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Simulation of Heat Transfer during Paraffin And Gallium Melting and Solidification Processes Utilizing Star CCm+

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ABSTRACT

Energy storage systems are essential as the world works to minimize its dependency on fossil fuel energy for environmental and economic reasons. Because of their high capacity for latent heat storage. The numerical study of benchmark cases of solidification and melting was undertaken, and the results of these investigations are presented in this project. Numerical analysis is conducted to examine the brief solidification process of a pure liquid phase-change material within a rectangular enclosure when natural convection is present. The horizontal boundaries are both taken to be adiabatic, with one vertical barrier maintained at a temperature below the material's melting point and the other above. In this work, a numerical investigation of the melting of wax (namely N-octadecane) is presented. The numerical simulations of the experiments were carried out using STAR CCM+, and the results were compared with the results of other numerical simulations (FLOW 3D). The numerical simulations of gallium melting were carried out with a commercial code, STAR CCM+, which captures the solid-liquid interface with a fixed grid. This software captures the solid-liquid interface for phase change simulations in complex geometries with the enthalpy formulation technique. In addition, it demonstrates that computational fluid mechanics has reached a state of development where it permits reliable flow computations with solidification and melting. Casting with metal melts can be studied to provide information to engineers during the design process of new casting tools. The available simulation tools can also be used to predict existing casting processes and determine the origins of defects. The key findings are as follows: The interface shape during the solidification of gallium from above is always determined in large part by anisotropy in heat conductivity and interface growth morphology. Natural convection in the liquid slows down the rate of melting and adds more complexity to the morphology and transport mechanisms at the interface.

1. Introduction

There are numerous engineering applications for improving heat transfer and fluid properties, including the use of nanotechnology [1-4], jet impingement technique [5-7], and phase change

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materials [8-10], which play a significant part in increasing the effectiveness of electronic equipment and cutting down on consumption. Enhancing heat transfer and fluid flow characteristic is one of the most promising strategies to maximize heat recovery in engineering and industrial applications [11-16] and to optimize heat transfer equipment.

A thermoeconomic- environmental model was studied by Yan *et al.,* [17] in order to optimize the energy efficiency of a waste heat recovery system with integrated phase change materials (PCM) in greenhouses. For heating systems fitted with PCM HRS and HRSs, the 2nd law efficiency rose by 127% and 263%, respectively, while the mean energy efficiency increased by 40% and 33%. The temperature of the exhaust gas and inside air changed by -8.2% and +17%, respectively, using PCM HRS. With investment return periods of three and four months, the fuel savings achieved by implementing HRS with and without integrated PCM are 19% and 48%, respectively.

Sadr and associates [18] Simulate the mixed convection of water and nano-encapsulated phase-changing material into a square cavity using a rotating, heated cylinder. Phase change material (PCM) in the core is encased in a solid shell to improve base fluids' thermal properties. The latent heat of the NEPCM core causes a significant increase in the heat content and heat transfer rate of the nanofluid. A particular temperature range is also where a phase transition occurs. In this work, n-nonadecane and polyurethane, accordingly, represent the core and shell of NEPCM. According to the findings, adding NEPCM can increase the Nusselt number by over 13%.

Miansari *et al.,* [19] investigation looks into how phase-change materials' thermophysical characteristics affect melting. Using phase-change materials (PCMs) to investigate thermal energy storage inside a double-wall tank, the melting of PCMs was reduced from 60% to 80% in about 8 hours after adding fins. In the water zone, raising the inlet temperature from 340 to 360 K greatly shortens the phase-change material's melting time; after around 8 hours, the percentage of melted material increased from 67 to 87%; the Reynolds number has no discernible impact on this process. The results show that employing materials with lower specific heat and melting temperatures reduces melting time.

Using the enthalpy-based lattice Boltzmann method (LBM), Jourabian *et al.,* [20] investigated the NePCM melting in the inclined oval ring. It is necessary to determine the efficacy of heat transfer optimization approaches such as the incorporation of copper nanoparticles and a porous metal matrix into this heat storage system. Due to improved conduction heat transfer, it was discovered that inserting nanoparticles is the most effective way for increasing the liquid percentage in the oblate annulus. For prolate and inclined layouts, a porous matrix is recommended. As a thermal storage unit, it eliminates a relatively stable stratification at the bottom of the elliptical annulus.

Bayat *et al.,* [21] investigated numerically the performance of finned heat sinks with nano enhanced phase change material (NePCM). The effects of adding copper oxide and aluminum oxide nanoparticles to paraffin PCMs on low thermal conductivity were explored. The results suggest that adding a low fraction of nanoparticles (2%), improves heat sink performance. However, raising the volume percentage of nanoparticles to 6% not only does not improve, but substantially degrades heatsink performance.

Acoustics, electrochemistry, and electromagnetic, fluid dynamics, heat transfer, particle fluxes, rheology, multi phase flows and solid mechanics, reactive flows can all be modeled with Star-CCM. A package of multidisciplinary engineering simulations is called STAR-CCM+. It was developed by Siemens [22–24]. Complex system design and analysis are increasingly being driven by computer simulations. With its approach to modeling fluid flow phenomena, computational simulations are now acknowledged as a part of the spectrum of computer-aided engineering (CAE) Widely used instruments in today's industries. This gives technical analysts and equipment designers the power of a virtual wind tunnel on their desktop computer. Software for computational simulation has

advanced well beyond the dreams of Navier, Stokes, and Da Vinci. Numerical simulation is known to provide an advantage over experimental. Despite these advancements, some of the main problems with fluid dynamic simulations remain, such as accuracy [25,26].

The objective of this research is to explore the dynamic melting behavior of paraffin and gallium by comparing the outcomes of numerical simulations using STAR CCM+ and Flow 3D.. The following is how the paper is structured: Section 1 introduces Melting and solidification, Problem Formulation, Gallium melting, and wax (a paraffin) melting. Section 2 presents the mathematical formulation, and the governing equations. The numerical system is presented in Section 3. Section 4 depicts the results and discussions with thorough analysis for the different cases; Section 5 depicts the conclusions; and Section 6 is devoted to the future perspective (future recommendations).

1.1 Melting and Solidification

The previously described current numerical techniques were generally used to simulate individual melting or solidification problems, and only recently were they used to simulate alternating melting and solidification cycles by Wang *et al.,* [27]. On the other hand, cyclic or periodic melting and solidification matters have drawn a lot of attention in the literature. Numerically periodic melting in a square enclosure was studied by Voller and Ho and Chu [28,29]. Recently, Hosseini and others. A previous study [30] reported experimental research on the melting and solidification of a cylindrical PCM during the charging and discharging process by Gosselin and chabot [31] conducted an analytical study on the impact of periodic boundary conditions and alternating cooling and heating in a cylindrical PCM.

A high accuracy numerical model was utilized by Rakotondrandisa *et al.,* [32] to simulate a phase-change material's (PCM) alternate cycle of melting and solidification to solve a single-domain model based on the Navier-Stokes-Boussinesq equations. The first study case covers total melting of the PCM (95%) and lastly, total solidification. In the second scenario, solidification occurs after a partial melting (liquid component of 50%). During the melting-solidification process, different regimes are found and explained through scaling correlation analysis.

Solutal phase transition is an isothermal diffusion-controlled process that will result in either solidification of the liquid or melting of the solid under specific process conditions. The direction and pace of the liquid-solid interface's evolution are determined by maintaining equilibrium. Phase change of metals and alloys numerical modeling is still one of the hardest challenges in materials science. This is because it's necessary to solve a coupled, highly non-linear free boundary issue at the same time as predicting the future location of the unknown liquid-solid interface [33]. In manufacturing processes like crystal growth, surface alloying, dip forming, spray coating, casting, welding and printed circuit electronics fabrication, solidification and melting are crucial steps.

Heat transmission to and from both phases on either side of the interface is what causes phase shifts in the material in all of these processes. These result in solidification when the net heat is subtracted and melting when the net heat is added to the solid portion of the interface. The total heat transport problem is commonly known as the Stefan problem [34]. The observable additional heat that is involved in the phase transition is known as the latent heat. Shabgard *et al.,* [35] created a thermal network model to mimic the charging (melting) and discharging (solidification) of a high temperature system LHTES (Latent heat thermal energy storage) [36], driven by applications utilizing concentrated solar power.

As a result, partial melting is not optimum. When a shorter discharge period is required, external cooling measures must be used to provide a cooler discharge temperature. the inability of thePCM systems to entirely discharge during night-time. However, if the PCM does not completely harden,

the system's effectiveness may be significantly decreased. It is not recommended in this scenario to completely melt the PCM in order to have a shorter cooling period. However, for solar energy storage applications, the PCM must be completely melted in order to use its latent heat storage capability.

1.2 Problem Formulation

The authors studied two sections in order to validate the solidification and melting processes with STAR CCM+. The first problem simulated with STAR CCM+ is gallium melting, and the thermophysical characteristics and boundary conditions were explored numerically in this study. The quantitative validation of applicable models and numerical approaches of STAR CCM+ for melting wax (N-octadecane) (paraffin) is described in the second part of the research. The growth of the solid-liquid interface during melting in a rectangular chamber is essentially three-dimensional and is converted to a two-dimensional shape, hence the numerical simulation using STAR CCM+ is carried out using a two-dimensional assumption with symmetry boundary conditions in the Y-direction. Figure 1 depicts the general configurations of both issues [37,38]. Table 1.

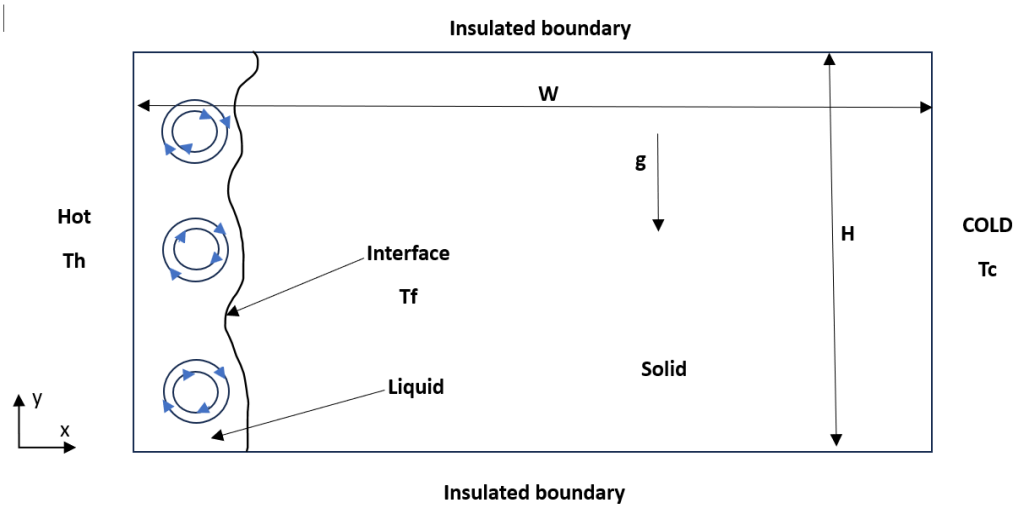


Fig. 1. A schematic view of the test cases [37]

Table1
Dimensions of the rectangular chamber of aspect ratio 1.0 [37]

Property	Symbol	Value	Units
Length	X	168	mm
Width	Y	80	mm
Height	Z	80	mm

1.3 Gallium Melting

The challenge at hand concerns the melting of pure gallium. The Prandtl number (Pr = v/), global aspect ratio (A = H/L), and temperature gradient in the cavity characterize this challenge. At a homogeneous temperature T0 = Tl = 28.3C, a two-dimensional cavity is initially filled with a solid material. At time t = 0, the temperature of one of the vertical walls (the left wall in the instance of gallium melting in the Figure 1 above is raised to T1 = 38.0C > Tl, while the temperature of the other vertical wall remains constant at T0. It is assumed that the horizontal walls are adiabatic and have no

slide. Table 2 shows the thermophysical characteristics of gallium employed in the melting simulation.

Table 2
Properties of gallium used in the melting simulation

Property	Symbol	Value	Units
Melting temperature	T_l	29.78	° C
Thermal conductivity	λ	$3.2 \times 10^{+6}$	dyn cm^{-1} K^{-1}
Density	ρ	6.093	gm cm^{-3}
Dynamic viscosity	μ	1.81×10^{-2}	dyn s cm^{-2}
Thermal expansion coefficient	β	1.2×10^{-4}	K^{-1}
Specific heat	C_p	$3.81 \times 10^{+6}$	dyn gm^{-1} K^{-1}
Latent heat of fusion	ΔH	$8.02 \times 10^{+8}$	dyn gm^{-1}
Prandtl number	Pr	0.02	-

1.4 Wax (a Paraffin) Melting

The challenge at hand concerns the melting of a pure material, specifically (N-octadecane). Melting difficulties are often dominated by conduction in the early stages of the melting process and spontaneous convection later in the process. At a constant temperature T0 = Tl = 20 C, a two-dimensional cavity is initially filled with a solid substance. At time t = 0, transient heat flow is given as boundary conditions at one of the rectangular chamber's vertical walls (left wall in the case of melting in Figure 1 above, while the other vertical surface is kept insulated. The horizontal surfaces are also examined to ensure that they are near to being insulated. Table 3 shows the thermophysical characteristics of paraffin employed in the melting simulation.

Table 3
Thermo-physical properties of N-octadecane [31]

Property	Symbol	Value	Units
Melting temperature	T_m	28	° C
Density at 20 °C	P_{20}	778	kg m^{-3}
Density at 50 °C	P_{50}	762.4	kg m^{-3}
Dynamic viscosity	μ	3.813×10^{-3}	N s m^{-2}
Thermal expansion coefficient	β	0.001	K^{-1}
Thermal conductivity	λ	0.1493	W m^{-1} K^{-1}
Specific heat	C_p	1.6498	J kg^{-1} K^{-1}
Latent heat of fusion	ΔH	355.32	J kg^{-1}
Surface tension at 30 °C	σ_{30}	27.59×10^{-3}	N /m
Surface tension at 50 °C	σ_{50}	25.92×10^{-3}	N /m

2. Mathematical Formulation

The researchers take into consideration, as illustrated in Figure 1, a rectangular enclosure with width W and height H that initially holds liquid at temperature T_{hot}. The liquid then begins to solidify when the temperature at x = 0 is lowered to $T_{cold,}$ where T_{cold} is the solid material's melting temperature. The horizontal walls at y = 0 H are adiabatic, but the wall at x = W is kept at T_{hot} temperature throughout. Over time, it is expected that a solid layer and a natural convection flow pattern will form; x = s(y, t) determines the location of the solid–liquid interface.

2.1 Governing Equation

Regarding the area, we have :

$$\rho_s C_{ps} \frac{\partial T_s}{\partial t} = k_s \left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} \right) \tag{1}$$
$$0 \le x \le s(y,t)$$

that is, the transient heat conduction equation. Applying the Boussinesq approximation to the transient mass, heat transfer equations and momentum for the liquid area, s(y, t) < x < W, gives us.

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0, \tag{2}$$
$$\rho_{l.melt} \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \tag{3}$$
$$\rho_{l.melt} \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \rho_{l.melt} \beta g \left(T - T_{melt} \right) \tag{4}$$
$$\rho_{l.melt} C_{pl} \left(\frac{\partial T_1}{\partial t} + u \frac{\partial T_1}{\partial x} + v \frac{\partial T_1}{\partial y} \right) = k_1 \left(\frac{\partial^2 T_1}{\partial x^2} + \frac{\partial^2 T_1}{\partial y^2} \right) \tag{5}$$

In Eq. (4), we have applied the expression ρ1, to the liquid density.

$$\rho_l = \rho_{l.melt} \left(1 - \beta \left(T - T_{melt} \right) \right); \tag{6}$$

We made the assumption that all other physical attributes were temperature-independent for simplicity's sake. Eq. (1) – Eq. (5) transform into;

$$St \frac{\partial \theta_s}{\partial t} = \left(\frac{\partial^2 \theta_s}{\partial x^2} + \frac{\partial^2 \theta_s}{\partial y^2} \right)$$
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0,$$
$$\frac{\Lambda}{\Pr} \frac{\partial u}{\partial t} + \frac{1}{\Pr} \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2},$$
$$\frac{\Lambda}{\Pr} \frac{\partial v}{\partial t} + \frac{1}{\Pr} \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial x} + \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + Ra\theta_1,$$
$$\Lambda \frac{\partial \theta_1}{\partial t} + u \frac{\partial \theta_1}{\partial x} + v \frac{\partial \theta_l}{\partial y} = \frac{\partial^2 \theta_1}{\partial x^2} + \frac{\partial^2 \theta_1}{\partial y^2}$$

where the Rayleigh number (Ra), the Prandtl number (Pr) and the Stefan number (St) are given as follow:

$$Ra = \frac{\rho^2_{l.melt} \beta g C_{pl} \left(T_{hot} - T_{melt}\right)}{\mu k_1}, pr = \frac{\mu C_{pl}}{k_1},$$
$$St = \frac{C_{ps} \left(T_{melt} - T_{cold}\right)}{\Delta H_f},$$

And

$$\Lambda = St\left(\frac{k_s}{k_1}\right)$$

where the liquid and solid thermal diffusivity, ks and kl, are given respectively by [35]

$$k_s = k_s / \rho_s C_{ps}, k_1 = k_1 / \rho_{l,melt} C_{pl}$$

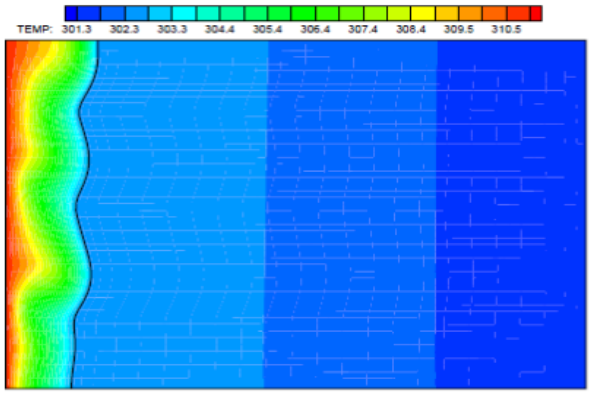
3. Numerical Simulation

The employed numerical mesh consisted of 160 cells for Gallium, a paraffin. The details of the applied numerical methods within STAR CCM+ are as follows:

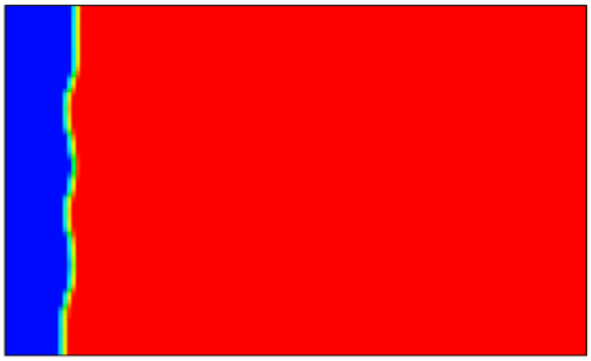
i. The gravity is in the z direction.
ii. The initial time step is 0.01 sec.
iii. The time step during computation is adjusted automatically taking the minimum time step from the viscous time step, convective time step and the Courant time step.

4. Result and Discussion

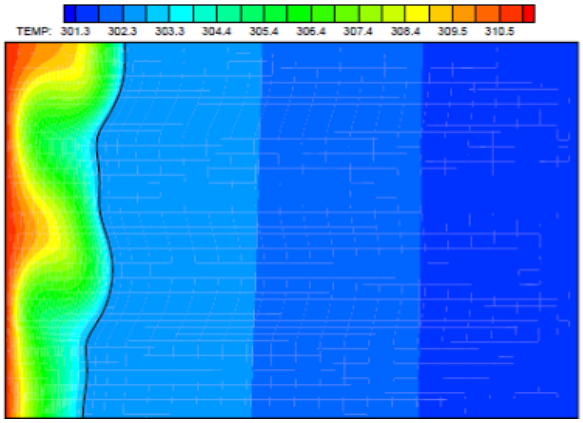
The primary goal of this comparison is to contrast the outcomes of STAR CCM+'s complete numerical simulation with the simulation of FLOW 3D. The authors begin by presenting some outcomes from the comprehensive numerical simulation of Gallium melting. Figure 2 shows Solid-liquid interface during gallium melting at different times.



(a) FASTEST3D computation at time = 2 min

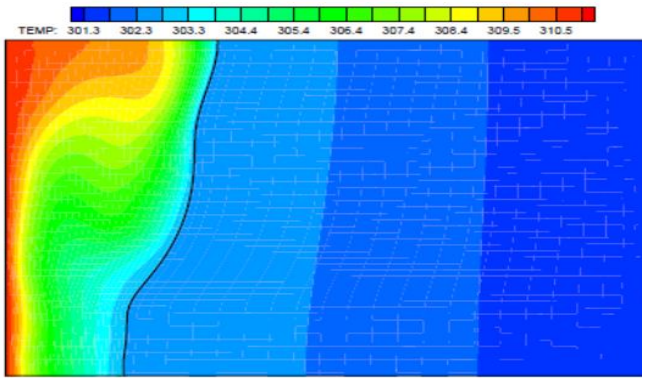


(b) FLOW3D validation at time = 2 min

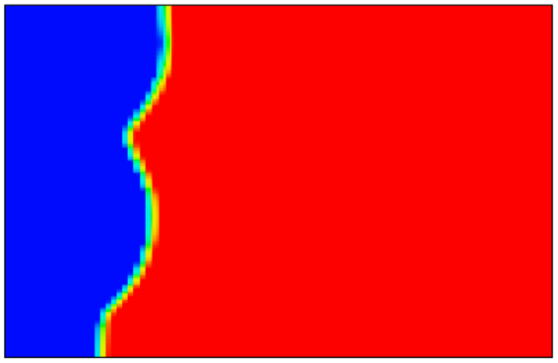


(c) FASTEST3D computation at time = 3 min

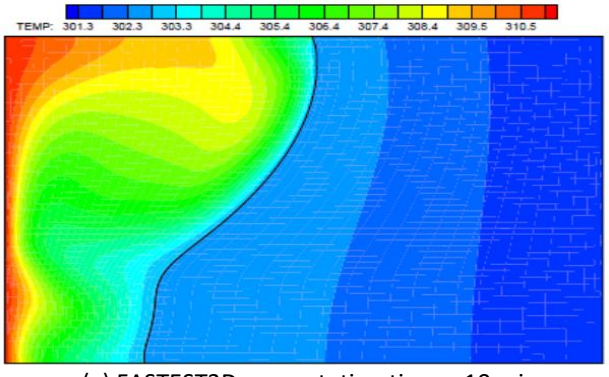
(d) FLOW3D validation at time = 3 min



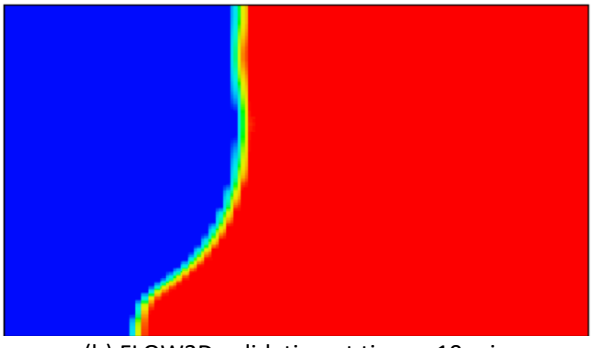
(e) FASTEST3D computation at time = 6 min



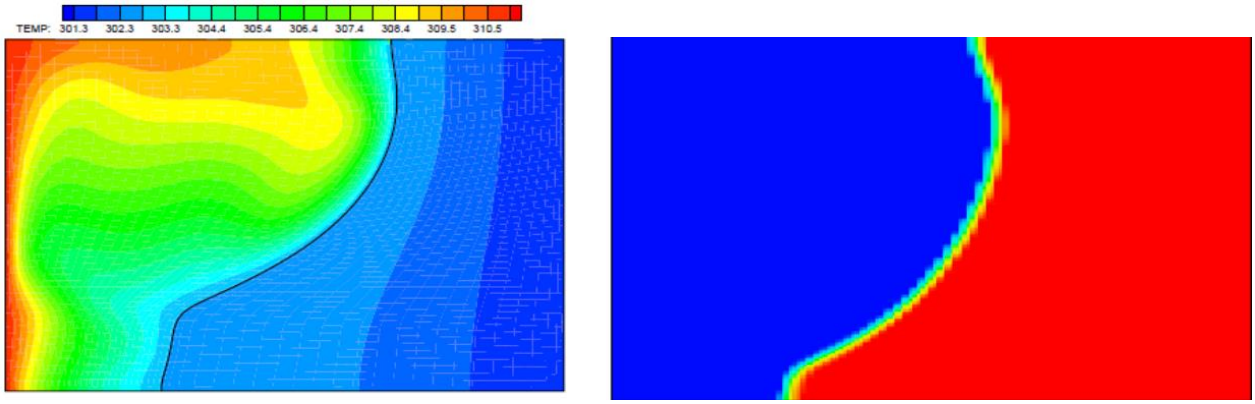
(f) FLOW3D validation at time = 6 min



(g) FASTEST3D computation time = 10 min



(h) FLOW3D validation at time = 10 min

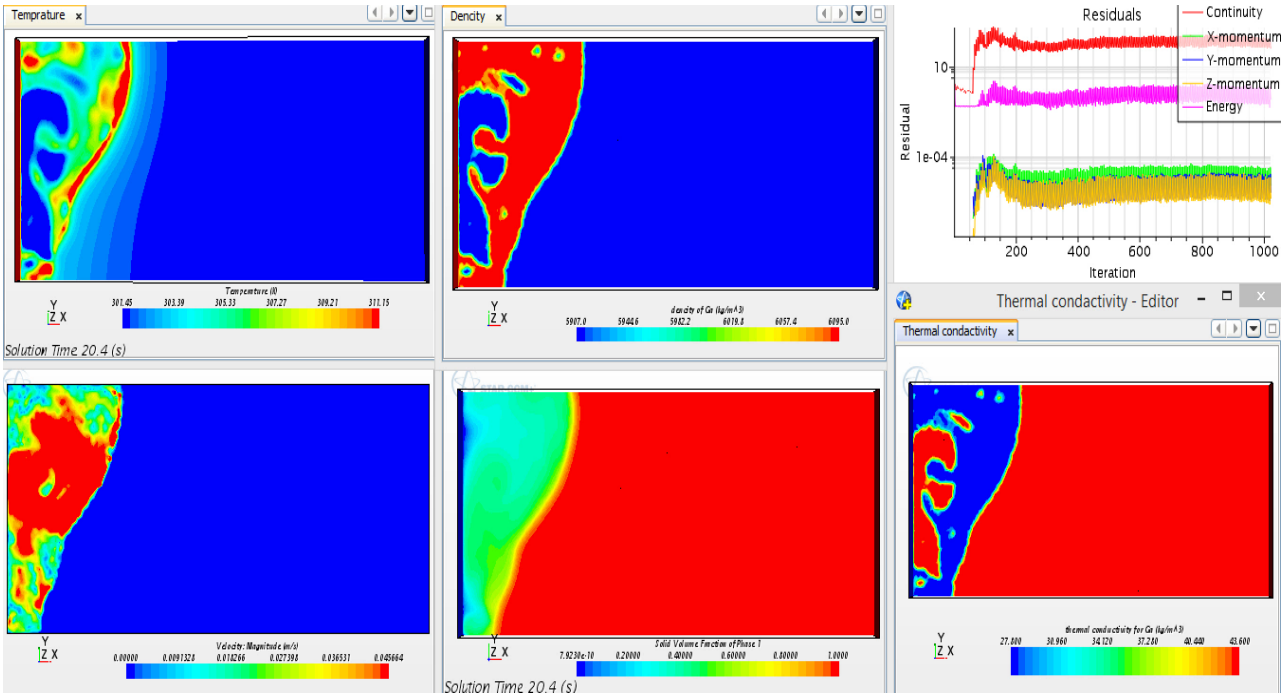


(i) FASTEST3D computation at time = 15min (j) FLOW3D validation at time = 15 min

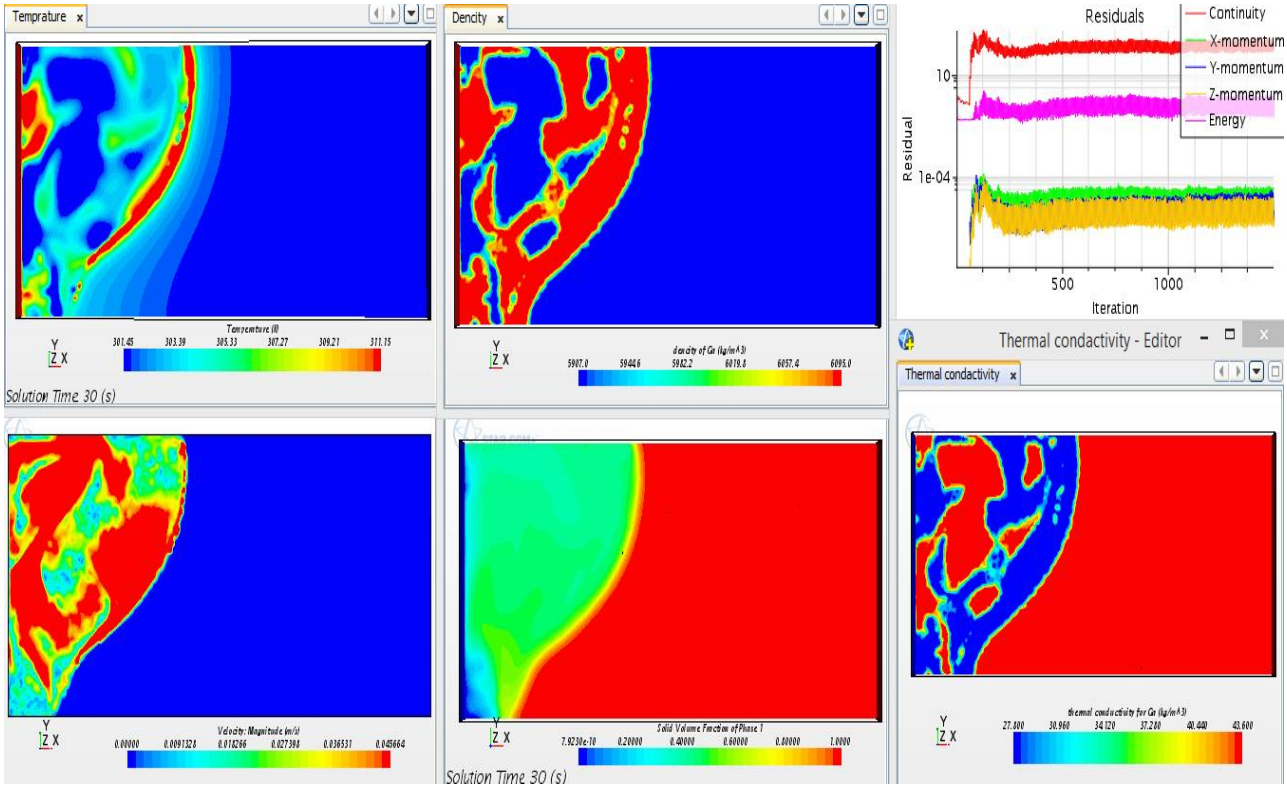
Fig. 2. Solid-liquid interface during gallium melting at different times

Figure 3 shows Solid-liquid interface during gallium melting at different times. Gallium computation times were significantly longer, owing to its substantially smaller Prandtl number than paraffin. Vertical stratification between the heated wall on the right and the front's thermal boundary layers during solidificatio. Although Figure 4 appear to be identical, there is a difference in melting time.

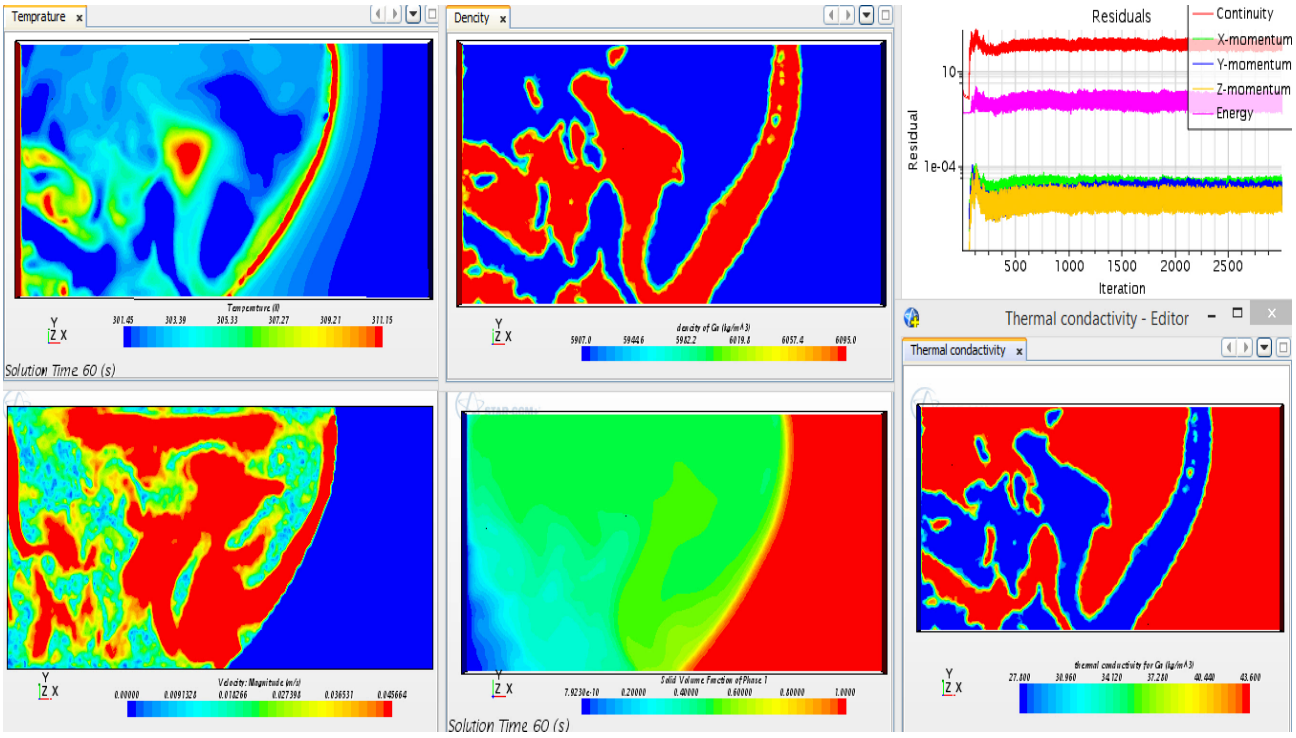
This point, as we will see in later figures, decides when a steady-state is finally reached. Second, for the paraffin melting, we show some results from the whole numerical simulation.



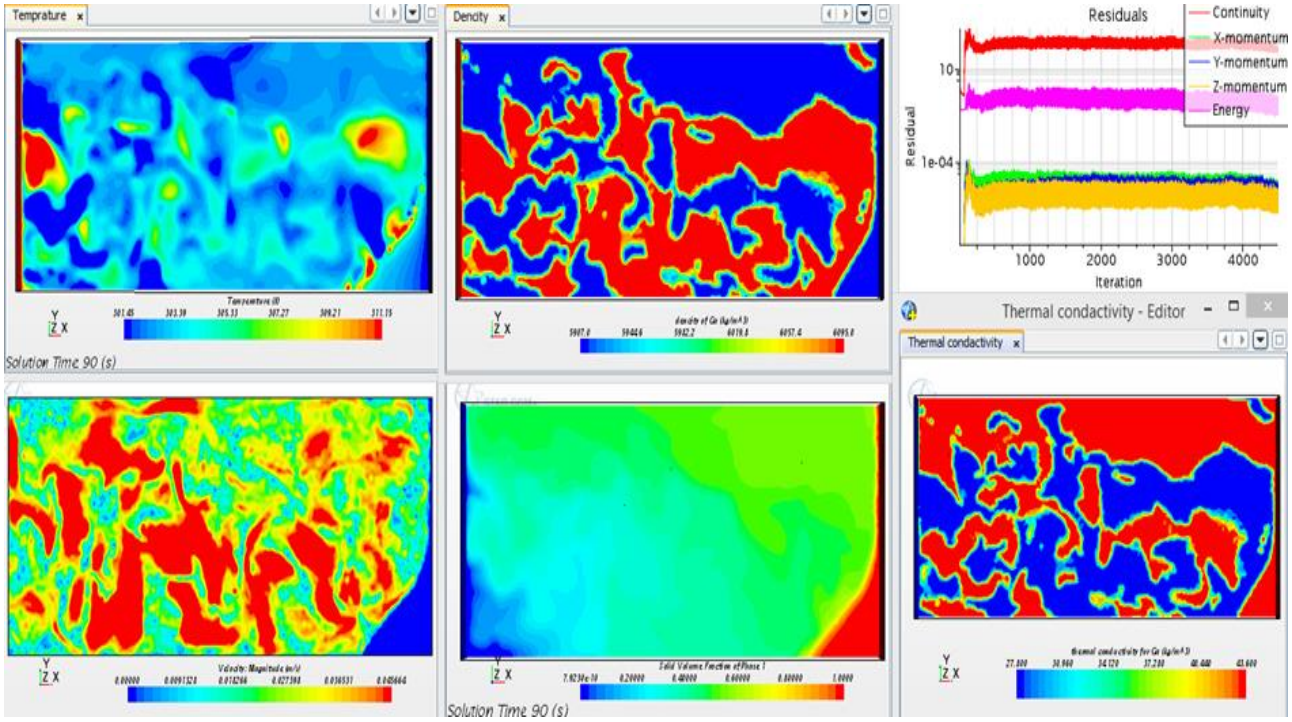
(a) STAR CC M+ validation at time = 20(s)



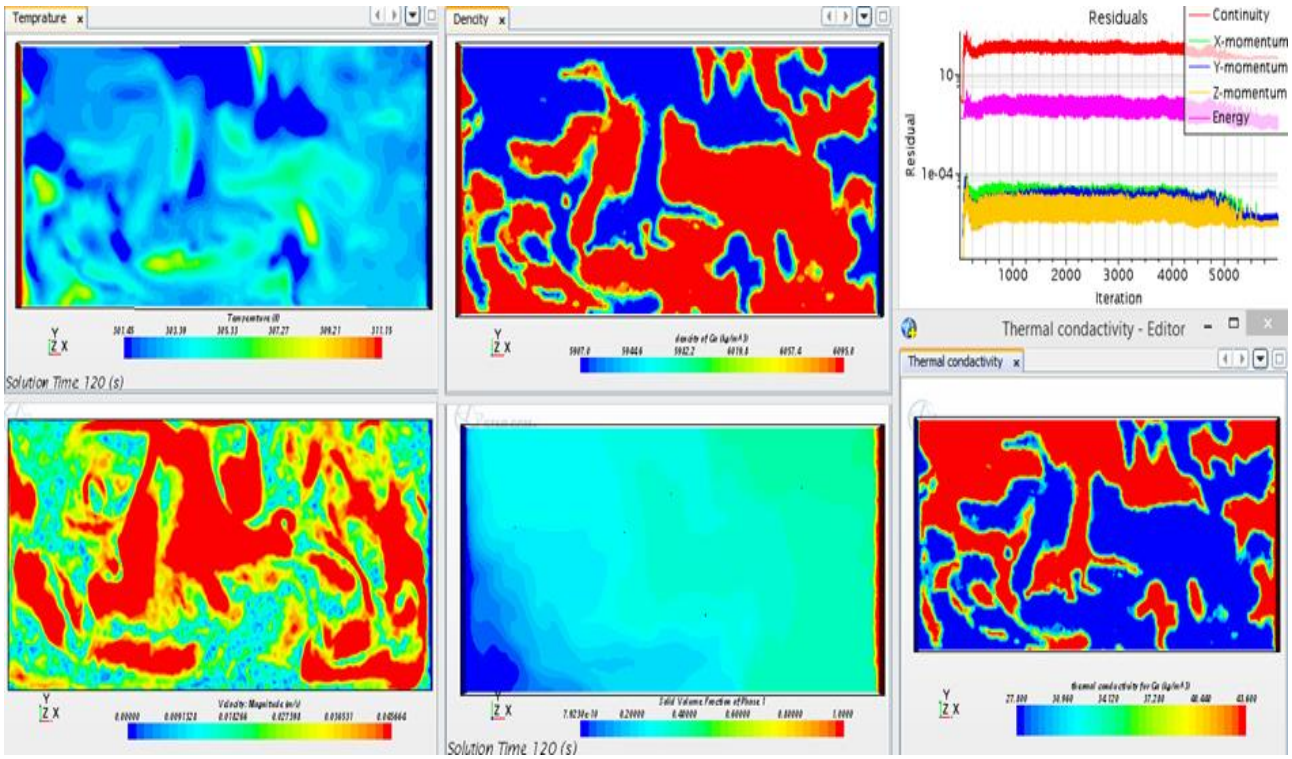
(b) STAR CC M+ validation at time = 30(s)



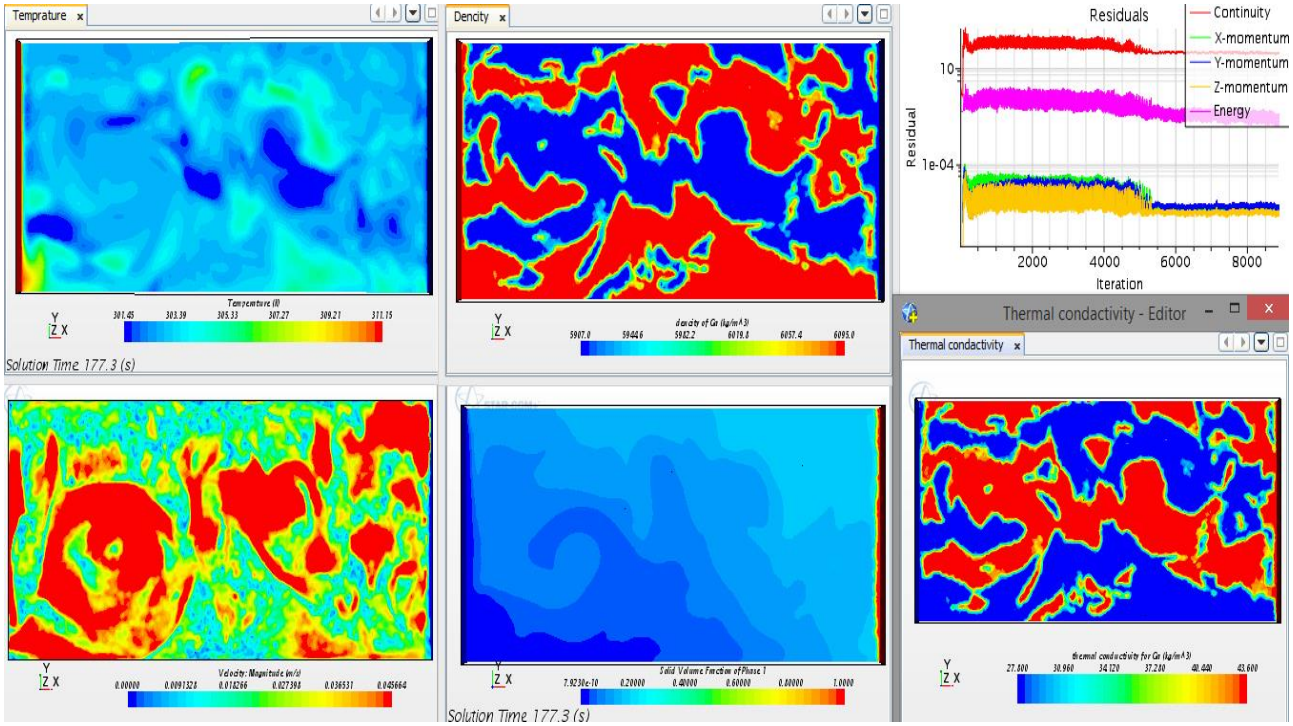
(c) STAR CC M+ validation at time = 60(s)



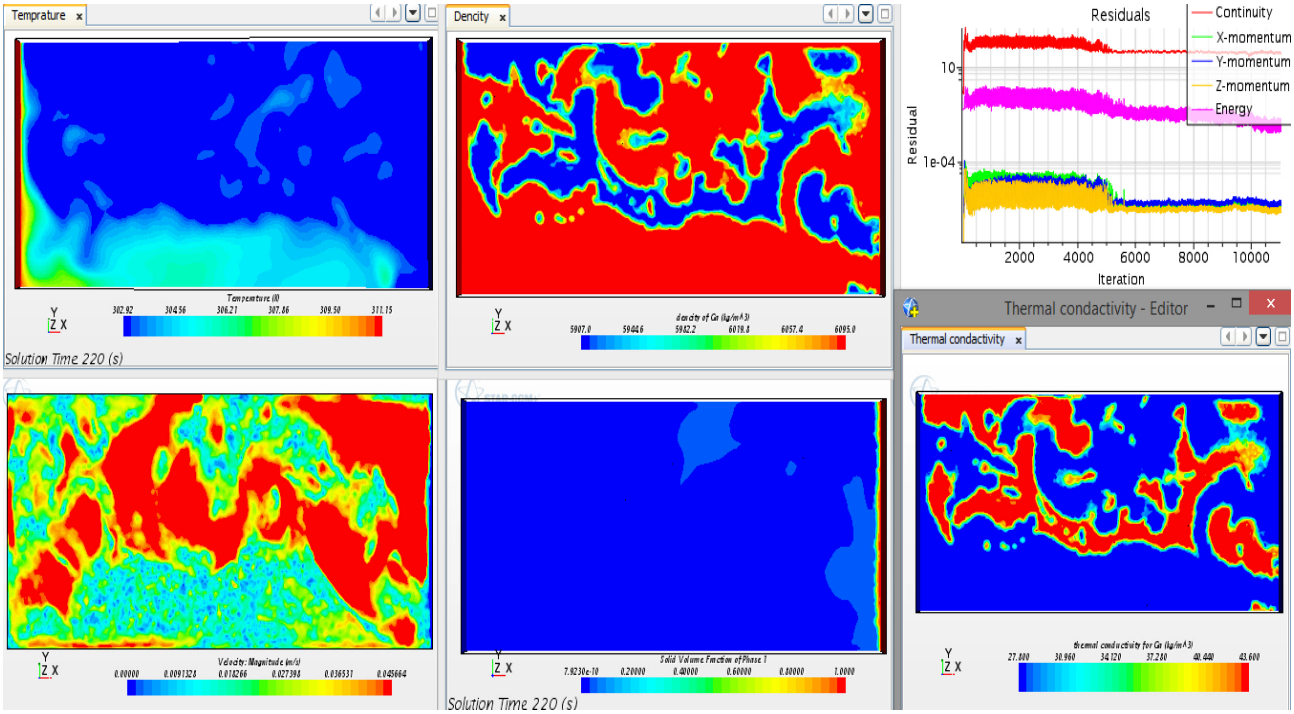
(d) STAR CC M+ validation at time = 90(s)



(e) STAR CC M+ validation at time = 120(s)

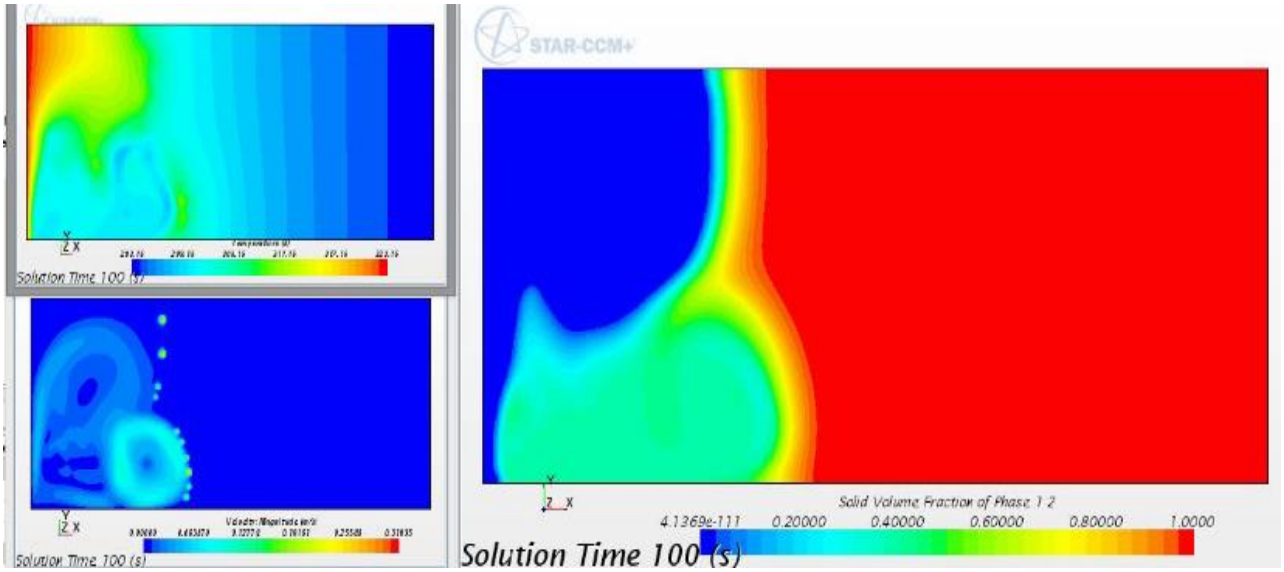


(f) STAR CC M+ validation at time = 177.3(s)

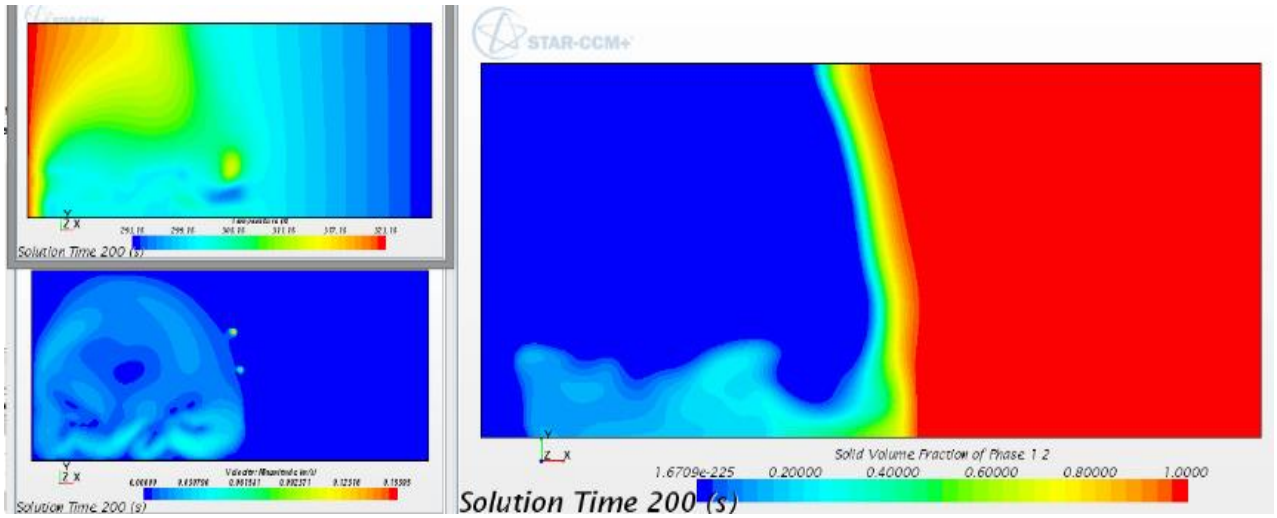


(g) STAR CC M+ validation at time = 220(s)

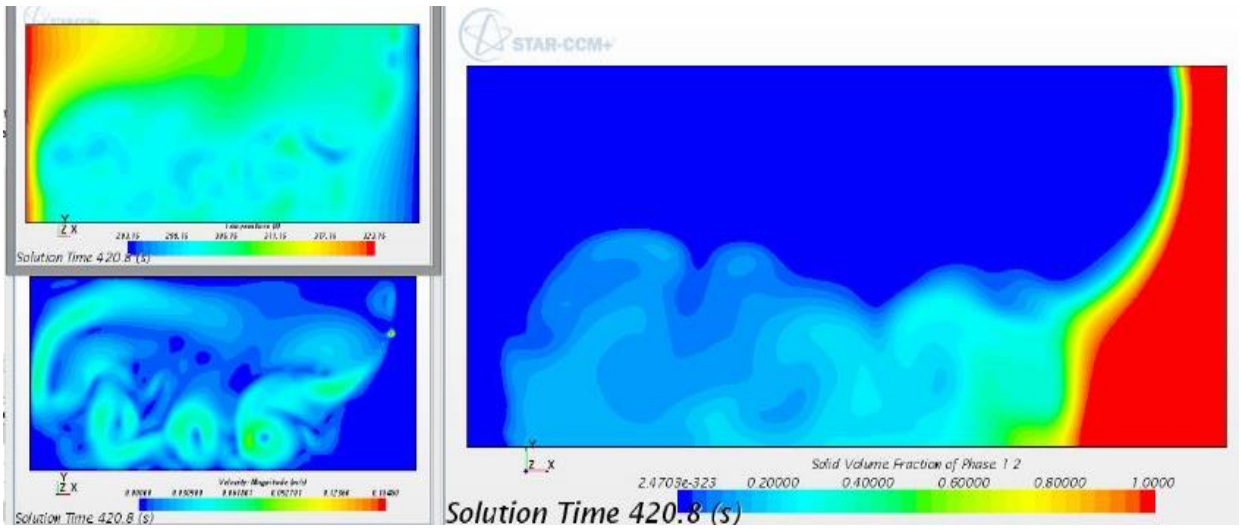
Fig. 3. Solid-liquid interface during gallium melting at different times



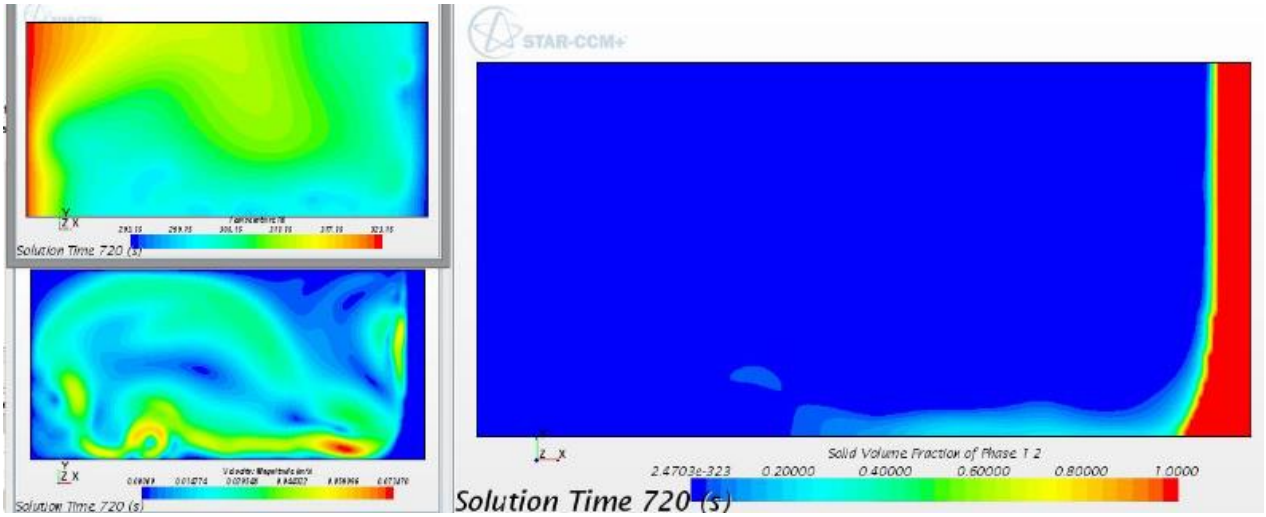
(a) Starccm+ validation at time =100 s



(b) star ccm+ validation at time =200 s



c) starccm+ validation at time =420 s



d)starccm+ validation at time =720 s

Fig. 4. Temperature and velocity vector field during paraffin melting at different times

Optimizing the process and the end product microstructure requires careful consideration of process factors like temperature, time, and solute concentration. Consequently, it is not unexpected that numerical modeling plays a crucial role in determining how procedure parameters affect the interfacial dynamics during phase transformation. Numerical analysis is particularly difficult because of the intricate topological evolution of the interface and the treatment of interfacial dynamics like splitting and merging [34]. Low heat conductivity is a characteristic shared by several of the phase change materials (PCMs) that are typically taken into consideration, including paraffins, hydrated salts, and salt mixes.

As a result, various tactics are taken into consideration to raise the rate of heat transfer of devices that use PCMs. Capturing PCM in capsules to get a high surface-to-volume ratio is one of the most researched methods for thermal improvement. The evolution of the solid-liquid interface's form and melting rate has been observed to be significantly influenced by natural convection effects during the melting of PCMs encased in various mesh types and time steps. In addition to the fluid phase dynamics and heat transfer phenomena involved [39,40].

The impact of two different fins and hybrid nanoparticles (MoS_2-TiO_2) on solidification in a triplex latent heat thermal energy storage system has been investigated by Hosseinzadeh *et al.,* [41]. The findings show that, although the use of both tree-like fins and nanoparticles reduces the solidification time by 78% when compared to bare tube, tree-like fins claim the best performance, taking 1700 s, followed by rectangular fins with 3500 s in the absence of nanoparticles. also, Hosseinzadeh *et al.,* [42,43] have simulate the influence of hybrid nanoparticles and internal fins on the solid process in a triplex latent heat thermal energy storage system shaped like a star. The results show that utilizing each strategy independently results in a significant improvement, while combining both techniques lead in the lowest solidification rate. Furthermore, the comparisons made in this paper show that when compared to the results of HNPs alone, fins perform better. Furthermore, According to the findings, the total solidification time can be lowered by up to 12% when fins and HNPs are used, and the total solidification time can be lowered by up to 4% more when lamina-shaped HNPs are used than brick-shaped HNPs.

The outcomes were contrasted with Song *et al.,* [44] solid melting computational approach in their validation of the method for reactor vessel ablation under external reactor vessel cooling conditions. An experiment that already exists for gallium melting in a two-dimensional cavity was used to validate the computational method of solid melting. The findings show that the present

computation of melt front advancement agrees well with experimental data and current simulations. In addition, when compared to Racotondrandisa *et al.,* [45] numerical technique, Numerical simulation of a phase-change material's melting-solidification cycle with complete or partial melting to simulate the alternating melting and solidification cycles of a phase-change material (PCM), a high-accuracy numerical model is used. The fundamental structure of a differentially heated square cavity filled with octadecane paraffin was explored, and the numerical system was validated using experimental and numerical results from the literature. The instances are thoroughly examined, with the time evolution of the solid-liquid interface, liquid fraction, Nusselt number, and accumulated heat input provided. Using scaling correlation analysis, different regimes are detected and explained during the melting-solidification process. In comparison to the previous two experiments [44,45], anisotropy in heat conductivity and interface growth morphology are consistently important in determining the interface shape during gallium solidification from above. Natural convection in the liquid lowers the melting rate and complicates the transport processes and interface morphology in defining interface shape even more. As can be seen, the results are in good agreement.

5. Conclusions

The authors of this study examined the melting of a phase-change material (PCM) in a rectangular enclosure with natural convection numerically. The methodology described here can be used to understand melting via time-dependent heating as well, even though the numerical results presented here were for melting that resulted from heating at a vertical boundary held at a constant temperature. Numerical research has been done on the impact of natural convection on solid-liquid phase-change heat transfer in gravitationally unstable conditions (melting from the left and solidification from the right). It is permitted to use pure metals (paraffin and gallium). The study's conclusions are based on the data that were collected. During the solidification of gallium from above, anisotropy in the thermal conductivity and the interface growth morphology are always important in controlling the interface shape. The liquid's natural convection slows the melting rate and increases the intricacy of the transport and interface morphology processes. The researchers evaluated numerous past studies relating to the issue of the current study. The authors compared the results with others, and as can be seen, the results are pretty consistent.

6. Future Perspectives

This study was based on Simulation of solidification and melting processes of Phase change materials for paraffin and Gallium by using star CCM+. The review of earlier research in this field raises a number of intriguing unanswered questions, such as (i) determining the best design parameters to maximize heat transfer during charging and discharging cycles, (ii) using simulations to forecast PCM thermal performance under various operating conditions, and (iv) the practical and financial implications of the suggested methods. A rising trend in recent years has been to look at how PCMs and heat sources might enhance heat transmission for a variety of industrial applications. Numerous studies have been published in this area that examine the use of various improvement techniques.

As far as the writers are aware, no thorough review has been done to emphasize how PCMs and nano-enhanced PCMs (NEPCMs) perform in terms of thermal storage at different container geometries. The literature lacks comprehensive analyses of the numerous conclusions from diverse experimental and numerical studies pertaining to the impact of these methods. This research seeks to evaluate the emerging trends in improving the rate of heat transfer and reducing the

melting/solidification time of PCMs/NEPCMs for various industrial applications, given their notable contribution to improved heat transfer [46, 47]. Additionally, a number of concerns have been raised by previous studies [48, 49] regarding the PCM systems' inability to fully discharge at night. However, if the PCM does not fully harden, the system's effectiveness could be significantly diminished. It is not recommended to fully melt the PCM in this situation in order to shorten the cooling time. To use the PCM's latent heat storage capacity, however, complete melting is required for solar energy storage applications. A partial melting is therefore not ideal. In other cases, external cooling methods must be used to maintain a lower discharge temperature when a shorter discharge duration is required [50].

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