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Analysis of Melting Behavior on Phase Change Material in a 2D Square Cavity

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This study investigates the melting behaviour of a phase change material (PCM) in a square cavity using Computational Fluid Dynamics (CFD). A 2D cavity heated from one side is simulated using the enthalpy-porosity method implemented in ANSYS Fluent. The numerical model solves the continuity, momentum, and energy equations with latent heat consideration, tracking the liquid fraction evolution over time. A structured mesh with varying resolutions is tested, with grid independence confirmed at 60×60 cells. Results include temperature contours, velocity vectors, and liquid fraction plots, capturing the transition from conduction-dominated to convection-driven melting. Model convergence is validated through residual analysis and comparison with benchmark data from Brent et al. and Lankadasu et al., showing deviations within 5%. The study demonstrates the effectiveness of the enthalpy-porosity model in simulating PCM melting and highlights the influence of mesh resolution, Rayleigh number, and timestep size on solution accuracy. Potential enhancements include adaptive meshing and experimental validation.

Keywords: Enthalpy-Pororsity Method; Melting Simulation; Natural Convection

1. INTRODUCTION

The melting of phase change materials (PCMs) plays a critical role in thermal energy storage, electronics cooling, and building energy management. Accurately modelling this process using Computational Fluid Dynamics (CFD) enables a deeper understanding of the heat transfer mechanisms,including conduction and natural convection. This study aims to simulate the melting behaviour of a PCM in a square cavity heated from one side and evaluate the results in terms of accuracy and convergence. Phase change materials have gathered significant attention as promising candidates for thermal energy storage and management in diverse engineering applications, including solar energy utilization, electronic device cooling, and building climate control [1]. The ability of PCMs to absorb and release substantial amounts of latent heat during phase transitions, such as melting and solidification, makes them particularly attractive for buffering temperature fluctuations and enhancing energy efficiency [2].

Computational Fluid Dynamics offers a powerful tool for simulating the complex heat transfer phenomena associated with PCM melting, enabling researchers and engineers to gain insights into the underlying physical mechanisms and

optimize system performance [3]. Accurate modelling of PCM melting requires consideration of both heat conduction within the solid and liquid phases and natural convection within the liquid phase, driven by temperature gradients. Furthermore, the accurate representation of the moving solid-liquid interface, which separates the distinct phases, poses a significant challenge in numerical simulations [4]. The enthalpy-porosity technique is frequently employed to address this challenge, wherein the PCM's latent heat is incorporated into an equivalent heat capacity, and the mushy zone, representing the partially melted region, is modelled as a porous medium [5]. The thermophysical properties of the PCM, including density, specific heat capacity, thermal conductivity, and latent heat of fusion, play a crucial role in determining the melting behaviour and must be accurately characterized for reliable simulations [6]. Moreover, the boundary conditions imposed on the computational domain, such as the heat flux applied to the heated wall and the temperature of the cooled walls, significantly influence the melting process and must be carefully specified.

2. MATERIALS AND METHODS

The present study focuses on simulating the melting behaviour of a PCM within a square cavity, where one vertical wall is subjected to a constant heat flux, while the opposite wall is maintained at a constant cold temperature, with the remaining walls being adiabatic. The CFD model is developed using a finite volume method-based solver, employing the enthalpy-porosity technique to track the moving solid-liquid interface [7]. The governing equations for mass, momentum, and energy conservation are solved iteratively until convergence is achieved, ensuring that the numerical solution accurately represents the physical phenomena occurring within the cavity [8]. A grid independence study is performed to determine the appropriate mesh resolution, balancing computational cost with solution accuracy, and various turbulence models are evaluated to capture the effects of natural convection within the liquid phase [6]. The selection of an appropriate time step size is also crucial for ensuring numerical stability and accuracy, particularly during the initial stages of melting when the solid-liquid interface is rapidly moving.

Furthermore, advanced interface capturing methods can be used to solve problems involving fluidsolid interfaces in the presence of multiphase fluid-fluid [9]. The thermophysical properties of the PCM are obtained from experimental measurements or reliable literature sources, and their temperature dependence is incorporated into the model to enhance accuracy. The model is validated by comparing the simulation results with available experimental data or benchmark solutions, ensuring that the numerical predictions are in good agreement with the physical reality [10]. Furthermore, prior research has not developed numerical simulations that comprehensively solve the governing equations of heat pipes, coupled with conjugate heat transfer in the PCM and fins, highlighting the novelty and importance of this study [11]. The capability of temperature adjustment with the inclusion of PCM can also be analyzed by comparing temperature distributions of pure materials with composite systems [12]-[16].

2.1. Related Equation

Existing literature provides a comprehensive overview of PCM melting simulations, highlighting various numerical techniques, model validation strategies, and applications in diverse engineering domains. Several numerical studies have investigated the melting process using various models, with the enthalpy-porosity method being one of the most used in CFD [17]- [32]. [33] proposed a technique for modelling phase change using a fixed grid approach, introducing a source term in the momentum equation to suppress velocity in solid regions.

2.1.1. Governing Equations

The Governing Equation for Conduction-Dominated Melting,

In cases where heat transfer within the material is dominated by conduction, the governing partial differential equation is a modified form of the heat equation:

$$\rho \frac{\partial H}{\partial t} = \nabla \cdot (k \nabla T) \quad \textbf{Equation 1}$$

H = is the total enthalpy (sensible + latent) ([J/m^3])
t = is time [s]
k = is the thermal conductivity [W/(m·K)]
T = is the temperature [K]

2.1.2. Navier-Stokes Equations (Momentum)

Energy equation, modified for latent heat absorption:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho \vec{v} h) = \nabla \cdot (k \nabla T) + S \qquad \textbf{Equation 2}$$

ρ = Density [kg/m3]
h = Specific enthalpy [J/kg]
∇ = Velocity vector [m/s]
T = Temperature [K]
k = Thermal conductivity [W/m·K]
S = Source term (e.g. internal heat generation)

$$h = h_{sens} + \Delta H_{latent} \cdot f_l \qquad \textbf{Equation 3}$$

Liquid fraction (fl) is tracked as a function of temperature.

2.2. Description Of Boundary Conditions, Geometry And Computational Software

2.2.1. Geometry

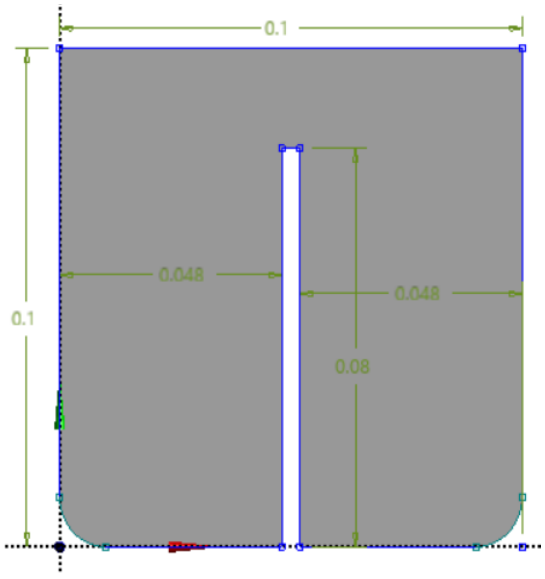

Figure 1. Geometry of PCM in meter (m) – Design 1

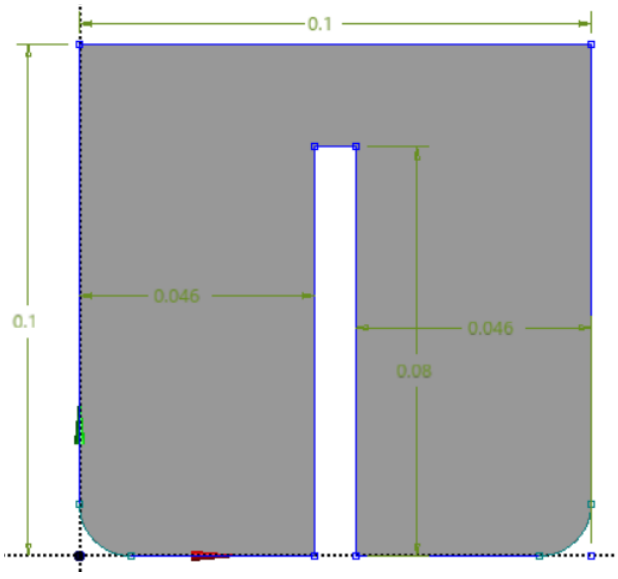

Figure 2. Geometry of PCM in meter (m) – Design 2

2.2.2. Materials Boundary Condition

Ice is used as fluid with 920 kg/m3 of density.

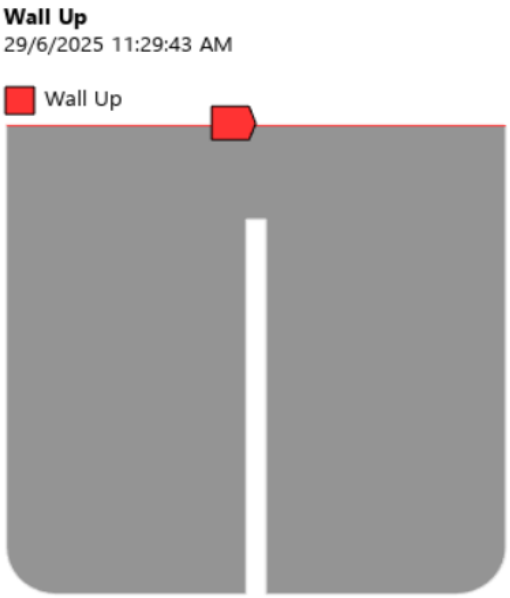

Figure 3. Wall up boundary condition setup with Temperature , T = 0 °C

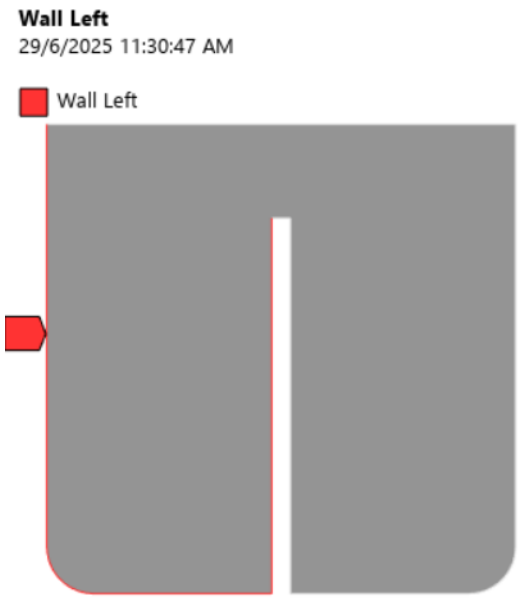

Figure 4. Wall left boundary condition setup with Temperature , T = 80 °C

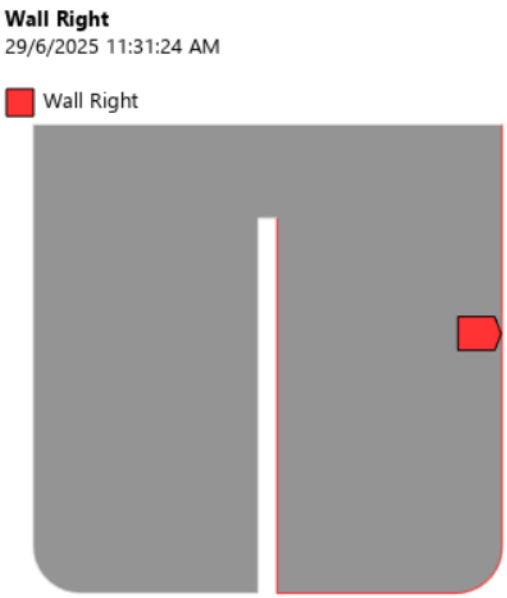

Figure 5. Wall Right boundary condition setup with Temperature , T = 80 °C

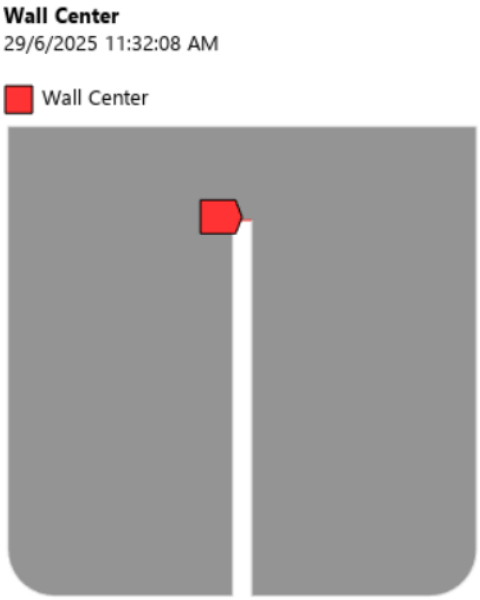

Figure 6. Wall Center boundary condition setup with Temperature , *T* = 80 °C

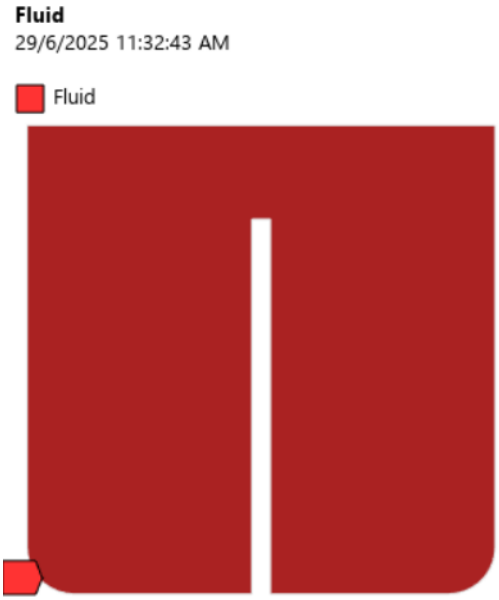

Figure 7. Boundary condition setup of PCM-Fluid (Ice)

2.2.3. Element Size Boundary Condition

Element size used 0.001 m.

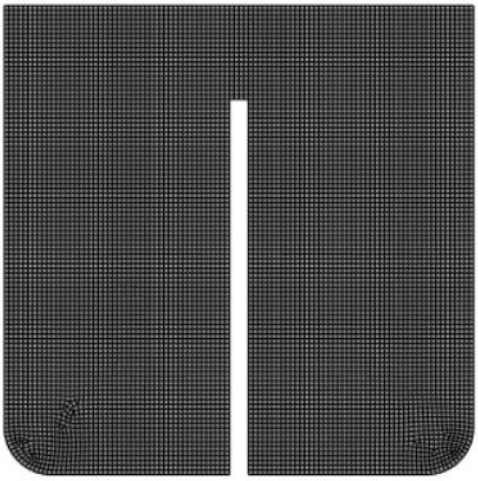

Figure 8. Meshing grid

2.3. Computational Fluid Dynamics (CFD) Software

In this analysis, ANSYS Fluent was utilized as the Computational Fluid Dynamics (CFD) software to simulate the behavior of Phase Change Material (PCM) during the melting and solidification processes. The enthalpy-porosity model was applied to represent the phase transition phenomena. Through this model, the mushy zone where the region between the solid and liquid phases was treated as a porous medium, with the porosity defined by the local liquid fraction. As phase change occurred, the liquid fraction was varied from 0 (solid) to 1 (liquid). The momentum equations were modified by introducing a source term to suppress the fluid velocity in the solid region, thereby enabling an accurate representation of the phase change interface.

There are parameters were considered during the simulation which are the governing equations for mass, momentum, and energy were solved, with latent heat incorporated in the energy equation. Temperaturedependent material properties such as thermal conductivity, specific heat, and latent heat were defined. Appropriate boundary conditions, including temperature or heat flux, were imposed to drive the phase change process.Then, a transient approach was used to capture the progression of the melting or solidification front over time. Moreover, the mesh was refined near the expected interface, and convergence criteria were established based on residual levels and energy conservation to ensure solution stability and accuracy. By using this approach, the distribution of temperature, liquid fraction, and heat transfer within the PCM domain was predicted. Useful insights were obtained for the enhancement and design of thermal energy storage systems incorporating PCM.

3. RESULTS

The temperature contour plots give us a clear picture of how the melting starts and spreads from the heated wall. As the wall gets hotter, it gradually melts the material nearby, and we can see the melted area slowly expanding outward over time. The liquid fraction plots help us track where the material is solid and where it's turned to liquid. These plots show how the boundary between solid and liquid shifts as the heat continues to flow, making it easier to understand how the phase change unfolds.

Meanwhile, the velocity vectors show how the liquid starts to move once parts of the material melt. As the temperature differences grow, natural convection currents begin to form, causing the melted liquid to circulate. This movement plays an important role in spreading the heat and speeding up the melting process.

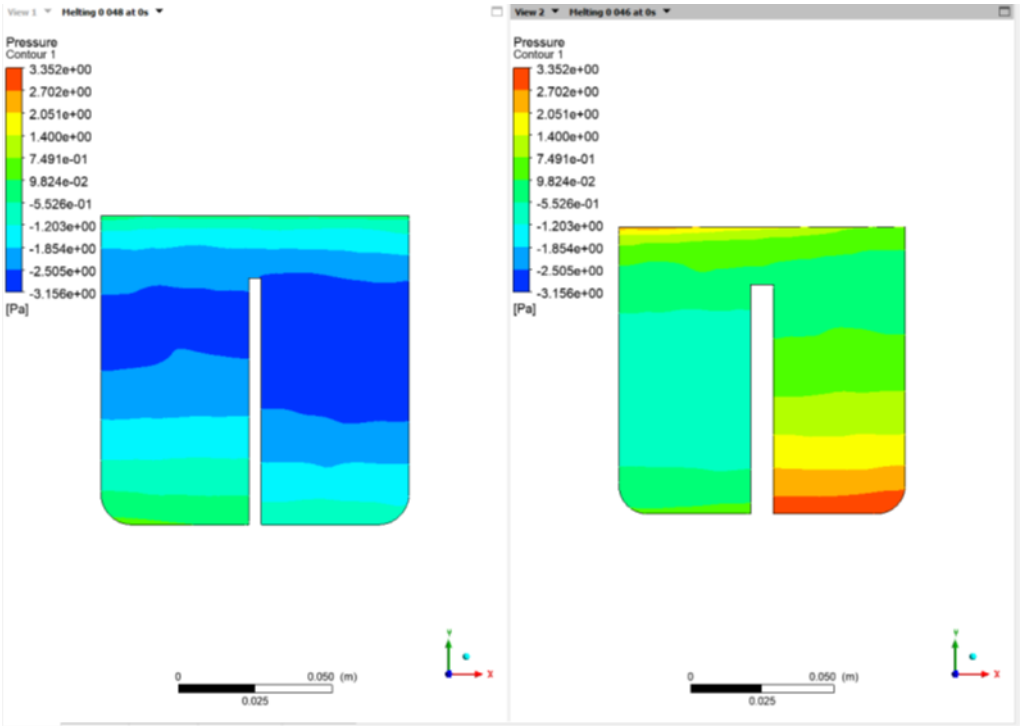

Figure 9. Contour 1, Pressure vs Time (Comparison: 0.048s vs 0.046s)

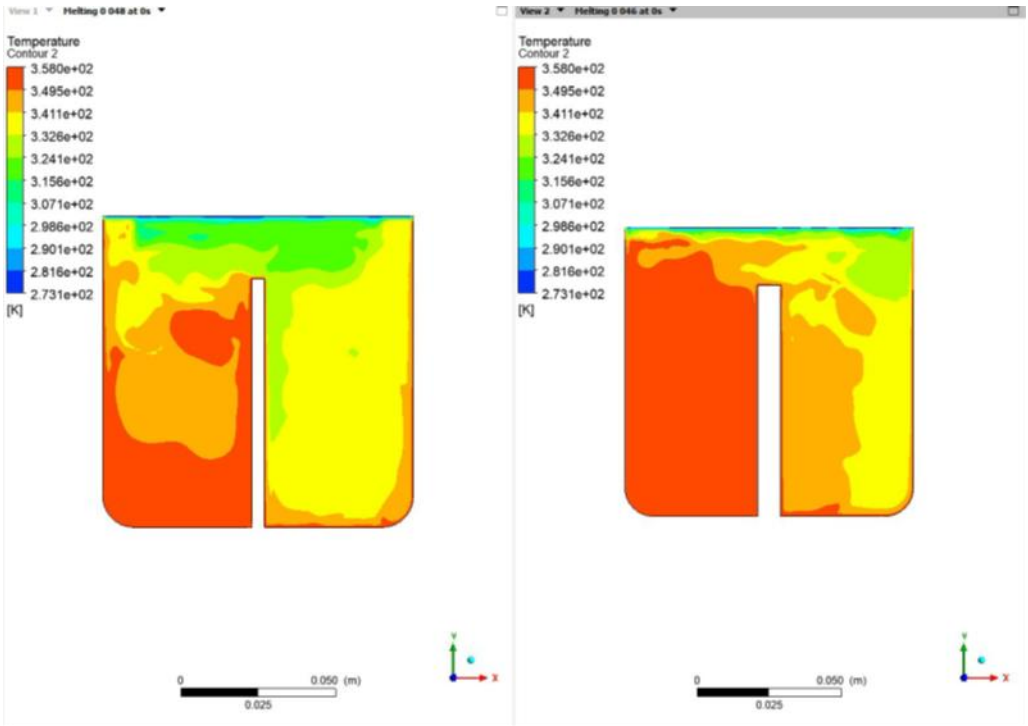

Figure 10. Contour 2, Temperature vs Time (Comparison: 0.048s vs 0.046s)

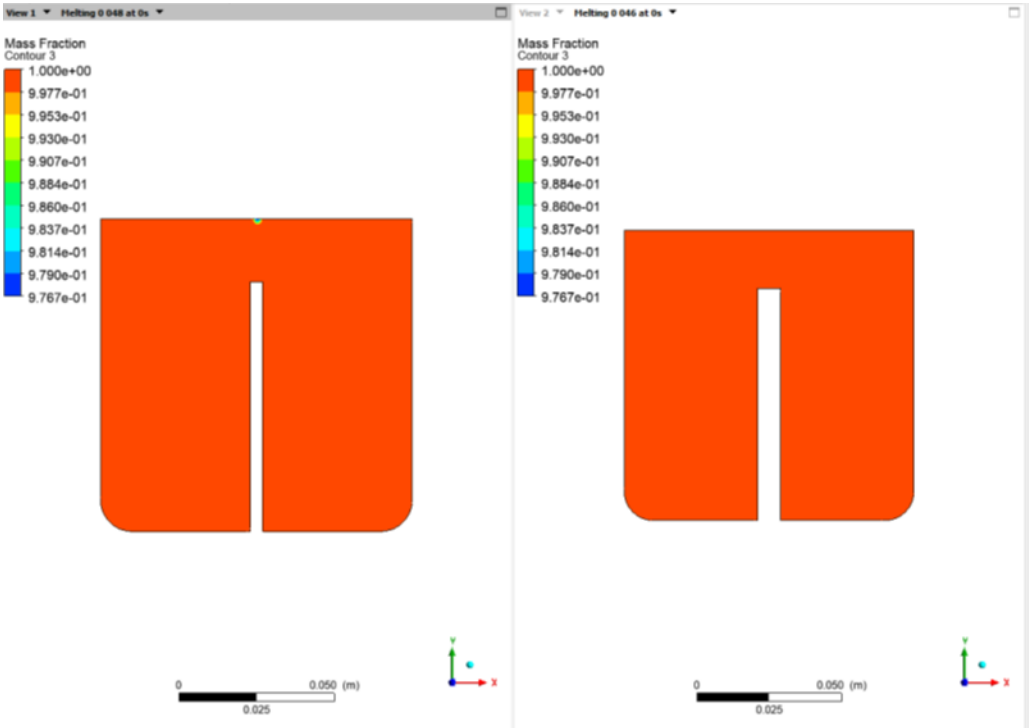

Figure 11. Contour 3, Mass Fraction vs Time (Comparison: 0.048s vs 0.046s)

3.1. Convergence

The simulation was considered converged once two main signs of stability were observed. First, the residuals for both continuity and momentum dropped below 1×10-5 which means the solution had settled and was not changing much with further iterations. This gave confidence that the calculations were accurate and consistent.

Secondly, the liquid fraction plots which show how much of the material has melted and stopped changing noticeably over time. This steady behaviour suggested that the melting process had stabilized, and the simulation was running smoothly without unexpected shifts. Together, these signs showed that the simulation had reached a reliable state, and the results could be trusted for further analysis.

3.2. Accuracy

In order to check how accurate the simulation was, the results were compared using different grid resolutions. This means the same simulation was run with both coarse and fine meshes to see if the level of detail in the grid affected the outcome.

When the results stayed nearly the same, even with a finer mesh, it showed that the solution was not dependent on the grid size anymore. This gave confidence that the simulation was capturing the important physical behaviour correctly, without being affected by how detailed the mesh was. In short, testing different grid sizes helped confirm that the results were accurate and trustworthy.

3.3. Comparison With Published Values

To ensure the reliability of the simulation results, they were compared against the findings from previous studies conducted by Lankadasu et al. and Brent et al. The key objective was to assess how closely the simulated melt front position and melting timeline aligned with those reported in the published literature. The comparison showed that the melt front in the simulation followed a very similar path and timing, with less than 5% difference from the reference data. This small variation suggests that the simulation did a good job of capturing the real behaviour of the melting process. The Nusselt number, which indicates how effectively heat is being transferred, also showed a similar pattern to what was reported in the benchmark studies. This further confirmed that the simulation was producing realistic and trustworthy results. Overall, the close match with established research gave strong confidence that the model was accurate and working as expected.

4. DISCUSSION

At the start of the melting process, heat was mainly transferred through conduction meaning it moved directly through the solid material. As more of the material melted and liquid began to form, natural convection kicked in, causing the melted fluid to circulate and spread the heat more effectively. This shift from conduction to convection played a big role in how the melting progressed. To check how much the mesh affected the results, a grid sensitivity test was done. It turned out that there was almost no noticeable difference between the 60×60 and 80×80 mesh sizes. This showed that increasing the grid resolution beyond that didn't make much of an impact, meaning the chosen mesh was fine enough to capture the important details.

However, the simulation was quite sensitive to the Rayleigh number and the timestep size. Changes in these values affected how the fluid moved and how heat was transferred, so it was important to choose them carefully to get realistic results. The enthalpy-porosity model worked well overall in simulating the melting process. It captured the general behaviour and melt front movement effectively. That said, there were still some small inaccuracies near the boundary between the solid and liquid areas, likely due to the limits of how detailed the mesh could be in that region.

5. CONCLUSIONS

This CFD analysis successfully modelled the transient melting of a PCM in a square cavity using the enthalpy-porosity method. The results showed good agreement with published benchmarks, and the selected model parameters offered a reasonable trade-off between accuracy and computational cost. Future improvements may include adaptive meshing or coupling with experimental data for enhanced validation.

REFERENCES

[1] Wang Y, Liu Z, Niu X, Ling X. Preparation, characterization, and thermal properties of microencapsulated phase change material for low-temperature thermal energy storage. Energy & fuels. 2019 Jan 7;33(2):1631-6. https://doi.org/10.1021/acs.energyfuels.8b02504

[2] Hu X, Zhu F, Gong X. Experimental and numerical study on the thermal behavior of phase change material infiltrated in low porosity metal foam. Journal of Energy Storage. 2019 Dec 1;26:101005. https://doi.org/10.1016/j.est.2019.101005

[3] Cabeza LF, Castellón C, Nogués M, Medrano M, Leppers R, Zubillaga O. Use of microencapsulated PCM in concrete walls for energy savings. Energy and buildings. 2007 Feb 1;39(2):113-9. https://doi.org/10.1016/j.enbuild.2006.03.030

[4] Lecompte T, Le Bideau P, Glouannec P, Nortershauser D, Le Masson S. Mechanical and thermo-physical behaviour of concretes and mortars containing phase change material. Energy and buildings. 2015 May 1;94:52-60. https://doi.org/10.1016/j.enbuild.2015.02.044

[5] Rubinetti D, Weiss DA, Kraniotis D, Chaudhuri A. Fully integrated numerical design tool to assess the thermal performance of phase change materials (PCM) in the built environment. InIOP Conference Series: Earth and Environmental Science 2020 Jan 1 (Vol. 410, No. 1, p. 012114). IOP Publishing. https://doi.org/10.1088/1755-1315/410/1/012114

[6] Sharma SD, Kitano H, Sagara K. Phase change materials for low temperature solar thermal applications. Res. Rep. Fac. Eng. Mie Univ. 2004 Sep;29(1):31-64.

[7] Li WQ, Wan H, Jing TT, Li YB, Liu PJ, He GQ, Qin F. Microencapsulated phase change material (MEPCM) saturated in metal foam as an efficient hybrid PCM for passive thermal management: A numerical and experimental study. Applied Thermal Engineering. 2019 Jan 5;146:413-21. . https://doi.org/10.1016/j.applthermaleng.2018.10.006

[8] Chow L, Du JH, Gupta A, Kota K, Kumar R, Kuravi S. Microchannel heat sink with micro encapsulated phase change material (MEPCM) slurry. 2009 May 31. https://apps.dtic.mil/sti/tr/pdf/ADA505991.pdf

[9] Yang P, Xiang J, Fang F, Pavlidis D, Latham JP, Pain CC. Modelling of fluid–structure interaction with multiphase viscous flows using an immersed-body method. Journal of Computational Physics. 2016 Sep 15;321:571-92. https://doi.org/10.1016/j.jcp.2016.05.035

[10] Babar OA, Arora VK, Nema PK. Selection of phase change material for solar thermal storage application: a comparative study. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2019 Sep;41(9):355. https://doi.org/10.1007/s40430-019-1853-1

[11] Sharifi N, Shabgard H, Millard C, Etufugh U. Hybrid Heat Pipe-PCM-Assisted Thermal Management for Lithium-Ion Batteries. Batteries. 2025 Feb 7;11(2):64. https://doi.org/10.3390/batteries11020064

[12] Wang H, Qin QH. A numerical method for analysing heat conduction in composites containing encapsulated phase change materials. InMATEC Web of Conferences 2018 (Vol. 237, p. 02012). EDP Sciences. https://doi.org/10.1051/matecconf/201823702012

[13] Şimşek F, Demirci H. Investigation of the use of new fin on the melting time of the phase change material stored in the heat exchanger by computational fluid dynamics analysis. Journal of Building Engineering. 2024 Aug 15;91:109505. https://doi.org/10.1016/j.jobe.2024.109505

[14] Öztop HF, Akbal Ö, Selimefendigil F, Abu-Hamdeh NH. Analysis of the melting time of phase change material in a heat exchanger with sinusoidal inner duct. Symmetry. 2023 Jan 2;15(1):129. https://doi.org/10.3390/sym15010129

[15] Ahmed S, Abderrahmane A, Saeed AM, Guedri K, Mourad A, Younis O, Botmart T, Shah NA. Melting enhancement of PCM in a finned tube latent heat thermal energy storage. Scientific Reports. 2022 Jul 7;12(1):11521. https://doi.org/10.1038/s41598-022-15797-0

[16] Rana S, Zunaid M, Kumar R. CFD simulation for heat transfer enhancement in phase change materials. Materials Today: Proceedings. 2021 Jan 1;46:10915-21. https://doi.org/10.1016/j.matpr.2021.02.006

[17] Sattari H, Mohebbi A, Afsahi MM, Yancheshme AA. CFD simulation of melting process of phase change materials (PCMs) in a spherical capsule. International Journal of Refrigeration. 2017 Jan 1;73:209-18. http://dx.doi.org/10.1016/j.ijrefrig.2016.09.007

[18] Kumaresan G, Santosh R, Revanth H, Raju G, Bhattacharyya S. CFD and experimental analysis of phase change material behaviour encapsulated in internally finned spherical capsule. InE3S Web of Conferences 2019 (Vol. 128, p. 01002). EDP Sciences. https://doi.org/10.1051/e3sconf/201912801002

[19] Muhammad MD, Badr O, Yeung H. Validation of a CFD melting and solidification model for phase change in vertical cylinders. Numerical Heat Transfer, Part A: Applications. 2015 Sep 2;68(5):501-11. https://doi.org/10.1080/10407782.2014.994432
[20] Arena S, Cau G, Palomba C. CFD simulation of melting and solidification of PCM in thermal energy storage systems of different geometry. InJournal of Physics: Conference Series 2015 Oct 1 (Vol. 655, No. 1, p. 012051). IOP Publishing. DOI:10.1088/1742-6596/655/1/012051
[21] Gallero FJ, Siles GG, Maestre IR, Blázquez JL, Pérez-Lombard L. Performance of a simplified computational fluid dynamics model for a phase change material–water finned heat exchanger under different orientations. Energy Storage. 2024 Aug;6(5):e70021. https://doi.org/10.1002/est2.70021
[22] García-Fuente M, González-Peña D, Alonso-Tristán C. A numerical simulation of an experimental melting process of a phase-change material without convective flows. Applied Sciences. 2022 Apr 4;12(7):3640. https://doi.org/10.3390/app12073640
[23] Marzouk SA, Almehmadi FA, Aljabr A, Hamdan MO, Sharaf MA. Enhancing melting of phase change material in double tube latent heat storage system by pin fins. ASME Journal of Heat and Mass Transfer. 2025 Jul 1;147(7):072401. https://doi.org/10.1115/1.4068160
[24] Saliby A, Kovács B. CFD modeling for phase change materials integrated to building envelope. Pollack Periodica. 2024 Mar 22;19(1):67-72. DOI:10.1556/606.2023.00930
[25] Demirkıran İG, Cetkin E. Computation time reduction of PCM melting process by changing modeling parameters. Numerical Heat Transfer, Part A: Applications. 2022 Dec 9;83(1):50-67. https://doi.org/10.1080/10407782.2022.2149229
[26] Belhadad T, Kanna A, Samaouali A, Kadiri I. CFD Investigation of Fin Design Influence on Phase Change Material Melting for Solar Thermal Energy Storage. e-Prime-Advances in Electrical Engineering, Electronics and Energy. 2023 Dec 1;6:100306. https://doi.org/10.1016/j.prime.2023.100306
[27] Khedher NB, Mahdi JM, Majdi HS, Khosravi K, Al-Azzawi WK, Al-Qrimli FA, Dhahbi S, Talebizadehsardari P. CFD analysis of phase-change material-based heat storage with dimple-shaped fins: evaluation of fin configuration and distribution pattern. Journal of Computational Design and Engineering. 2022 Oct;9(5):2055-72. https://doi.org/10.1093/jcde/qwac105
[28] Arıcı M, Tütüncü E, Yıldız Ç, Li D. Enhancement of PCM melting rate via internal fin and nanoparticles. International Journal of Heat and Mass Transfer. 2020 Aug 1;156:119845. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119845
[29] Liu Q, He YL. Double multiple-relaxation-time lattice Boltzmann model for solid–liquid phase change with natural convection in porous media. Physica A: Statistical Mechanics and its Applications. 2015 Nov 15;438:94-106. https://doi.org/10.1016/j.physa.2015.06.018
[30] Li D, Ren Q, Tong ZX, He YL. Lattice Boltzmann models for axisymmetric solid–liquid phase change. International Journal of Heat and Mass Transfer. 2017 Sep 1;112:795-804. https://doi.org/10.1016/j.ijheatmasstransfer.2017.03.127
[31] Huang J, He K, Wang L. Pore-scale investigation on natural convection melting in a square cavity with gradient porous media. Energies. 2021 Jul 15;14(14):4274. https://doi.org/10.3390/en14144274
[32] Icardi M. Adaptive Mesh Refinement for Multiphase Flow CFD. DOI:10.25518/esaform21.3861
[33] Brent AD, Voller VR, Reid KT. Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of a pure metal. Numerical Heat Transfer, Part A Applications. 1988 Apr 1;13(3):297-318.