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A numerical study on the melting behaviors of paraffin with and without Al_2O_3 nanoparticles

Al_2O_3 nanopartiküllü ve nanopartikülsüz parafinin erime davranışları üzerine sayısal bir çalışma

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A Numerical Study on the Melting Behaviors of Paraffin with and without Al_2O_3 Nanoparticles

Highlights

- *Melting processes of pure paraffin and paraffin containing nanoparticles in a rectangular melting area were numerically investigated.*
- *Liquid fraction & time contours and temperature & time graphs were illustrated both for pure paraffin and paraffin with nanoparticles at different wall temperatures (65 °C, 70 °C and 75 °C)*
- *Nanoparticle addition into the pure paraffin enhanced the heat transfer characteristics and shortened PCM melting time.*

Grafik Özet (Graphical Abstract)

A series of numerical simulation was performed for observe the effect of temperature on melting time.

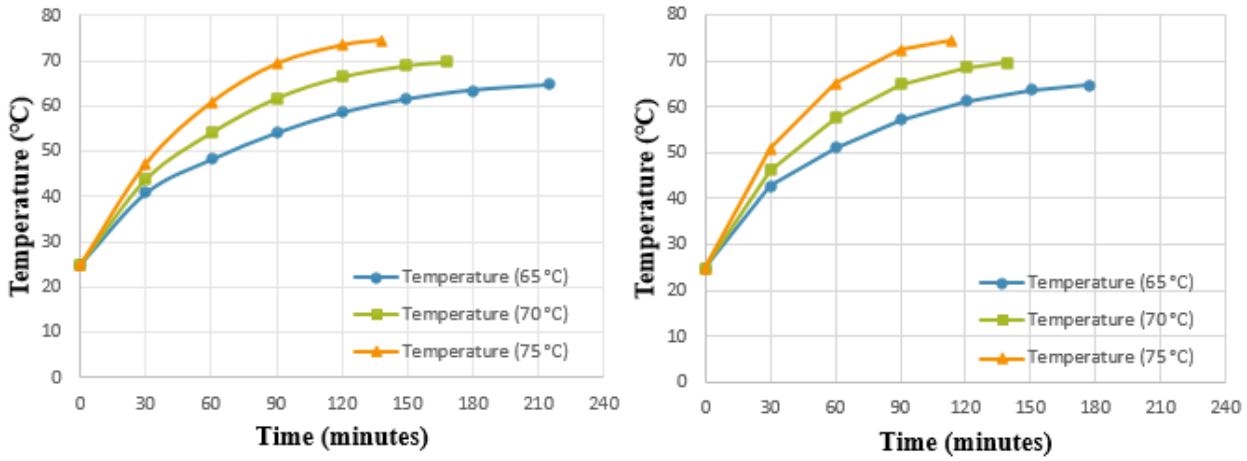

Figure. Average temperature profile (a) in pure paraffin (b) in Al_2O_3 nanoparticle added paraffin for different left surface temperatures

Aim

This research aims to investigate the effects on the melting process of nanoparticles in phase change material (PCM).

Design & Methodology

ANSYS Fluent was used in numerical simulations.

Originality

Although there are studies in the literature for different nanoparticles, studies comparing the melting processes of Al_2O_3 nanoparticles are very limited.

Findings

When the left surface temperature is 65 ° C, the nano-PCM melts in 177 minutes, at 70 ° C in 139 minutes and at 75 ° C in 114 minutes.

Conclusion

With the use of Al_2O_3 nanoparticles, thermal conductivity is increased and the heat transfer with conduction increases, so PCM melts significantly.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Al_2O_3 Nanopartiküllü ve Nanopartikülsüz Parafinin Erime Davranışları Üzerine Sayısal Bir Çalışma

Araştırma Makalesi / Research Article

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ÖZ

Faz Değiştiren Malzemelerin (FDM) kullanımı ısıl enerji depolamadaki en verimli yöntemlerden biridir. Organik FDM'ler arasında olan parafin, kolay ulaşılabilir olması ve yüksek ısı depolama kapasitelerine sahip olması sebebiyle ısıl depolama uygulamalarında sıklıkla kullanılmaktadır. Ancak düşük ısıl iletkenlikleri sebebiyle sistemlerin ısıl şarj/deşarj (erime/katılaşma) hızını önemli ölçüde sınırlamaktadır. Parafinin ısıl iletkenliğini arttırmak amacıyla uygulanan birçok yöntem bulunmaktadır. Bu çalışmada dikdörtgen bir erime alanı içinde saf parafin (Rubitherm RT50) ve kütlece %10 Al_2O_3 nanopartikül katkılı parafinin erime süreçleri sayısal olarak araştırılmıştır. Karşılaştırma yapabilmek için, hem erime sıcaklığı 50 °C olan saf parafin hem de nanopartikül katkılı parafin için dikdörtgen alanın duvar sıcaklığının 65 °C, 70 °C ve 75 °C'ye arttırılmasının toplam erime zamanına etkisi incelenmiştir. Hesaplamalı Akışkanlar Dinamiği (HAD) yaklaşımının kullanıldığı bu çalışmada, sayısal analizleri yapmak için ANSYS Fluent yazılımı kullanılmıştır Çalışma sonucunda Al_2O_3 nanopartikül kullanımının parafinin ısı transfer hızını arttırdığı tespit edilmiştir.

Anahtar Kelimeler: Faz değiştiren malzeme, parafin, Al_2O_3 nanopartikül, erime, hesaplamalı akışkanlar dinamiği.

A Numerical Study on the Melting Behaviors of Paraffin with and without Al_2O_3 Nanoparticles

ABSTRACT

One of the most effective methods of thermal energy storage is the use of Phase Change Materials (PCM). Paraffin, which is among the organic PCMs, is frequently used in thermal storage applications due to its easy accessibility and high heat storage capacity. However, it significantly limits the thermal charge / discharge (melting / solidification) rate of systems caused by their low thermal conductivity. There are many methods applied to enhance the thermal conductivity of paraffin. In this research, the melting processes of pure paraffin (Rubitherm RT50) and paraffin containing 10% Al_2O_3 nanoparticle in a rectangular melting area were numerically investigated. For comparison, the effect of increasing the wall temperature of the rectangular area to 65 ° C, 70 ° C and 75 ° C on the total melting time was investigated for both pure paraffin (melting temperature 50 ° C) and paraffin with nanoparticle additives. In this study, in which the Computational Fluid Dynamics (CFD) approach was used, ANSYS Fluent software was used to perform numerical analysis. Consequently it was determined that the use of Al_2O_3 nanoparticles improved the rate of paraffin heat transfer.

Keywords: Phase change materials, paraffin, Al_2O_3 nanoparticle, melting, computational fluid dynamics.

1. INTRODUCTION

Innovations in the industrial and technological fields, increasing population and the rapid urbanization process it causes increase energy consumption rapidly. Energy has become a basic need for people. Dependence on foreign resources and negative effects on the environment in energy production and use increase the importance of energy storage day by day. Energy storage; It can be summarized as energizing a storage system for later use. Thermal energy storage (TES) can be performed by melting, solidifying, cooling, heating or evaporating a material.

TES; It is used in different applications in areas such asbuilding heating, hot water, cooling, greenhouse heating and drying [1]. TES technologies can be categorized as sensible heat storage (SHS) and latent heat storage (LHS). In LHS methods, energy is stored in PCMs. When the phase change from solid phase to liquid phase occurs, the material stores the heat, when it returns to its former state, heat is released. LHS method has smaller temperature change and greater energy storage density than SHS method. For this reason, LHS is assumed to be the most promising method for TES among existing systems [2].

As organic, inorganic and eutectic, PCMs are separated into three major groups [3]. PCMs have advantages and disadvantages depending on the area of use. Paraffin, an organic type of PCM, is one of the primary PCMs used in energy storage caused by its latent heat amount in the desired range, chemical stability, lack of phase separation and commercial availability [4,5]. In addition to all these

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positive properties, paraffin; It has low thermal conductivity that will reduce efficiency in TES. The low thermal conductivity of paraffin significantly limits charge / discharge rate of paraffin systems used in heat storage [6].

In literature researches, studies are carried out on many methods, both numerical and experimental, to improve the conductivity of paraffin. These; adding metal plates, adding paraffin to a metal structure, adding nanoparticles with high thermal conductivity to paraffin, microencapsulation paraffin, preparation of paraffin-graphite mixtures, etc. are methods. In this direction, there are many studies conducted by adding different nanoparticles in different proportions to increase the thermal conductivity of paraffin [7].

Ho and Gao (2013) used paraffin (n-octadecane) and 0%, 5% and 10% nanoparticles (Al_2O_3) as PCM and performed the experiments using an insulated tank with dimensions of 25 x 25 mm and a length of 60 mm [8]. In a similar study, where thermophysical properties such as dynamic viscosity, density and thermal conductivity were experimentally investigated, it was determined that the conductivity and dynamic viscosity values measured for paraffin with added nanoparticle showed a nonlinear increase in the mass fraction of nanoparticles compared to pure paraffin based on temperature [9]. Arasu et al. (2012) performed numerical simulations using FLUENT software in double-tube heat exchanger to examine the impact of Al_2O_3 nanoparticles on paraffin wax. The thermo-physical properties of paraffin containing Al_2O_3 nanoparticles have been observed to be consistent with the measurements made by Ho and Gao. It was concluded that, relative to pure paraffin, Al_2O_3 nanoparticles have a important impact on determining the charge-discharge rate of thermal energy. The heat transfer rate and conductivity of composite materials have seen a similar improvement. In addition, as the volumetric fraction of Al_2O_3 nanoparticles increased, the viscosity of the composite materials increased, thus the natural convection heat transfer efficiency was improved [10]. For a enclosure heated vertically and below, a related study by the authors replicated this analysis. As a result, paraffin wax containing nanoparticles displayed higher thermo-physical properties compared to pure paraffin [11]. Arasu et al. (2011) performed a study to examine the impact of volume fraction on melting and solidification processes for Al_2O_3 and CuO nanoparticles. When the authors compared Al_2O_3 and CuO nanoparticles, they found that Al_2O_3 nanoparticles increased the thermal performance of paraffin wax more [12].

In this study, the melting processes of pure paraffin (Rubitherm RT50) and 10% Al_2O_3 nanoparticle added as PCM in a rectangular melting area were numerically investigated. For comparison, for both pure paraffin (melting temperature 50 °C) and paraffin with nanoparticle additives, the effect of rising the wall temperature of the rectangular region to 65 °C, 70 °C and 75 °C on the total melting period was investigated. In this study, in which the Computational Fluid Dynamics (CFD) approach was used, ANSYS Fluent software was used to perform numerical analysis. As a result of the analysis, it was determined that the use of Al_2O_3 nanoparticles improved the rate of heat transfer.

2. NUMERICAL ANALYSIS

There are three analysis methods for the solution of engineering problems: experimental, numerical and theoretical solutions. One of the widely used solution methods for solving heat transfer problems is numerical analysis, since it is cheap and easily applicable [13-14]. CFD is a potent instrument used in academic research and industry for fluid mechanics and thermal design. CFD is a branch of fluid mechanics that analyzes fluid behavior problems by using numerical techniques and algorithms to solve them on a processor [15]. Fluent is a CFD software using the finite volume method. Fluent, which is used in many industries around the world and has become one of the most used software in the CFD market all over the world, is able to offer easy and short solutions to its users' most difficult problems as advanced technology commercial CFD software [16].

In this study, for numerical simulation of the phase transition during the melting process, ANSYS Fluent software (18.2) was used. In the Design Modeler unit of the program, a 2D model was initially created as a rectangular melting region. The produced 2D model had a width of 50 mm and a height of 400 mm. The inner parts of the melting area are filled with pure paraffin whose properties are given in Table 1. Due to its high heat storage capacity and suitable melting temperature, Rubitherm RT50 is the type of paraffin chosen for this analysis. In addition to pure RT50 paraffin, Al_2O_3 nanoparticle-added paraffin structure, which is improved in thermal conductivity, is also used as PCM. Al_2O_3 has 99,5% purity and 78 nm average particle size.

Table 1. Physical properties of Paraffin RT50 [17].

Properties	**Values**	**Units**
Melting temperature	318-324	K
Latent heat	160000	J/kg
Specific heat capacity	2000	J/kgK
Density (solid)	880	kg/m^3
Density (liquid)	760	kg/m^3
Thermal conductivity	0,2	W/mK
Volume expansion	12,5	%

Quadrilateral mesh structure was used in the MESH sub-program of ANSYS software and the meshing process of the model (Figure 1) was performed. The generated mesh model contained 5226 nodes and 5000 elements. The left surface temperature of the rectangular melting area was defined as 65 ° C, 70 ° C and 75 ° C to examine the effect

of PCM on heat transfer, and all other surfaces were defined as the adiabatic surface. The PCM is at first in a solid state and the PCM's initial temperature is 25°C.

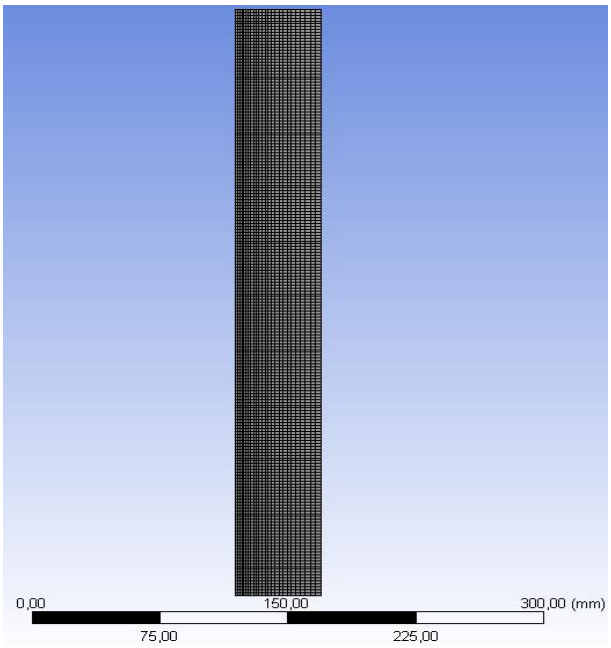

Figure 1. Generated mesh model

Using the finite volume method in numerical analysis, ANSYS Fluent program analyzes phase change problems according to the enthalpy-porosity method [16]. In this study, some assumptions have been made to simplify numerical analysis.

- PCM is isentropic and homogeneous.
- For solid and liquid phases, PCM thermophysical properties are distinct, but are temperature-independent.
- The phase change process in the PCM is considered to occur isothermally.
- Heat transfer occurs through conduction as well as through natural convection.
- Movement of PCM in liquid state is laminar, unsteady and incompressible.

According to these assumptions, continuity, momentum and energy equations for two dimensional transient laminar flow are given below.

Continuity:

$$\nabla.\vec{V} = 0 \tag{1}$$

Momentum:

$$\frac{\partial \vec{V}}{\partial t} + \vec{V}.\nabla\vec{V} = \frac{1}{\rho}\left(-\nabla P + \mu\nabla^2\vec{V} + \rho\beta\vec{g}(T - T_{ref})) + \vec{S}\right) \tag{2}$$

Thermal Energy:

$$\frac{\partial h}{\partial t} + \frac{\partial H}{\partial t} + \nabla.\left(\vec{V}h\right) = \nabla.\left(\frac{k}{\rho C_p}\nabla h\right) \tag{3}$$

The substance enthalpy is determined as the sensible enthalpy, h, and the latent heat, ΔH [16]:

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

where,

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

It is possible to write the latent heat content in terms of the material's latent heat, L:

$$\Delta H = \lambda L \tag{6}$$

Here ΔH can differ between zero (solid) and L (liquid). Thus, the liquid fraction, λ, can be described as [16]:

$$\lambda = \begin{cases} \frac{\Delta H}{L} = 0 & if\ T < T_{solidus} \\ \frac{\Delta H}{L} = 1 & if\ T < T_{liquidus} \\ \frac{\Delta H}{L} = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & if\ T_{solidus} < T < T_{liquidus} \end{cases} \tag{7}$$

In Eq. (2), $\vec{S}$ is the damping terms of Darcy's law that are applied to the momentum equation because of the effect of phase change on convection. It is defined as being:

$$\vec{S} = \frac{(1-\lambda)^2}{\lambda^3} A_{mush}\vec{V} \tag{8}$$

The coefficient A_{mush} is a mushy zone constant. This constant, which is normally a very big number such as 10^4–10^7 [18] is assumed to be constant in the current study and set to 10^6.

In the unsteady solver in ANSYS Fluent program, governing equations are decomposed using the finite element method. The melting / solidification model was studied by applying the enthalpy-porosity method for laminar flow. Governing equations for PCM were solved at the same time in all computational areas with Fluent's Solver-set COUPLED algorithm. In this study, PRESTO method (Pressure Staggering Option) recommended for natural convection was applied for pressure. To solve the momentum and energy equations, the SECOND ORDER UPWIND approach was used.

3. RESULTS & DISCUSSION

In Figure 2, when the left surface temperature of the rectangular melting area is 65 ° C, 70 ° C and 75 ° C, variation of liquid fraction versus time that during the melting (charging) process of pure paraffin are shown. Here, the blue color (the region where the liquid fraction is 0) indicates the amount of PCM in the solid state, the red color (the region where the liquid fraction is 1) the amount of PCM in the liquid state. The solid-liquid interface that separates the two phases is called the mushy zone. The mushy zone is shown by the yellow-green color (the area where the liquid fraction is between 0 and 1) composed between the solid and liquid phase. With the initiation of the melting, the heat transfer from the hot wall on the left to the solid PCM causes the PCM to melt. Initially, heat transfer occurs by conduction in all regions. Then, with the melting of PCM, natural convection begins to show its effect. Because of the effect of natural convection, the heat increases towards

the upper part of the melting area filled with PCM, and the molten liquid PCM stays in the higher sections as its density is smaller. The melting rate is very high at the beginning, but over time, it begins to slow down. The PCM takes the heat from the hot left surface and stores it with the initiation of melting.

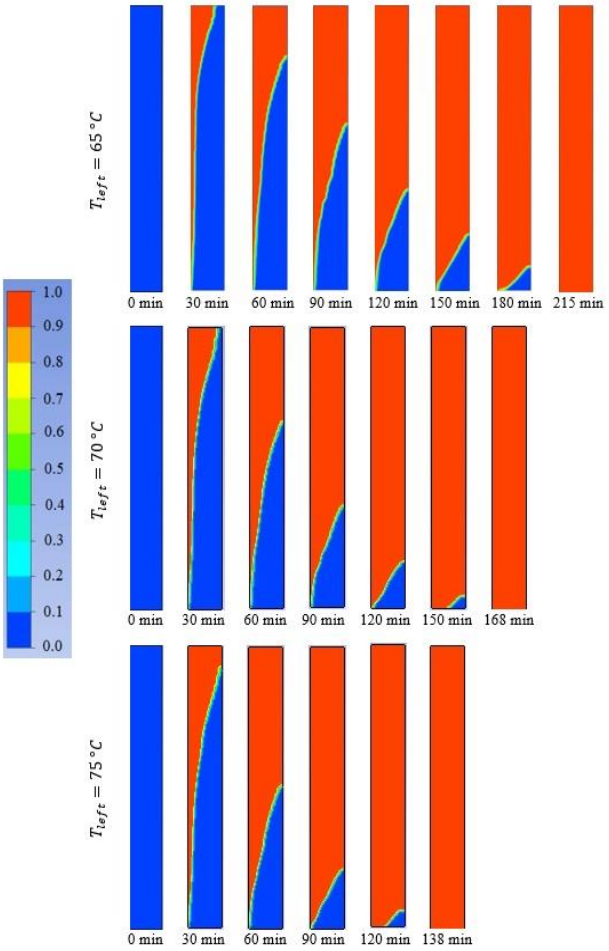

Figure 2. Time-varying liquid fraction of pure paraffin during melting (charging) with different left surface temperatures

The melting process depends on the left surface temperature of the rectangular melting area. The temperature-time graph of the study performed with left surface temperature 65 ° C, 70 ° C and 75 ° C in a two-dimensional rectangular model is given in Figure 3. The temperature here is the average surface temperature of pure paraffin during the melting process. When the left surface temperature is 65 ° C, PCM melts in 215 minutes, at 70 ° C in 168 minutes and at 75 ° C in 138 minutes. As the left surface temperature increases, the heat transfer occurs faster and the melting time of the PCM decreases significantly.

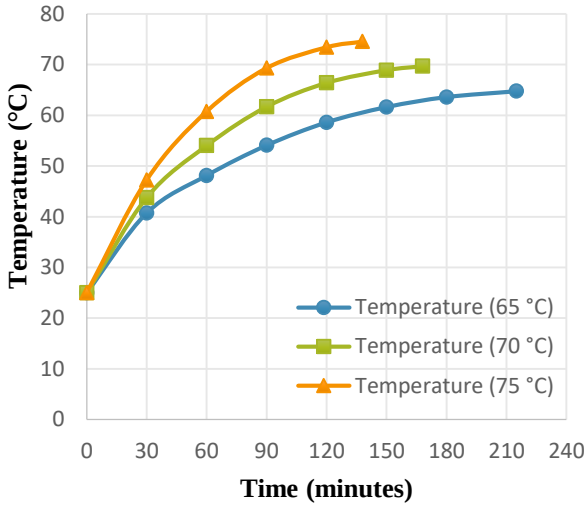

Figure 3. Average temperature profile in pure paraffin for different left surface temperatures

The melting time of PCM is very important and most of the studies on this subject are in this direction. Another method of reducing the melting time is adding nanoparticles into the PCM. Temperature-time graph of 10% Al_2O_3 nanoparticle doped paraffin is given in Figure 4, and liquid fractions are given in Figure 5. As seen in the figures, as the left surface temperature increased, the heat transfer rate increased significantly. When the left surface temperature is 65 ° C, the nano-PCM melts in 177 minutes, at 70 ° C in 139 minutes and at 75 ° C in 114 minutes. Compared with pure paraffin, the use of Al_2O_3 nanoparticles significantly increases heat transfer rate due to the poor thermal conductivity of pure paraffin.

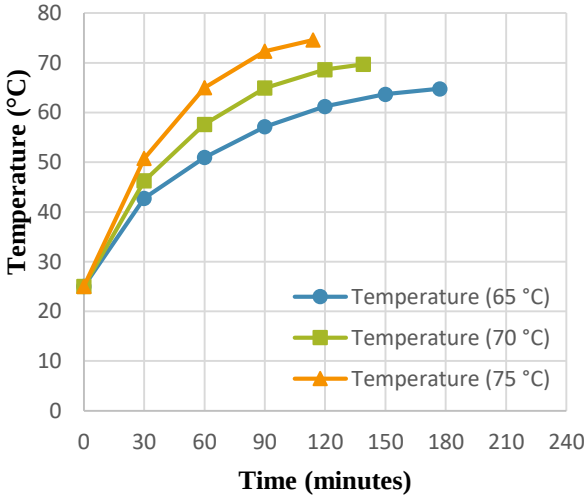

Figure 4. Average temperature profile in Al_2O_3 nanoparticle added paraffin for different left surface temperatures

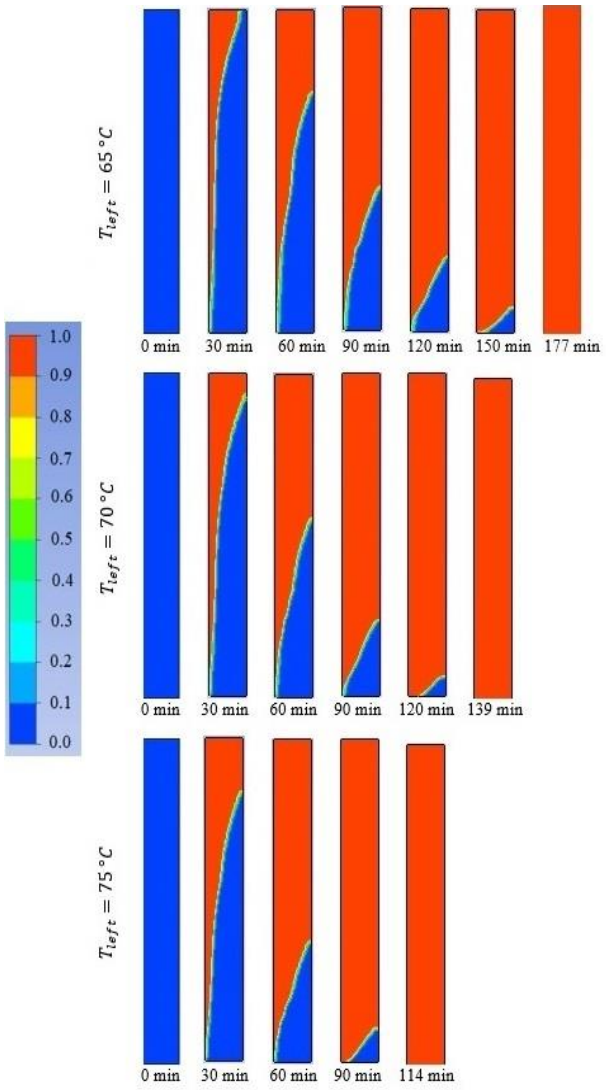

Figure 5. Time-varying liquid fraction of Al_2O_3 nanoparticle added paraffin during melting (charging) with different left surface temperatures

When compared our findings to those published in the literature, it was discovered that investigators reported similar results. To illustrate; Arasu et al. (2012) performed numerical simulations using FLUENT software in double-tube heat exchanger to examine the impact of Al_2O_3 nanoparticles on paraffin wax. It was concluded that Al_2O_3 nanoparticles have a significant effect on determining the charge-discharge rate of thermal energy as compared to pure paraffin [10]. Waghmare (2014) performed an experimental research to examine the performance enhancement of paraffin wax with nanoalumina particles with a mass fraction of 1, 2, 3, 4 and 5% in a latent heat storage system. The comparative results indicate that the charging rate of thermal energy can be improved using paraffin wax with alumina as compared with a pure paraffin wax as phase change material [19].

4. CONCLUSION

In this numerical work, the melting processes of pure paraffin (Rubitherm RT50) and paraffin containing 10% Al_2O_3 nanoparticle as PCM in a rectangular melting area were numerically investigated. Numerical studies have been performed as two dimensionals, unsteady and have been carried out using ANSYS Fluent commercial software package. The main concluding remarks are presented as follows:

- The thermal behavior of the rectangular melting area got filled up with PCM were numerically analysed. The melting process in the PCM were modelled for the left surface temperature value of 65 ° C, 70 ° C and 75 ° C respectively.
- The amount of heat transfer to the PCM increases as the left surface temperature increases.
- It melts in a shorter time, in other words, it stores (charges) heat faster when surface temperature is high.
- With the use of Al_2O_3 nanoparticles, thermal conductivity is increased and the heat transfer with conduction increases, so PCM melts significantly.

NOMENCLATURE

C_p	Specific Heat
h	Sensible Enthalpy
H	Total Enthalpy
k	Thermal Conductivity
L	Latent Heat
P	Pressure
$\vec{S}$	Source Term
t	Time
T	Temperature
$\vec{V}$	Velocity Vector

Greek symbols

λ	Liquid Fraction
β	Volumetric Expansion Coefficient
ρ	Density
μ	Dynamic Viscosity

Subscripts

mush	Mushy Zone
ref	Reference

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Büşra ARSLAN: Performed the numerical studies and analyse the results. Wrote the manuscript.

Mustafa İLBAŞ: Performed the numerical studies and analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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