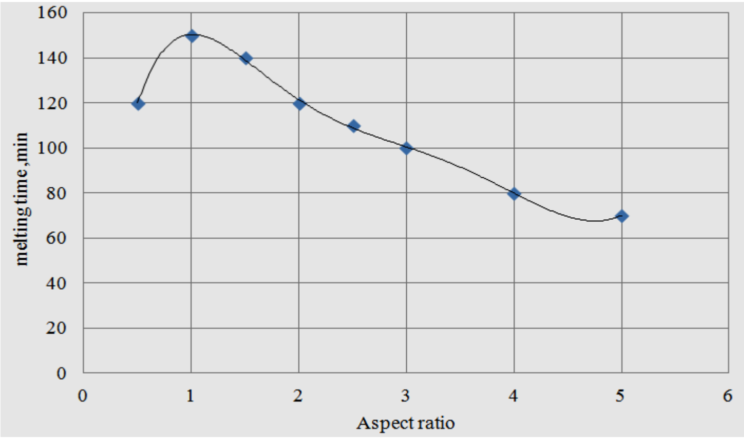

Fig12. *Melting time Vs Aspect ratio*

Melting time also strongly depends on the wall temperature and when wall temperature changes meting time also changes. In all shapes and configurations melting time is depends on the wall temperature and aspect ratio.

4. Conclusion

The modelling of PCM melting in three dimensional using the cell-cantered finite volume method of a fully implicit time scheme associated with a fixed grid, latent heat source approach is successfully performed. As the melting front should be of a one control volume thickness, this dominating restriction controls both the time interval and the grid sizes. The temperature distributions show that PCM cells heat up faster with a temperature gradient of almost a linear shape. Once a PCM cell is melted, its temperature increase will be slow. This clearly illustrates that the rate of heat transfer is predominantly controlled by the position of the melting front.

In 3-dimensional numerical analysis was performed using FLUENT software. Analyse is done in different shape and configurations and find out the suitable configuration for heat storage applications.

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