International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 42, No. 6, December, 2024, pp. 2108-2114
Journal homepage: http://iieta.org/journals/ijht

A Numerical Study to Improve Heat Transfer in a Rectangular Cell Filled with Phase Change Materials Using Several Types of Rods

Ali K. Jasim[1], Sabah H. Alwan[2], Ahmed K. Nemah[3], Hasan Qahtan Hussein[1], Karrar A. Hammoodi[4*]

[1] Petroleum Department, College of Engineering, University of Kerbala, Karbala 56001, Iraq
[2] Electrical and Electronic Department, College of Engineering, University of Kerbala, Karbala 56001, Iraq
[3] Department of Chemical Engineering and Petroleum Industries, Al-Amarah University College, Maysan 62001, Iraq
[4] Air Conditioning and Refrigeration Department, College of Technical Engineering, Warith Al-Anbiyaa University College, Karbala 56001, Iraq

Corresponding Author Email: karrar.al@uowa.edu.iq

https://doi.org/10.18280/ijht.420629

Received: 5 August 2024
Revised: 18 October 2024
Accepted: 6 November 2024
Available online: 31 December 2024

Keywords:
paraffin, FLUENT 16 software, PCMs, rectangular cell, rods (copper, iron, aluminum, and silver)

ABSTRACT

This computer study seeks to identify the most effective rod material—copper, iron, aluminum, or silver—for heat transfer to phase-changing materials within a rectangular cell. This study utilizes the enthalpy-porosity formulation and the ANSYS/FLUENT 16 software to investigate the impact of various rod materials on the heat transfer dynamics in paraffin wax-based phase transition materials (RT58). The findings indicate that heat transmission efficiency is contingent upon the rod material, with iron rods resulting in an 11% reduction in the phase change process and aluminum rods generating a 6% reduction compared to copper and silver rods. These findings underscore the need of choosing suitable materials to enhance heat transfer in phase change systems. This work is significant due to its possible uses in improving the thermal management of contemporary electronic devices through the use of phase transition materials.

1. INTRODUCTION

Energy has a tremendous effect on how contemporary human civilization evolves since it is required by many service businesses and impacts people's everyday lives. Given that certain energy sources are practically depleted, while others have a major detrimental influence on our surroundings.

Renewable energy is the foremost alternative that global specialists are examining. A significant advantage of renewable energy is its long-term cost-effectiveness, absence of adverse environmental effects, and potential for usability. It is ubiquitous; yet, its principal drawback is that, unlike solar and wind energy, it is not consistently accessible [1, 2].

The use of thermal energy storage has solved the problem of intermittent availability, with phase-change materials being the most popular option [3, 4]. The most significant of these developments is the use of copper rods. Many studies investigated the various forms of containers that carry phase-changing materials, as well as how those shapes influence heat storage, energy efficiency, and heat transfer.

To enhance the design of passive solar walls containing PCMs utilizing a rectangular cell, it was quantitatively analyzed. The presented work proves the expediency of numerical predictions during the conducted experimental study [5, 6]. Experimental investigations on the melting procedure of the PCM were conducted in a rectangular cell. Further, the research showed that depths increased with a corresponding increase in the temperature informing a melting process [7-9]. He also did an experimental investigation in the heat transfer with PCM using a rectangular cell. This was evidence by the fact that phase-change materials absorbed and released heat faster when the air temperature elevated; therefore, enhancing the energy charge of PCM’s sensible and latent heat [10, 11].

This paper presents some results of the experimental and numerical investigation for a rectangular container filled with PCM. The investigation proved that the process of melting increased relative to the heat flow in the system [12, 13], computer-analysis of energy storage using a PCM packed cylindrical container. From the research, it was evident that the last cylinders in the column melt the least compared to the first cylinders in the column, and the PCM temperature depends on the position of the cylinders, it is cold at the outer pieces and hotter at the central section [14, 15]. A horizontal, cylindrical container with PCM is involved in the dissolution process to carry out a numerical investigation. Based on the study, the process of melting is controlled by natural convection and this really affects the time that is taken to complete the process of melting. The majority of the rise in temperature of the solid that occurs during the first stages of melting may be attributed to conduction [16, 17]. The study investigates the melting of phase change materials (PCM) and conducts a numerical analysis of this process in a vertical cylindrical tube that is half-filled with PCM. The findings suggest that the melting process is highly sensitive to several factors including temperature, tube diameter, wall thickness, outer wall surface, and the thermophysical properties of the tube shell. This sensitivity is highlighted by the significant impact these factors have on the melting process. Basem et al. [18] further explores this phenomenon through an experimental study on the melting within a sphere that has a cavity embedded with PCM. As a result of this study, it is evident that the rate of melting rises any time the heater outputs are raised [19, 20]. Research made on the activity of melting in a spherical shape that contains PCM. As cell diameter increased the period required to dissolve was perceived to be long in previous studies [21, 22], analytical solution of the dissolution in a PCM encapsulated in a spherical container. Therefore, from the study, the action of natural convection was shown to enhance dissolution in the top part of the spherical capsule than the bottom part [23]. The experimental investigation of the PCM usage for covering casing and tube of a solar dryer for latent heat storage. The investigation demonstrated that natural convection influences heat conductivity and the buoyancy impact enhances the parcel's heating or, in this case, melting at the thermocouple zone [24], study on the dissolving process in manifold tubes with PCM loaded. The findings of the study pointed out that both, raising the temperature and the number of tubes intensifies the melting process [25], a research work that demonstrates the manner in which phase change happens under the influence of PCMs in a tube and casing. This research also points the heat pipe has a big influence on the smelting process. Also, the melting process increases with the increasing of the number of inner HTF tubes [26, 27]. Investigations demonstrating the benefits of employing nanoparticles to improve heat transport. The study found that by including nanoparticles into PCM, the dissolving process may be completed faster due to increased heat transmission [28-30]. By integrating nanofluids into phase change materials (PCMs), experimental research has shown the significance of employing nanofluids as a new phase change material for the purpose of increasing thermal energy storage.

According to the findings of the research, the incorporation of nanofluids into PCM results in an increase in thermal conductivity and increases the rate at which the melting process occurs [31, 32]. In order to demonstrate the significance of employing various rods and to determine which one is ideal for enhancing heat transmission to the PCM, thereby shortening the period required to complete the melting process, the usage of different types of rods (copper, iron, aluminum, and silver) has been explored in this work.

2. NUMERICAL PROCEDURE

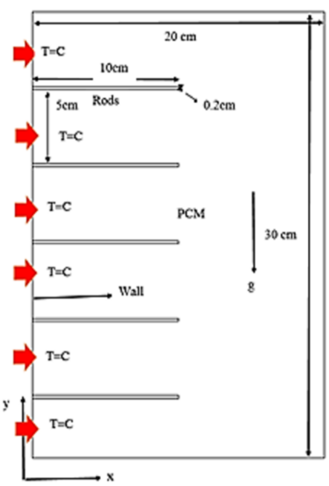

Figure 1. Setup of the physical model

2.1 Physical model

Figure 1 illustrates the physical model studied, consisting of a rectangular cell insulated on three sides, with one side exposed to hot water as a heat source. The cell is 20 cm wide and 30 cm long. Five rods, each 10 cm long and 0.2 cm thick, are positioned within the cell. Various materials, including copper, iron, aluminum, and silver, were used for the rods to demonstrate the most effective and common methods of heat transfer, thereby accelerating the melting process. A copper rod is positioned 0.5 cm away from the wall adjacent to the heat source.

2.2 Computational procedure

It is possible to predict the type of melting procedure that takes place in the rectangular container with rods through numerical analysis. The flow was assumed to be steady, incompressible and fully developed both in the stream wise direction and normal to the wall. Since the attempt is made to model the process of melting, it is considered herein that both the liquid and solid phases of the system are isotropic and homogeneous which also requires that interfaces between the two are in the state of thermal equilibrium. The enthalpy-porosity approach was used to quantify the area of the PCM that undergoes phase shift. PCM fusion is a challenging score due to its non-linear aspects of behavior and temporal evolution and also due to its ever-changing phase front or the solid-liquid interface. Eqs. (1)-(3) are models for the simultaneous continuity, momentum, and energy governing partial differential equations that explain the melted state of PCM, respectively:

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho V)=0 \tag{1}$$

$$\frac{\partial(\rho v)}{\partial t}+\nabla\cdot(\rho V)=-\nabla P+\mu\nabla^2 V+\rho g+S \tag{2}$$

$$\frac{\partial}{\partial t}(\rho H)+\nabla\cdot(\rho V H)=\nabla\cdot(K\nabla T) \tag{3}$$

The sensible enthalpy (h) and latent heat (H) are added to create the specific enthalpy (H).

$$H=h+\Delta \mathrm{H} \tag{4}$$

where,

$$h=h_{ref}+\int_{T_{ref}}^{T} C_p dT \tag{5}$$

$$\Delta H=\beta L_f \tag{6}$$

The percentage of liquid (β) can be expressed as follows: The heat that is latent content might be zero (for a solid) or one (for a liquid).

$$\beta=\begin{cases} 0 \text{ solidus, if } T<T_s \\ 1 \text{ liquidus, if } T>T_l \\ \dfrac{T-T_s}{T_l-T_s}, \quad \text{if } T_s\le T\le T_l \end{cases} \tag{7}$$

Table 1. Thermophysical properties of the materials

Thermal Properties	RT58 [33]	Copper [34]	Iron [35]	Aluminum [36]	Silver [37]
Density, ρ (kg/m^3)	840	8933	7860	2425	10.5
Specific heat capacity, Cp (J/kg.K)	2100	385	448	900	235
Thermal conductivity, k (W/m.K)	0.21	401	80	229	429
Dynamic viscosity, μ (kg/m.s)	0.0269				
Thermal expansion rate, α (1/K)	0.00011				
Latent heat, L (J/kg)	180000				
Solidus temperature, (°C)	48				
Liquidous temperature, (°C)	62				

The source of term S in the formula for momentum represents the Darcy's law damping component, which is included because to the phase shift has an impact on convection. These terms originate from: The momentum equation's source term is as follows:

$$S = \frac{C(1-\beta)^2}{\beta^3} V \quad (8)$$

where, the melting front shape is incorporated in the constant C, which may be usually referred as mushy zone constant. This constant is fairly high, generally of the order 10^4-10^7. In the current study, C is set to be equal to 10^5, and like what was concluded in prior studies, it is considered as a constant value.

2.3 Boundary conditions

In the present study, heated water is supplied to the wall at a flow rate of 0. At a flow rate of 833 m^3/s and a heat input temperature of 368 K. Even though dividing the cell into three sections has minimized the conductivity of heat transmission, it is assumed that heat is conducted from the wall through to the PCM without any loss. RT58 is a chemical and it follows the phase transition nature. Table 1 comprises of all the necessary information concerning the thermophysical properties of paraffin.

2.4 Assumptions

When addressing the computational format of the melting process into a rectangular cell, a variety of circumstances are taken into consideration, including the following situations: The viscous dissipation term is insignificant, any volume change that is related with the transition from the solid to the liquid phase is ignored, and there is neither a gain nor a loss of heat from the surrounding environment. It is assumed that the fluid is incompressible, having a laminar motion, and moving un an irregular manner. It is assumed that the thermophysical characteristics of the PCM do not change in either the solid or liquid phases of the material. A representation of melting is a process that occurs in two dimensions.

3. RESULTS AND DISCUSSION

The importance of using thermal energy storage and reuse requires finding solutions that accelerate heat transfer within the PCM. In this numerical study, four cases were studied, where, we study the cell with bars from (copper, iron, aluminum, and silver) to show which types are used best in heat transfer and to clarify the importance is their use and the effect of the melting process.

3.1 The first case (The cell with copper rod)

Since the PCM is melted by plug at the beginning of the melting process and has a copper rod inside of it, it has increased thermal conductivity inside of it, as is evident in Figure 2, and since the heat transfer is based on natural thermal pregnancy, the process of solubility is noted, which explains the importance of the use of a copper rod in this case.

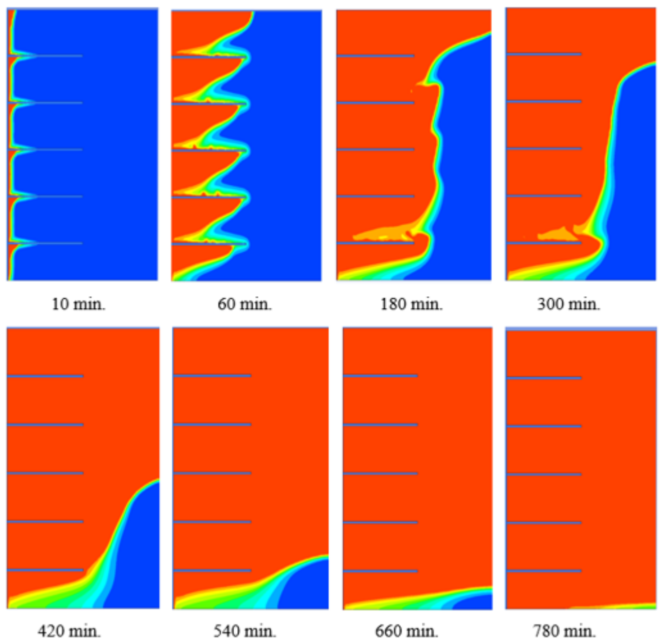

Figure 2. Evolution of the melting process in the rectangular copper rod container predicted

3.2 The second case (The cell with iron rod)

The study indicates that the utilization of an iron rod accelerates the melting process, albeit at a slower rate compared to a copper rod, which requires 790 minutes for complete melting. This phenomenon occurs because the phase change material (PCM) melting initiates by delivery at the onset of the melting process. The presence of an iron bar within PCM enhances its thermal conductivity, as evidenced in Figure 3. Consequently, the heat transmission relies on the conventional thermal properties, which underscores the significance of employing rods in the melting process.

3.3 The third case (The cell with aluminium rod)

As a result, the research demonstrates that the utilization of an aluminum rod accelerates the melting process, despite the fact that it is slower when compared to the utilization of a copper rod. However, it is most effectively compared to the utilization of an iron rod, which requires 750 minutes to finish melting. The reason for this is that the PCM melting is accomplished through delivery at the beginning of the melting process. It is evident in Figure 4 that the presence of an aluminum bar within PCM results in an increase in the thermal conductivity of the material. This is due to the fact that the heat transfer is dependent on the natural thermal pregnancy and its impact on the melting process. This highlights the significance of utilizing rods in the melting process.

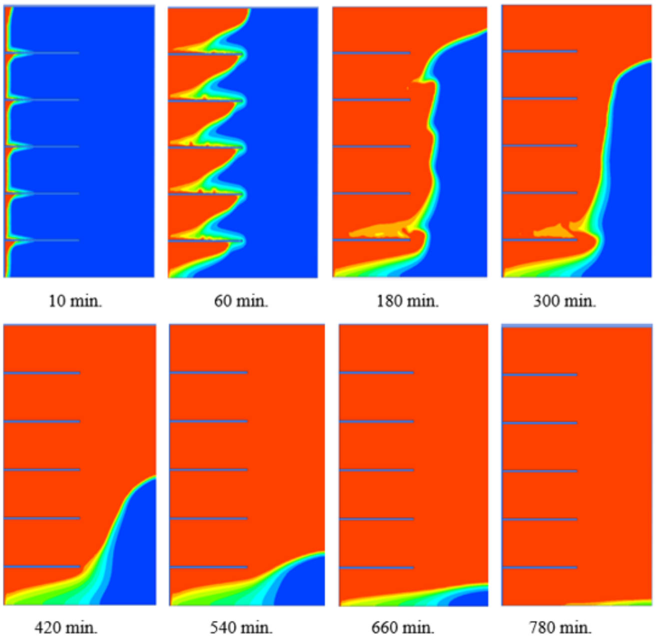

Figure 3. Predicted changes in the melting process at the three-rod rectangular cell

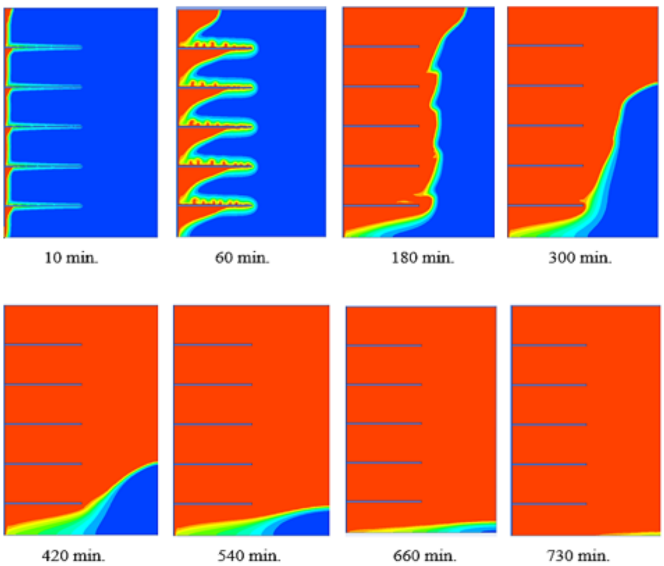

Figure 4. Predicted changes in the melting process at the five-rod rectangular cell

3.4 The fourth case (The cell with silver rod)

In this case, the study shows that the use of a silver rod, increases the melting process where you need (700 min.) to complete melting, and the reason is that the PCM melting is by delivery at the beginning of the melting. The existence of an aluminium bar within PCM increases thermal conductivity within it and is clear in Figure 5 and because the heat transfer depends on the natural thermal pregnancy and effect on the melting process, which illustrates the importance of using rods in the melting process.

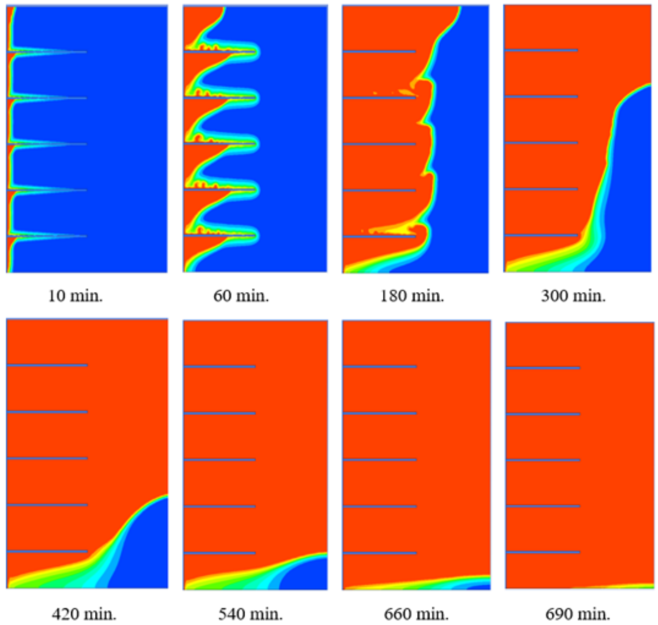

Figure 5. Projected melting process in a rectangular container filled with silver rods

3.5 A comparison of the four cases

Upon contrasting with the investigation's the results, it is evident that the utilization of rods (copper and silver) enhances heat transfer, thereby reducing the duration of the melting process. This is preferable to the use of rods (aluminum and iron), which necessitate additional time to finish the melting operation. The melting process is 11% slower with iron rods and 6% slower with aluminum rods than it is with copper and silver rods, as illustrated in Figure 6. This is due to the fact that heat transfer occurs preceding solubility, which is contingent upon the connection and occurs along the wall. Consequently, the dissolving process is contingent upon the natural cycle of a woman, which is characterized by a delayed rate of heat transfer.

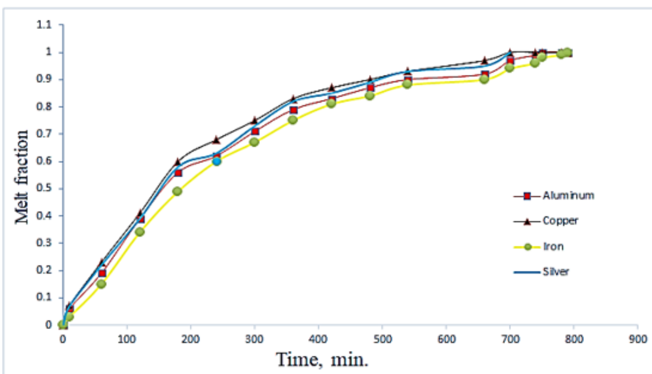

Figure 6. Melt part variation with period and flow rate = 50L/min. at Tin = 95°C

The relevance of utilizing copper and silver rods in the cell is highlighted in Figure 7 due to the clear impact that these rods have on the melting process. In spite of this, it is worth noting that the utilization of bars results in an increase in the melting process, as well as an increase in the heat conductivity of the PCM. As a result, the amount of time required to finish the melting process is reduced.

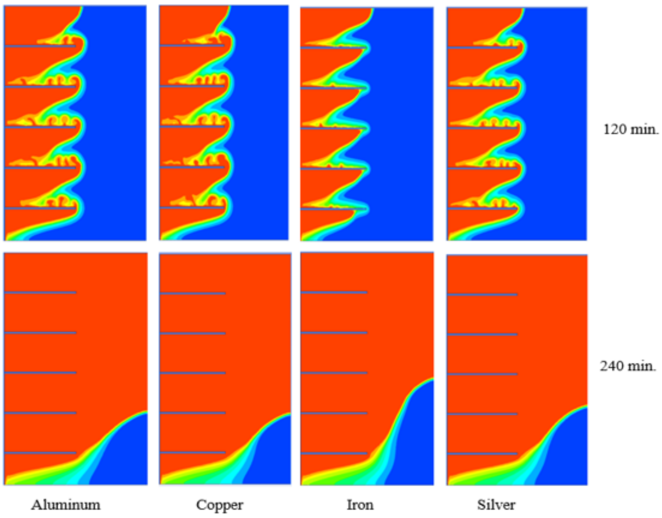

Figure 7. Comparison of how the cells' melting differs

4. CONCLUSIONS

The current study conducted a numerical analysis to evaluate the impact of different materials—copper, iron, aluminium, and silver—used as rods in a rectangular container on the melting process. The aim was to determine how these materials influence the efficiency of heat transfer during the melting phase. The study yielded the following key results:

•A numerical analysis was conducted to evaluate the influence of using copper, iron, aluminum, and silver rods in a rectangular container on the melting process.

•The study utilized Phase Change Materials (PCMs) with a specific temperature of 58 degrees Celsius, combined with the enthalpy-porosity formulation integrated into the ANSYS/FLUENT 16 program.

•The heat transfer at the onset of melting is affected by the interaction between the wall and the rods.

•The melting rate is 11% lower with iron rods and 6% lower with aluminum rods compared to copper and silver rods.

•The melting process is influenced by the inherent cycle of the material, which is prolonged due to the slower heat transfer.

•The significance of this finding lies in the role of phase change materials in advanced electronics, where they play a key role in protecting devices from damage caused by high temperatures.

•Efficient heat transfer in phase change materials is crucial for effectively absorbing the energy generated in these devices.

•The study's findings may be applied to facilitate the production of a physical model incorporating rods inside it.

5. FUTURE RESEARCH RECOMMENDATIONS

Future studies could investigate other materials beyond copper, iron, aluminum, and silver to further optimize heat transfer efficiency, especially materials with higher thermal conductivities or novel composite materials.

Researchers could examine the effects of different rod geometries (e.g., cylindrical, hollow, or finned structures) on heat transfer efficiency in phase change materials.

Investigating how phase change materials combined with optimized rod materials can be used to enhance the performance of solar thermal energy storage systems would be valuable.

Research could also explore the performance of these materials in larger-scale systems or under long-term operational conditions to better understand their real-world applicability.

6. POTENTIAL REAL-WORLD APPLICATIONS

The findings could be applied to the design of cooling systems in modern electronic devices, where efficient heat dissipation is crucial to maintaining performance and longevity.

Phase change materials, combined with the most efficient rod materials, could be used to improve thermal energy storage in solar or geothermal power systems, leading to better energy efficiency and storage capabilities.

These materials may also be useful in passive heating and cooling systems for buildings, contributing to energy savings and improved temperature control in urban environments.

REFERENCES

[1] Dhaidan, N.S., Khalaf, A.F. (2020). Experimental evaluation of the melting behaviours of paraffin within a hemicylindrical storage cell. International Communications in Heat and Mass Transfer, 111: 104476. https://doi.org/1016/j.icheatmasstransfer.2020.104476

[2] Hussein, H.Q., Khalaf, A.F., Jasim, A.K., Rashid, F.L. (2021). Experimental investigation for the influence of a basement inside collector on solar chimney effectiveness. Journal of Mechanical Engineering Research and Developments, 44(4): 346-354.

[3] Bull, S.R. (2001). Renewable energy today and tomorrow. Proceedings of the IEEE, 89(8): 1216-1226. https://doi.org/10.1109/5.940290

[4] Dhaidan, N.S., Khalaf, A.F., Khodadadi, J.M. (2021). Numerical and experimental investigation of melting of paraffin in a hemicylindrical capsule. Journal of Thermal Science and Engineering Applications, 13(5): 051008. https://doi.org/1115/1.4049873

[5] Hussein, H.Q., Khalaf, A.F., Al-Tajer, A.M., Hammoodi, K.A., Basem, A. (2022). Numerical investigated to improve heat transfer in a pipe using nanofluid. Mathematical Modelling of Engineering Problems, 9(4): 1073-1078. https://doi.org/10.18280/mmep.090425

[6] Sharma, A., Tyagi, V.V., Chen, C.R., Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 13(2): 318-345. https://doi.org/10.1016/j.rser.2007.10.005

[7] Younsi, Z., Joulin, A., Zalewski, L., Lassue, S., Rousse, D.R. (2009). Phase change materials: A numerical method for the behavior predictions. In Proceedings of the Fourth International Conference on Thermal Engineering: Theory and Applications, Abu Dhabi,

UAE, pp. 12-14.
[8] Eleiwi, M.A., Rashid, F.L., Khalaf, A.F., Tuama, S.A. (2022). Numerical investigation of conjugate heat transfer between spherical solid body and fluid. Mathematical Modelling of Engineering Problems, 9(2): 491-497. https://doi.org/10.18280/mmep.090227
[9] Al-Tajer, A.M., Basem, A., Khalaf, A.F., Jasim, A.K., Hammoodi, K.A., Hussein, H.Q. (2022). A numerical simulation to select the optimal thermal agents for building parts. Mathematical Modelling of Engineering Problems, 9(5): 1393-1398. https://doi.org/10.18280/mmep.090530
[10] Shokouhmand, H., Kamkari, B. (2013). Experimental investigation on melting heat transfer characteristics of lauric acid in a rectangular thermal storage unit. Experimental Thermal and Fluid Science, 50: 201-212. https://doi.org/10.1016/j.expthermflusci.2013.06.010
[11] Khalaf, A.F., Basem, A., Hussein, H.Q., Jasim, A.K., Hammoodi, K.A., Al-Tajer, A.M., Omer, I., Flayyih, M.A. (2022). Improvement of heat transfer by using porous media, nanofluid, and fins: A review. International Journal of Heat and Technology, 40(2): 497-521. https://doi.org/10.18280/ijht.400218
[12] Younis, O., Rashid, F., Khalaf, A., Hussein, A., Ben Hamida, M., Ali, B. (2022). Thermal-hydraulic analysis of transient conjugate heating between hemi-spherical body and air. Frontiers in Heat and Mass Transfer (FHMT), 19(21): 1-6.
[13] Sun, X., Chu, Y., Mo, Y., Fan, S., Liao, S. (2018). Experimental investigations on the heat transfer of melting phase change material (PCM). Energy Procedia, 152: 186-191. https://doi.org/10.1016/j.egypro.2018.09.079
[14] Hussein, H., FadhilKhalaf, A., Jasim, A.K. (2022). A numerical study to investigate several thermal insulators to choose the most suitable ones for thermal insulation in buildings. International Journal of Mechanical Engineering, 7(1): 921-929.
[15] Yadav, A., Samir, S. (2019). Experimental and numerical investigation of spatiotemporal characteristics of thermal energy storage system in a rectangular enclosure. Journal of Energy Storage, 21: 405-417. https://doi.org/10.1016/j.est.2018.12.005
[16] Rashid, F.L., Khalaf, A.F., Basem, A. (2023). A numerical study of a square cell filled with ice with the presence of different length slit inside the cell. Journal of Advanced Research in Numerical Heat Transfer, 14(1): 104-117. https://doi.org/10.37934/arnht.14.1.104117
[17] Alshara, A.K., Kadhim, M.K. (2014). Numerical investigation of energy storage in packed bed of cylindrical capsules of PCM. Engineering and Technology Journal, 32(2): 494-510.
[18] Basem, A., Omar, I., Al-Tajer, A.M.A., Khalaf, A.F. (2023). Operational efficiency assessment of the sewage pumping station using the Performance Index under real conditions. International Journal of Sustainable Development and Planning, 18(7): 2061-2067. https://doi.org/10.18280/ijsdp.180708
[19] Hlimi, M., Hamdaoui, S., Mahdaoui, M., Kousksou, T., Msaad, A.A., Jamil, A., El Bouardi, A. (2016). Melting inside a horizontal cylindrical capsule. Case Studies in Thermal Engineering, 8: 359-369. https://doi.org/10.1016/j.csite.2016.10.001
[20] Dhaidan, N.S., Khalaf, A.F., Khodadadi, J.M. (2021). Numerical and experimental investigation of melting of paraffin in a hemicylindrical capsule. Journal of Thermal Science and Engineering Applications, 13(5): 051008. https://doi.org/10.1115/1.4049873
[21] Bechiri, M., Mansouri, K. (2019). Study of heat and fluid flow during melting of PCM inside vertical cylindrical tube. International Journal of Thermal Sciences, 135: 235-246. https://doi.org/10.1016/j.ijthermalsci.2018.09.017
[22] Khalaf, A.F., Rashid, F.L., Basem, A., Abbas, M.H. (2022). Numerical analysis in a lid-driven square cavity with hemispherical obstacle in the bottom. Mathematical Modelling of Engineering Problems, 9(6): 1639-1647. https://doi.org/10.18280/mmep.090625
[23] Rizan, M.Z.M., Tan, F.L., Tso, C.P. (2012). An experimental study of n-octadecane melting inside a sphere subjected to constant heat rate at surface. International Communications in Heat and Mass Transfer, 39(10): 1624-1630. https://doi.org/10.1016/j.icheatmasstransfer.2012.08.003
[24] Khalaf, A.F., Rashid, F.L., Basem, A., Abbas, M.H. (2023). Numerical study of the effect of air bubble location on the PCM melting process in a rectangular cavity. Mathematical Modelling of Engineering Problems, 10(1): 71-83. https://doi.org/10.18280/mmep.100109
[25] Ismail, K.A.R., Moura, L.F., Lago, T., Lino, F.A.M., Nobrega, C. (2016). Experimental study of fusion and solidification of phase change material (PCM) in spherical geometry. In 12th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, pp. 1243-1248.
[26] Rashid, F.L., Basem, A., Khalaf, A.F., Al-Obaidi, M.A., Hussein, A.K., Ali, B., Younis, O. (2023). Air bubble position effect on phase change material melting in a semi-cylindrical container: A thermal analysis. Mathematical Modelling of Engineering Problems, 10(6): 2281-2290. https://doi.org/10.18280/mmep.100644
[27] Sattari, H., Mohebbi, A., Afsahi, M.M., Yancheshme, A.A. (2017). CFD simulation of melting process of phase change materials (PCMs) in a spherical capsule. International Journal of Refrigeration, 73: 209-218. https://doi.org/10.1016/j.ijrefrig.2016.09.007
[28] Agarwal, A., Sarviya, R.M. (2016). An experimental investigation of shell and tube latent heat storage for solar dryer using paraffin wax as heat storage material. Engineering Science and Technology, an International Journal, 19(1): 619-631. https://doi.org/10.1016/j.jestch.2015.09.014
[29] Esapour, M., Hosseini, M.J., Ranjbar, A.A., Pahamli, Y., Bahrampoury, R. (2016). Phase change in multi-tube heat exchangers. Renewable Energy, 85: 1017-1025. https://doi.org/10.1016/j.renene.2015.07.063
[30] Ebrahimi, A., Hosseini, M.J., Ranjbar, A.A., Rahimi, M., Bahrampoury, R. (2019). Melting process investigation of phase change materials in a shell and tube heat exchanger enhanced with heat pipe. Renewable Energy, 138: 378-394. https://doi.org/10.1016/j.renene.2019.01.110
[31] Jesumathy, S., Udayakumar, M., Suresh, S. (2012). Experimental study of enhanced heat transfer by addition of CuO nanoparticle. Heat and Mass Transfer, 48(6):

965-978. https://doi.org/10.1007/s00231-011-0945-y
[32] Harikrishnan, S., Kalaiselvam, S. (2012). Preparation and thermal characteristics of CuO–oleic acid nanofluids as a phase change material. Thermochimica Acta, 533: 46-55. https://doi.org/10.1016/j.tca.2012.01.018
[33] Buonomo, B., Manca, O., Ercole, D., Nardini, S. (2016). Numerical simulation of thermal energy storage with phase change material and aluminum foam. In Proceedings of the 6th International Conference on Porous Media and Its Applications in Science and Engineering, Waikoloa, Hawaii.
[34] Zheng, J., Yu, C., Chen, T., Yu, Y., Wang, F. (2019). Optimization of the melting performance of a thermal energy storage unit with fractal net fins. Processes, 7(1): 42. https://doi.org/10.3390/pr7010042
[35] Gómez Saro, A. (2013). Thermal conductivity in high silicon cast iron. https://repositorio.unican.es/xmlui/handle/10902/3170.
[36] Kaufman, J.G. (2016). Fire resistance of aluminum and aluminum alloys and measuring the effects of fire exposure on the properties of aluminum alloys. ASM International.
[37] Riahi, A., Ben-Cheikh, N., Campo, A. (2018). Water-based nanofluids for natural convection cooling of a pair of symmetrical heated blocks placed inside a rectangular enclosure of aspect ratio two. International Journal of Thermal and Environmental Engineering, 16(1): 1-10. https://doi.org/5383/ijtee.16.01.001

NOMENCLATURE

c	specifics heat (J/kg K^{-1})
β	melting fraction
h	average heat transfers coefficient (W m^{-2} K^{-1})
k	thermal of conductivity (W m^{-1} K^{-1})
L	latent heat melting (kJ/kg)
t_e	elapsed time of each test run (s)
T	temperatures (K)

Greek symbols

α	thermal of diffusivity (m^2 s^{-1})
β_f	liquid thermal of expansion coefficient (K^{-1})
ρ	density (kg m^{-3})
ν	kinematic of viscosity (m^2 s^{-1})

Subscripts

H	hot water
l	liquid PCM
m	melting
PCM	phase change material
s	solid PCM