Numerical Analysis of Double Pipe Heat Exchanger Using Different Internal Pipe Material in the Melting Process of PCM

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A B S T R A C T

This study investigated the full melting times of Phase Change Materials (PCMs) stored in the space between two pipes in a double-pipe heat exchanger using a two-dimensional Computational Fluid Dynamics (CFD) model. $CaCl_2.6H_2O$ and $Na_2SO_4.10H_2O$, salt hydrates in the inorganic group, were used as PCM in the intermediate space. The inner pipe material through which the heat transfer fluid passes was changed in the heat exchanger and analyses were continued for aluminum and copper. The melting thermal behavior of the heat exchanger, which is designed as a thermal energy storage unit with CFD analysis, is modeled under optimum design conditions created according to the enthalpy-porosity approach. As a result, in the heat exchanger where $CaCl_2.6H_2O$ is used as PCM, the full melting times of PCM were measured as 105 and 115 minutes if the inner tube was copper and aluminum and 130 and 140 minutes, respectively, when $Na_2SO_4.10H_2O$ was used. In the case of using copper instead of aluminum as the inner tube material, it was observed that the melting time shortened by 8.7% in the heat exchanger with $CaCl_2.6H_2O$ and by 7.1% in the heat exchanger with $Na_2SO_4.10H_2O$.

Contents

1.   Introduction

Because phase-change materials have a nearly constant operating temperature range and a high thermal energy density, they are crucial for thermal energy storage in discontinuous power-generating applications like waste heat recovery and solar energy systems. Because of this, research on using phase change materials for thermal energy storage has increased recently.

Heat transfer with phase-change materials, which use chemical bonds to store latent heat, occurs when the material structure changes from solid to liquid to liquid to solid with phase-change materials, which have a melting temperature between 20 and 32 °C, thermal energy storage is used both

passively and actively for heating and cooling purposes in systems such as solar energy or waste heat utilization. Thermodynamic, kinetic, and chemical properties [1]of phase change materials, which are desired to be suitable, economical, and easy to find, are classified as organic, inorganic, and eutectic [2, 3].

Metals, alloys, salts, and salt hydrates are examples of inorganic compounds. Sodium thiosulphate pentahydrate, calcium chloride hexahydrate, sodium sulfate decahydrate (also known as Glauber's salt), sodium acetate trihydrate, and barium hydroxide octahydrate are examples of salt hydrates. They are preferred due to their advantages, such as having a high latent melting temperature in terms of volume and having high thermal conductivity [4, 5]. These benefits led to adopting sodium sulfate decahydrate (Glauber's salt) and

calcium chloride hexahydrate in the current salt hydrate study.

Due to its crucial role in enhancing the performance of latent heat storage units and assisting in designing more suitable systems, phase change material has been the subject of several research on latent heat storage in the literature.

In the study conducted by Kenısarın and Mahkamov [6] various methods to enhance heat transfer in latent heat storage, the properties of PCMs, and their applications were analyzed for scientific research purposes [6]. The analysis revealed deficiencies and inaccuracies in the existing literature related to these topics, emphasizing the necessity to test the thermal stability of PCMs for at least 1000 thermal cycles, particularly when developing commercial latent heat storage materials. The study also provided insights into techniques that can be employed to improve heat transfer in latent heat storage using phase change materials. Zalba et al. [7] conducted a study where they examined over 150 PCMs used in cooling systems with minor temperature differences between daytime indoor and nighttime outdoor environments, along with their thermo-physical properties. The study highlighted significant discrepancies in the data for melting temperature and latent heat of the same PCM from existing studies. Additionally, due to the inadequate long-term thermal stability of PCMs, the widespread use of latent heat storage could have been improved. In this study, an empirical model was developed to design a real free cooling system, which was then economically evaluated [7].

It was clarified in Hasnain [8] study that the choice of phase change material is a critical factor in the efficiency of latent heat thermal energy storage systems and heat transfer mechanisms. It was emphasized that the thermal and physical properties of the phase change material in its solid and liquid states must be carefully examined. In order to create fusion heat storage systems for low-temperature solar energy heating and home hot water production applications, Abhat et al. [9] carried out an experimental investigation. The study includes research results on the two critical parameters of fusion heat storage technology: heat storage materials and heat exchangers. In the storage unit where a heat exchanger filled with PCM was used, aluminum fins were radially placed.

There are also many studies on the melting and solidification times of PCMs for latent heat storage in double-tube heat exchangers. Among these, in a study conducted by Fang and Chen [10], different types of PCMs (fusion-deposition modeling) were placed in the annular space between the tubes of a concentric heat exchanger, where the heat transfer fluid (HTF) passed through the inner tube. They used a theoretical model based on the enthalpy method to investigate the performance of a latent thermal energy storage (LTES) unit with multiple PCM fractions. They ran numerical simulations to investigate the impact of various multiple PCMs on the melting fraction, stored thermal energy, and liquid outlet temperature of the LTES unit. The numerical findings demonstrated that the PCM percentages and melting temperatures significantly influenced the LTES unit's performance. Consequently, it was emphasized that the appropriate selection of multiple PCMs is crucial for improving the performance of the LTES unit. Additionally, it was observed that using multiple PCMs played a significant role in the melting temperature difference [10].

Darzi et al. [11] conducted a numerical study using the FLUENT software to investigate the phase change process of N-eicosane phase change material within a double-pipe heat exchanger for both concentric and eccentric pipe configurations in a cylindrical container. In the unit where the HTF from the inner tube was stored in the PCM between intermediate cylinders, it was observed that the melting rate was approximately the same before 15 minutes. After this period, it was observed that the melting rate decreased in the concentric arrangement and sharply increased when the inner pipe moved downward from the center. At the same time, it was noted that heat transferred to the PCM dominated all regions at the onset of melting [11].

Bilen et al. [12] examined the melting and solidification processes of $CaCl_2.6H_2O$ in a vertical concentric heat exchanger to store thermal energy [10]. The results of this study, which examined many design and operating factors inside the PCM, such as mass flow rate and the temperature of the intake HTF, revealed that design parameters were more important than operating parameters. Additionally, they observed that the influence of fins placed inside the PCM on the melting and solidification durations was much more significant than the effects obtained from flow rate and vortex generators placed in the flow.

Literature reviews on selecting tube materials in heat exchanger systems often focus on heat pipes and heat pump studies. However, research on tube material selection for double-pipe heat exchangers still needs to be done. In this study, which addresses material selection in double-pipe heat exchangers, a literature review was conducted, and studies related to heat exchangers in other systems were examined.

Copper tubes and aluminum plate fins commonly use heat pipe heat exchangers in systems. In some applications, using the same material for both the tube and fins may be preferable because of differential thermal expansion. When the outlet temperature is below 220 °C, heat pipe heat exchangers are typically made from aluminum tubes and fins. Copper heat pipes, which have an efficiency similar to this design, are more expensive than aluminum. Copper-based designs are preferred over aluminum, mainly due to corrosion and fouling concerns, albeit at a higher cost. Protective coatings against corrosion can be applied to these systems in a way that minimally affects thermal efficiency. Heat pipe heat exchangers where the temperature exceeds 220 °C are generally manufactured from steel tubes and fins [13].

When examining studies related to the selection of pipe materials in heat pump systems, which also use heat exchangers, research has been conducted on the choice of pipe materials through which the refrigerant fluid, which is the working fluid, flows. In a study conducted by Javadi et al. [14], parameters such as geometric configuration, working fluid, and the depth of the ground heat exchanger affecting the heat flux, alongside pipe material selection, were considered to achieve a high coefficient of performance. In ground-source heat exchangers, where heat transfer between the refrigerant fluid and the heat source occurs along a pipe, criteria such as durability, longevity, flexibility, and high thermal conductivity are considered. According to statistics from 2010 to 2018, the usage of pipe materials in ground-source heat pumps is as follows: 60% polyethylene (PE), 14% Steel, 8% Copper, 4%

polypropylene (PP), 2% Polyurethane (PU), 8% Polyvinyl Chloride (PVC), 2% Plastic. Based on the usage rate of pipe materials, polyethylene is the most preferred, followed by steel and polyvinyl chloride (PVC). The results show that when copper pipes are used in such systems, the time before reaching thermal saturation and the effective period increase by 15.7% compared to high-density polyethylene (HDPE) pipes [14].

Serageldin et al. [15] researched the thermal performance of a horizontal ground-air Heat Exchanger (EAHE) used for heating and cooling. They investigated the temperature distribution of the moving air in the system experimentally, mathematically, and numerically. The researchers observed that the outlet air temperature was not significantly affected by the material change in their investigation, which employed three different pipe materials, including PVC, steel, and copper. The outlet air temperature was 19.7 °C for PVC, 19.8 °C for steel, and 19.8 °C for copper. As a result, they stated that the variation in outlet air temperature for different pipes had a negligible effect when evaluated based on material costs.

A ground-air Heat Exchanger (EAHE) system was analyzed for heating performance and operational feasibility in a study. A study evaluating the performance of two EAHE systems constructed of zinc and PVC revealed that the zinc pipe system performed better in arid or steppe environments with a moderate climate. On the other hand, PVC performed far better in arid climates than in steppe or temperate ones. The findings showed that the geo-climatic conditions and the kind of pipe material utilized significantly impact the thermal performance of EAHE [16].

When designing heat exchangers, selecting materials enhances heat transfer efficiency. Factors such as high thermal conductivity, resistance to corrosion, cost-effectiveness, low pollution formation rate, volume, or weight are important considerations. These parameters also influence the choice of materials for heat exchanger tubes. Common materials used for heat exchanger tubes include aluminum, copper, steel alloys, ceramics, or composite materials. The decision on which material to use is made based on several criteria. Aluminum is advantageous due to its low density, making it lighter.

Furthermore, even though aluminum alloys are more expensive than steel alloys, they are cheaper than copper alloys, which is an essential factor in their preference. Copper materials, which have a higher density than aluminum but are the same as steel, are chosen because of their highest thermal conductivity despite being more expensive. Copper, among the most corrosion-resistant metal materials, is also easier to repair than aluminum. On the other hand, steel alloys are more cost-effective than copper and aluminum, but copper material is more corrosion-resistant. Additionally, their thermal conductivity is lower than copper and aluminum materials [17, 18].

In one of the studies in the literature where aluminum and copper were used with PCM and paraffin wax (Rubitherm RT-25) was used as PCM, a detailed parametric study was carried out to investigate the melting process in a 5–10 mm

high system. Simulations have shown aluminum can be used as a phase change material in cooling systems [19].

Saha and Dutta [20] numerically analyzed the use of aluminum in the melting process on a flat plate using n-eicosane as PCM. Again, Lamberg and Siren [21] used octadecane paraffin as PCM with aluminum, and Ji et al. [22] used PCM paraffin RT-42 for thermal energy storage. Zhao et al. [23] used lauric acid as PCM. They numerically investigated the effect of fin spacing in thermal storage for two different fin materials (aluminum and stainless steel). Sharifi et al. [24] developed a numerical model to simulate the melting of phase change material placed inside a copper enclosure using Octadecane as PCM. He et al. [25] investigated the system's thermal efficiency using paraffin RT55 as PCM, copper as a HTF tube, and fin material in the specified flow rate range for the three-card design. It was reported that optimizing the fin shape increased the thermal efficiency of the melt by 21.9%.

Kamkari and Shokouhmand [26] used lauric acid as PCM and investigated the melting process for different wall temperatures of 55 ^{0}C, 60 ^{0}C, and 70 ^{0}C in a rectangular enclosure made of aluminum sheets. Increasing the heat transfer surface area provided more efficient melting.

To make informed decisions about selecting pipe materials for heat exchangers used for latent heat storage, it is beneficial to consider the corrosion parameter, as mentioned above. In this regard, Coen conducted a study investigating the corrosion resistance of stainless steel, carbon steel, Al alloys, and copper metal alloys against thirty hydrates used as phase change materials in latent heat storage. Commercially available hydrates with melting points ranging from 15°C to 32°C, including $CaCl_2.6H_2O$ (MP, 27 °C), $Na_2SO_4.10H_2O$ (MP, 32°C), $Na_2SO_4.1/2NaCl.10H_2O$ (MP, 20°C), and $NaOH.3,5H_2O$ (MP, 15°C), were examined. Additionally, the thermal performance reliability of these hydrates was investigated through repeated melting-solidification thermal cycles in the same system. The study determined that stainless steel exhibited the highest corrosion resistance among all the tested phase change materials. Copper and C20 steel were also usable, but a brittle corrosion layer would form in the latter's case. All Al alloys tested were susceptible to corrosion by the phase change materials. Among the tested hydrate PCMs, only $CaCl_2.6H_2O$ showed stability after 5650 thermal cycles [27].

When examining studies conducted on metals in contact with salt hydrates in the literature, specifically aluminum [28–31] and copper [29–31], it has been observed that traditional configurations, such as aluminum fins applied or aluminum-coated copper heat pipes, are susceptible to corrosion when used with salt hydrates. To reduce the effects of galvanic corrosion, it has been noted that the anode surface area of aluminum should be maximized. In contrast, the cathode surface area of the copper tube should be minimized. Additionally, it has been suggested that different aluminum alloys may offer increased protection against this type of corrosion. To address this issue, it has been suggested that using PCM separator plates or zinc coatings in areas where salt hydrate storage is employed may provide resistance against this corrosion [32].

In conclusion, this study employed inorganic phase change materials, specifically salt hydrates, which can retain their latent heat even after numerous melting and solidification cycles. Based on a literature review, salt hydrates such as $CaCl_2.6H_2O$ (MP 27 °C) and $Na_2SO_4.10H_2O$ (MP 32 °C) were chosen for latent heat storage due to their capacity to store twice as much energy per unit volume compared to organic phase change materials [5, 33–35].

Although these salt hydrates exhibit certain disadvantages, such as supercooling, moderate corrosiveness, slight toxicity, and inappropriate melting behavior, they are preferred due to their economic feasibility, high thermal conductivity, low volume changes, and good nucleation properties [4, 36].

In conclusion, this study aims to contribute to selecting materials for heat transfer components, such as pipes and fins used in latent heat storage with salt hydrates. Despite the corrosion effects observed in the literature, aluminum has been a popular choice due to its lightness in traditional applications and its superior thermal conductivity compared to steel. Copper, the most corrosion-resistant metal material with salt hydrates and higher thermal conductivity than other traditionally used materials, has also been favored. The literature needs to include studies explicitly addressing the impact of the choice of metal materials on the total melting time of phase-change materials in concentric heat exchangers used for storing phase-change materials. Therefore, this study is expected to contribute to the literature by providing insights into the material selection for the design of heat exchangers in latent heat storage applications involving phase change materials.

To achieve this goal, ANSYS analyses were conducted to investigate how the melting times of two salt hydrates change with different waste HTF temperatures at 50 °C, 60 °C, and 70 °C. The study aimed to determine how much reduction in melting times, especially at the optimum waste heat temperature of 60 °C, would be achieved through material selection. This research provides preliminary insights into the advantages of material selection in various heat exchangers in reducing phase change material melting times when designed for different waste heat temperatures.

Due to the low thermal conductivity of PCMs, there are different studies in the literature to improve heat transfer. In particular, there are many studies in the literature where metal or metal foams are placed in the PCM in the form of fins; materials with high thermal conductivity, such as graphite and carbon, are added to the PCM in the nanostructure, or the encapsulation method is used.

The difference between this study and the literature is to investigate how changing the material of the pipe through which the HTF enables the melting of two different salt hydrates in the interstitial space, such as aluminum and copper, affects the melting time of phase-change materials. In this study, changing the heat transfer tube material to improve heat transfer from a perspective different from that of the literature has been investigated. Thus, it aims to provide an idea for ANSYS analyses with superior materials produced in the developing materials sector.

2. Materials and Methods

In a 1000 mm-long concentric heat exchanger system, first, $CaCl_2.10H_2O$ and then $Na_2SO_4.10H_2O$ salt hydrates were deposited between the nested pipes. The ANSYS analysis method investigated how the melting times change if the inner tube through which the water used as HTF passes is made of aluminum and copper materials. The inner pipe through which the HTF passes and which was selected from copper and aluminum, respectively, was selected from the existing pipe diameters commonly used in practice with an outer diameter of 23 cm and a wall thickness of 1.5 cm, and the outer pipe with an inner diameter of 75 cm and a wall thickness of 7.5 cm. Plastic pipe was selected to support external insulation. The continuous system conditions of the analysis were chosen such that the internal HTF velocity was 0.7 m/s to ensure turbulent flow in the inner tube, the temperature (selected by the optimum industrial wastewater temperature) was 60 °C, and the ambient temperature of the PCM was 25 °C. Figure 1 shows the left side cross-section, front view, and dimensions of the double tube heat exchanger.
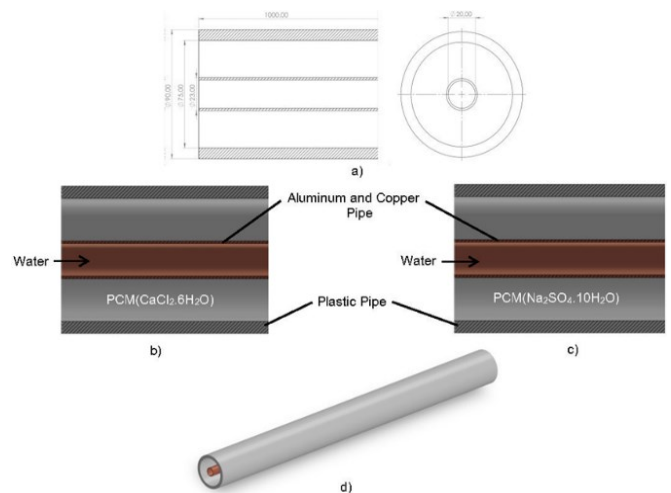

Figure 1 The left side cross-section view, front view, and dimensions of the double tube heat exchanger a), left side cross-sectional view of the double tube heat exchanger stored $CaCl_2.6H_2O$ b), left side cross-sectional view of the double tube heat exchanger stored $Na_2SO_4.10H_2O$ c), view of the double tube heat exchanger d).

In the space between the inner and outer tubes of the concentric heat exchanger, PCMs that can store latent heat by changing from solid to liquid phase are stored. PCMs are intended to melt and store thermal energy by taking heat from water, the heat transfer fluid at 60°C passing through the inner pipe.The thermophysical properties of $CaCl_2.6H_2O$ and $Na_2SO_4.10H_2O$, which are salt hydrates selected considering their suitability for temperatures between 0 °C and 100 °C [37] and the thermophysical properties of copper and aluminum selected as inner tube material are given in Table 1.

2.1. ANSYS Analysis

The enthalpy-porosity method, used to solve the problems of phase change at constant temperatures and temperature ranges, was used to analyze the phase change process in the melting time analysis of two inorganic phase transformation materials using the Ansys Fluent 2021 R2 program.

Table 1 Thermophysical properties of CaCl₂.6H₂O and Na₂SO₄.10H₂O aluminum and copper [12, 38, 39]

Physical Properties	CCaCl₂.6H₂O	Na₂SO₄.10H₂O**	Aluminum	Copper
Melting Temperature (°C)	28	32,4	660.32	1084.6
Latent heat (kJ/kg)	200	254	-	-
Density (kg/dm³)	1,71**	1,485	2700/-	8960/-
Specific Heat capacity solid/liquid (kJ/kg ⁰C)	1,25/2,13	1930	-	-
Thermal conductivity solid/liquid (W/m ⁰C)	0,626 (24 ⁰C) /0,454 (41 ⁰C)	0,544***	237	401

The fluid analysis using continuity, momentum, and energy conservation equations activated the "Solidification and Melting" process, and the pressure and velocity options were set to "second order." In the "transient," i.e., time-dependent analysis, each iteration time step was chosen to be 0.2 seconds due to the trial studies. In this analysis, the "k-epsilon" two-equation "solver" was used for the turbulent flow model because it provides very close to realistic solutions for the internal flow. The continuity, momentum, and energy equations used in the analysis are given in equations (1), (2), and (3) [40].

Continuity Equation:

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

Momentum Equation:

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

Energy Equation:

$$\frac{\partial h_{sensible}}{\partial t} + \frac{\partial h_{latent}}{\partial t} + \nabla . (\vec{V} h_{sensbl}) = \nabla \left(\frac{k}{\rho cp} h_{sensbl}\right) \tag{3}$$

where k is PCM's thermal conductivity, and h is PCM's enthalpy per unit mass.

$$h = h_s + h_l = 0 \tag{4}$$

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

$$h_L = x \times LH_F \tag{6}$$

LH_F is the heat of fusion of PCM, and x is the percentage of PCM converted to liquid [41]. In addition, λ The liquid fraction defined as the liquid fraction of the melting-solidification process is given below [42]

$$\lambda = \begin{cases} 0 & \iota f & T \leq T_{solid} \\ 1 & \iota f & T \geq T_{liquid} \\ \frac{T - T_{solid}}{T_{liquid} - T_{solid}} & \iota f & T_{solid} < T < T_{liquid} \end{cases} \tag{7}$$

In order to determine the number of mesh elements for the storage of CaCl₂.6H₂O inorganic salt hydrate as PCM in the space between the inner and outer tubes of the double tube heat exchanger, four mesh numbers were tested: 354.700, 549.000, 840.100, 1.612.530, and for Na₂SO₄.10H₂O, 354.704, 549.006, 840.103, 1.612.530. The melting time changes corresponding to different temperatures of PCM were analyzed. The PCM temperature-melting time change graph for CaCl₂.6H₂O is given in Figure 2, and the PCM

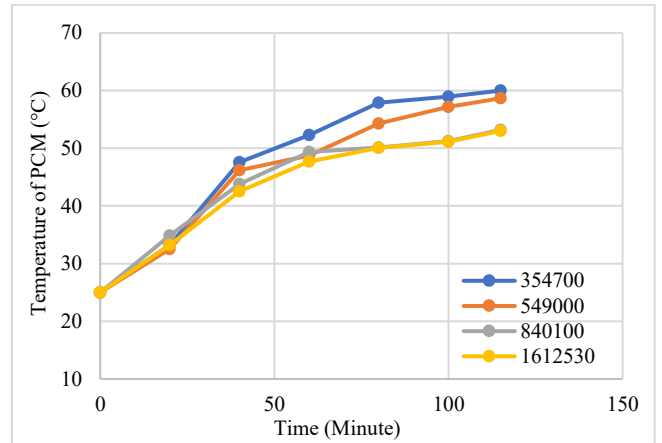temperature-melting time change graph for Na₂SO₄.10H₂O are given in Figure 3.

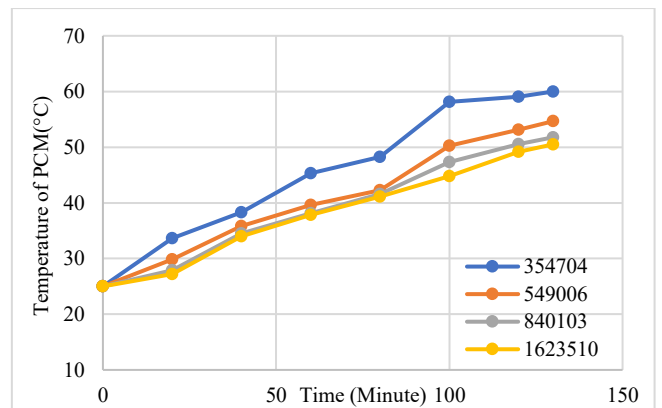Figure 2 PCM temperature-melting time variation for CaCl₂.6H₂O according to mesh number.

Figure 3 PCM temperature-melting time variation for Na₂SO₄.10H₂O according to mesh number.

In addition, while determining the appropriate mesh quality, the orthogonal and skewness values, which are effective parameters in determining whether the created network structure is knitted correctly, should be well analyzed. Namely, while the mesh quality of the model is evaluated between 0 and 1 in the orthogonal value, it should be taken into account that approaching the 1 limit increases the quality of the mesh structure. For skewness, in the value scale formed in the range of 0–1, the quality of the mesh structure will increase as it approaches 0.

The orthogonal value in this analysis was found to be predominantly 0.9999 (varying between 0.66 - 0.9999) and the skewness value was predominantly 0.015 (varying between 0.015-0.34).

As a result of the analyses carried out by considering these points, it was observed that this steady state was formed at mesh numbers 840.100 and 1.612.530 for $CaCl_2.6H_2O$ and 840.103 and 1.623.510 for $Na_2SO_4.10H_2O$, and the desired results were approached.

Since the convergence remains at very small values when the number of 1.612.530 meshes is reached after the number of 840.100 meshes, it is certain that increasing the number of elements further will increase the analysis time. For this reason, according to the logic of finite element analysis, the number of 1.612.530 meshes was preferred as the number of analysis meshes, since the more elements the process is carried out, the higher the convergence rate (the closer the correct result will be) for $CaCl_2.6H_2O$.

Therefore, since it was determined that increasing the mesh number further would not change the accuracy of the analysis, the mesh numbers were determined as 1.612.530 and 1.623.510 for $CaCl_2.6H_2O$ and $Na_2SO_4.10H_2O$, respectively. Figure 4 shows the mesh image of the concentric heat exchanger with 1.612.530 elements for ANSYS analyses.
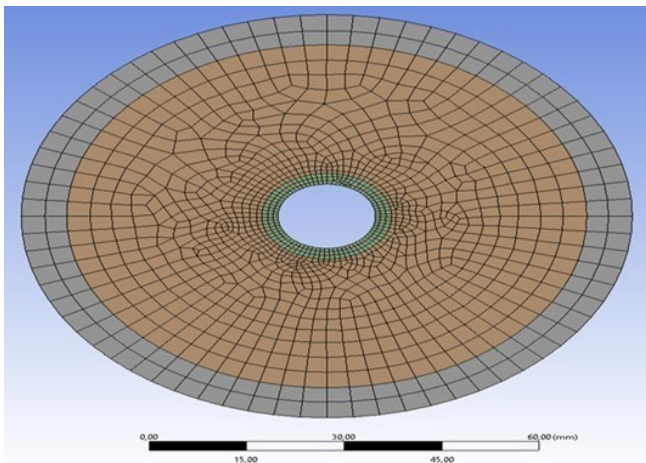

Figure 4 1.612.530 element mesh image of the concentric heat exchanger.

As the number of meshes increases in the model analyzed by the finite element method, it gets closer to obtaining realistic results. However, it should be noted that using a network structure (mesh quality) that is not suitable for the geometry and dimensions of the model under study will significantly negatively affect the analysis result, both in terms of time and in terms of distancing the designed model from the actual model in the analysis conditions.

3. Results and Discussion

The graph of PCM temperature and melting time variation for the heat exchanger in which $CaCl_2.6H_2O$ and $Na_2 SO_4.10H_2O$ are stored in the interstitial space, and the meshing process is applied with a 1.623.510 element number is given in Figure 5 and Figure 6, respectively. As can be seen in Figure 5, when the inner HTF tube is made of copper material, and the temperature is 50 °C, 60 °C, or 70 °C, the melting time of $CaCl_2.6H_2O$ decreases as the HTF temperature increases, and the PCM melting time shortens.
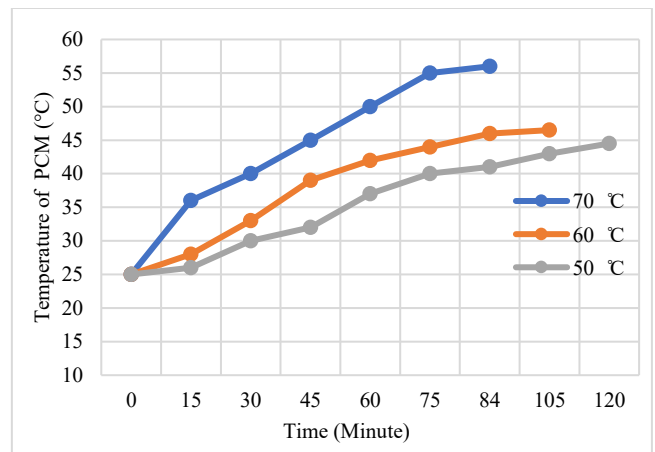

Figure 5 PCM temperature-melting time variation for $CaCl_2.6H_2O$ in a concentric heat exchanger with copper. The material was used in the HTF tube, and three different HTF temperatures were tested.

As is seen in the graph of the variation of the melting time of $CaCl_2.6H_2O$ with temperature in the cases where the inner HTF tube is made of aluminum material and the temperature is 50 ^{0}C, 60 ^{0}C, or 70 ^{0}C in Figure 6, the PCM melting time shortens as the HTF temperature increases. If the HTF tube material was copper, the shortening of the melting time with increasing HTF temperature was also observed when an aluminum HTF tube was used.
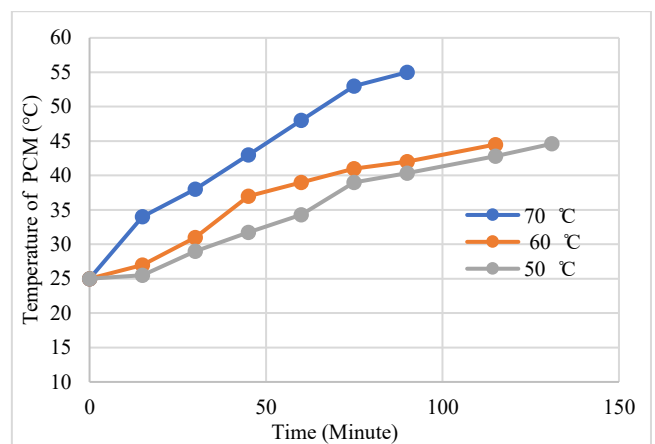

Figure 6 PCM temperature-melting time variation for $CaCl_2.6H_2O$ in a concentric heat exchanger with aluminum material used in an HTF tube and three different HTF temperatures tested.

In the heat exchanger system where $CaCl_2.6H_2O$ was used as phase transformation material, the complete melting time of PCM was 120 minutes when copper tubes were used at an HTF temperature of 50 °C. In comparison, it was 131 minutes when aluminum tubes were used. At 60 °C HTF temperature, the complete melting time of PCM was 105 minutes for copper pipe, 115 minutes for aluminum pipe, and again at 70 °C; these times were 84 and 90 minutes, according to the results obtained from the analysis.

As is seen in the graph of the change of the melting time of $Na_2SO_4.10H_2O$ with temperature in the case that the inner HTF tube is made of copper material and the temperature is 50 °C, 60 °C, and 70 °C in Figure 7, as the HTF temperature increases, the PCM melting time shortens.
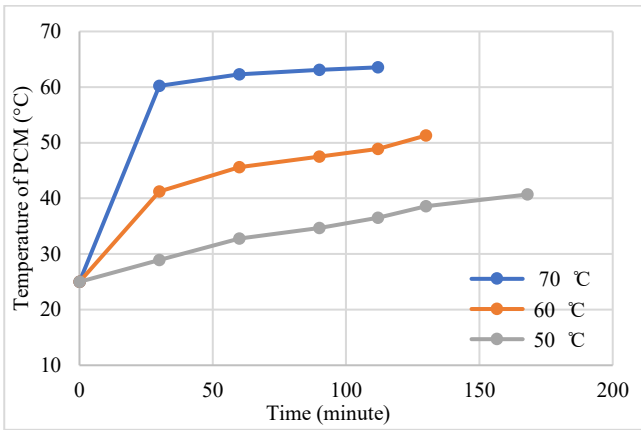
Figure 7 PCM temperature-melting time variation for $Na_2SO_4.10H_2O$ in the concentric heat exchanger with copper material used in the HTF tube and three different HTF temperatures tested.

As is seen in the graph of the variation of the melting time of $Na_2SO_4.10H_2O$ with temperature in the cases where the inner HTF tube is made of aluminum material and the temperature is 50 ^{0}C, 60 ^{0}C, or 70 ^{0}C in Figure 8, the PCM melting time shortens as the HTF temperature increases. If the HTF tube material was copper, the shortening of the melting time with increasing HTF temperature also occurred when an aluminum HTF tube was used.
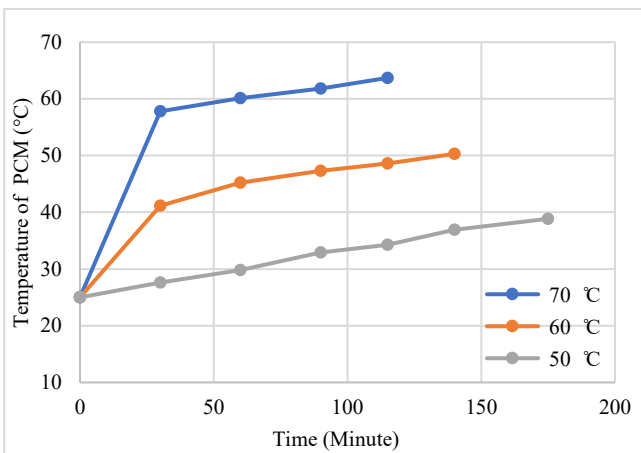

Figure 8 PCM temperature-melting time variation for $Na_2SO_4.10H_2O$ in a concentric heat exchanger with aluminum material used in an HTF tube and three different HTF temperatures tested.

In the heat exchanger system where $Na_2SO_4.10H_2O$ is used as phase change material, the complete melting time of PCM in the heat exchanger using a copper tube is 168 minutes at an HTF temperature of 50 °C, while it is determined to be 175 minutes if an aluminum tube is used. At 60 ^{0}C HTF temperature, the complete melting time of PCM for copper pipe is 130 minutes, 140 minutes for aluminum pipe, and again at 70 ^{0}C, these times are 112 and 115 minutes, according to the results obtained from the analysis. As in the presented study, in the experimental study conducted by Cano et al. [43], it was observed that increasing the HTF temperature shortens the melting time. The analyses continued assuming that the wastewater temperature of 60 °C in industrial plants would be an optimum value for the HTF temperature. In Figure 9, Figure 10, Figure 11, and Figure 12 the color scale on the left of the figure progresses from point 0 to point 1 (from dark blue to red). The changing

colors are defined to indicate the percentage melting processes in the PCM. When the color scale is dark blue, the range 0.0-0.1 indicates that the PCM is solid. When the color scale is red, the range 0.9-1 indicates that the PCM is completely liquid (complete melting). Under the conditions where the optimum HTF temperature is 60 °C, and the HTF velocity passing through the inner pipe is 0.7 m/s, the PCM complete melting images obtained from the analyses are presented in Figure 9 if copper is used with $CaCl_2.6H_2O$ and in Figure 10 if aluminum is used.
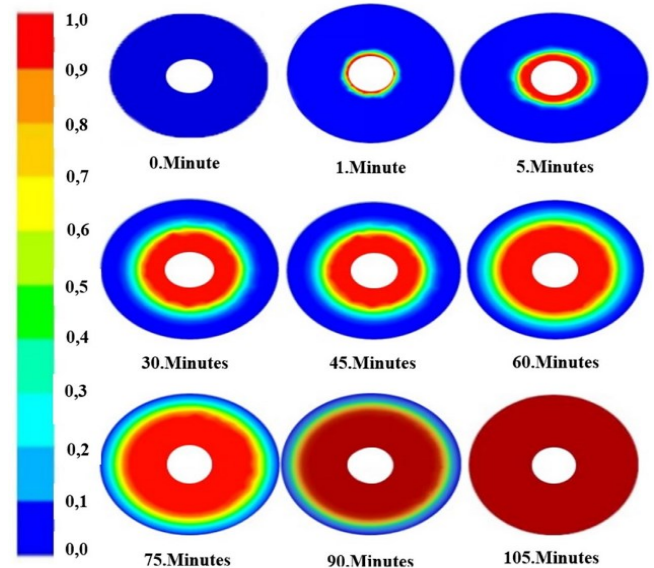

Figure 9 PCM melting time in case the inner HTF tube is copper in a concentric heat exchanger using $CaCl_2.6H_2O$ as PCM.

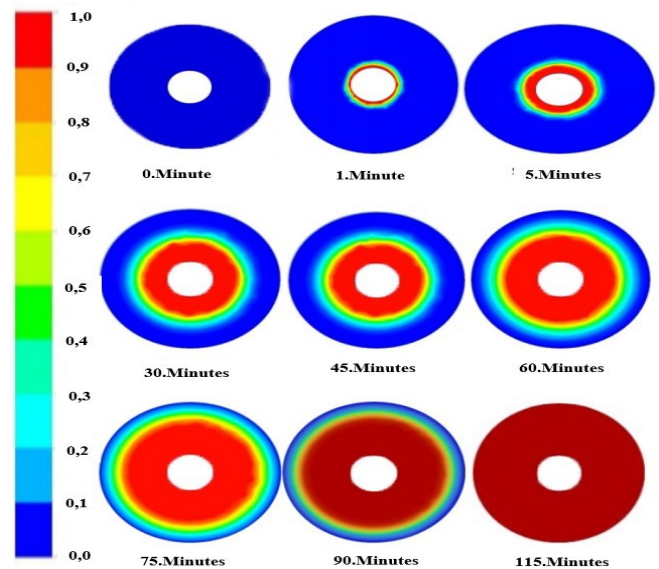Figure 10 PCM melting time in case the inner HTF tube is aluminum in a concentric heat exchanger using $CaCl_2.6H_2O$ as PCM.

Again, under the conditions where the optimum HTF temperature is 60 °C, and the HTF velocity passing through the inner tube is 0.7 m/s, the PCM complete melting images obtained from the analyses are presented in Figure 11 if copper is used with $Na_2SO_4.10H_2O$ and in Figure 12 if aluminum is used.
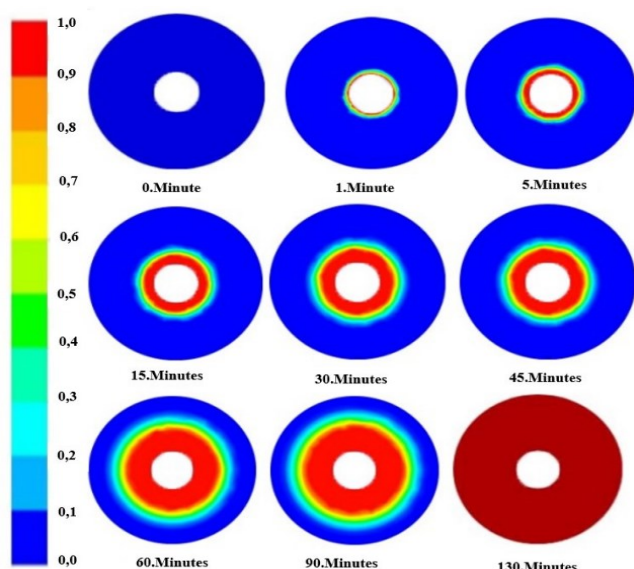
Figure 11 PCM melting time for a concentric heat exchanger using $Na_2SO_4.10H_2O$ as PCM when the inner HTF tube is copper.
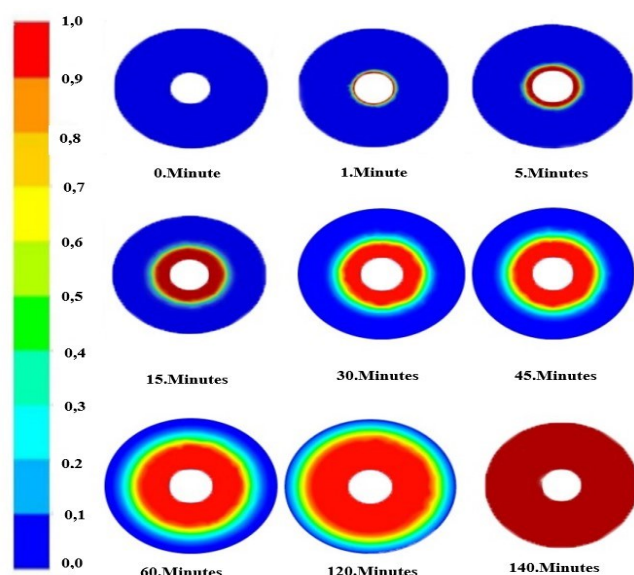

Figure 12 PCM melting time for a concentric heat exchanger using $Na_2SO_4.10H_2O$ as PCM when the inner HTF tube is aluminum.

Many studies are on improving heat transfer in systems using PCM. Tao and He [44] identified three basic categories to achieve this improvement: increasing the heat transfer surface area, increasing the effective thermal conductivity of the PCM compound, and increasing the homogeneity of the phase change process. In the present study, the role of the mentioned metals in heat transfer is investigated in the case where aluminum and copper are selected for the surface that the PCM contacts and the HTF pass through. In the literature, there are many studies in which aluminum material is used to increase PCM's heat transfer surface area, especially as a fin. In the study by Levin et al. [45], in which sodium-hydrate-based PCM and aluminum fins were used, a numerical study was carried out on the amount of PCM required to be stored for cooling an electronic device with transient and high heat generation. The results showed that the optimal PCM percentages depend on the number and length of fins, the heat flow at the interface, and the difference between the critical and liquid temperatures of the PCM.

Abdi et al. [46] used a PCM based on n-eicosane to study the solidification and melting of n-eicosane in a rectangular aluminum container. Expanding the heat transfer surface area in the melting stage showed that average power might rise by up to 90% while resulting in a 9% decrease in storage capacity. In addition, increasing the solidification power was more dependent on increasing the heat transfer area than the melting power [46].

Suresh and Saha [47] compared the performance of porous fins, solid fins, full porous foam, porous fins, solid fins, and porous fins with the performance of no fins in a study in which the shell and tube were made of copper, and the fins were made of solid and porous copper. The melting times were found to be decreased by 68.3, 32.8, and 32.9 percent for entire foam, solid fins, and porous fins, respectively [47]. Al-Mudhafar et al. [48] employed RT82 as the PCM in an ANSYS investigation where copper was used as the tube and fin material. The results revealed that employing T copper fins decreased the PCM's melting time by 33% compared to longitudinal fins.

Tiari et al. [49] conducted an experimental study using copper as PCM (Rubitherm RT55), heat transfer tubes, and fins [49]. Moreover, we obtained 84.1%, 85.77%, 58.5%, 85.5%, 85.5%, 89.45%, and 71.0% reduction in melting time for copper fin configurations used with variable diameter to increase the heat transfer rate to and from the PCM. In the study by Wang et al. [50] using RT50 (PCM) as PCM, it was observed that a significant performance improvement of up to 74% was obtained with the optimum copper fin design compared to the non-finned case in the study where the inner tube and fins were both made of copper [50].

As can be seen from the studies using copper and aluminum as heat transfer tube materials in the literature, these materials are frequently used in concentric heat exchanger systems. Considering the melting times of the phase change material stored in the interstitial space for three different operating temperatures of the mentioned tube materials used in such systems in this study will help researchers working at different temperatures in the selection of tube materials.

4. Conclusion

Because of the high thermal energy density and nearly constant working temperature of phase-change materials, thermal energy storage using these materials is a highly effective energy storage technique. The main objective of this study is to investigate the effect of using aluminum and copper as the inner tube materials to transfer heat to two different salt hydrates in the interstitial space of a concentric heat exchanger on the PCM melting time. The results obtained are given below.

•   When $CaCl_2.6H_2O$ was used as PCM, it was observed that the complete melting time was shorter for both copper and aluminum than $Na_2SO_4.10H_2O$.

•   In a concentric heat exchanger using $CaCl_2.6H_2O$ and $Na_2SO_4.10H_2O$ salt hydrates as phase change materials, the complete melting times of PCMs were compared by ANSYS analysis when the inner tube material through which the HTF passes was selected as copper and aluminum. Under the conditions of 60 °C and 0.7 m/s HTF velocity, which is accepted as the optimum HTF

temperature, the complete melting time for copper is 105 minutes and 115 minutes for aluminum if $CaCl_2.6H_2O$ is stored in the intermediate zone.The complete melting time for copper is 130 minutes and 140 minutes for aluminum if $Na_2SO_4.10H_2O$ is stored. This result showed that if the inner tube material was copper instead of aluminum, the melting time was shortened by 8.7% for $CaCl_2.6H_2O$ and 7.1% for $Na_2SO_4.10H_2O$.

• When $CaCl_2.6H_2O$ was used as phase change material, a 19.2% decrease in the complete melting time compared to $Na_2SO_4.10H_2O$ was found when copper was selected as the inner tube material, and a 17.8% decrease was found when aluminum was selected.

• ANSYS analyses of the heat exchanger, which is the thermal storage unit examined in this study, can be performed for different pipe diameters, different types of PCM stored in the annular space, and different HTF pipe materials with superior thermal properties, and their contributions to the PCM complete melting time can be investigated.

• Instead of the concentric heat exchanger investigated in the present study, the effects of changing the HTF tube material for different heat exchanger designs and different HTF tube types (multiple or helical tubes, finned tubes, etc.) on the PCM complete melting time can be investigated by experimental or simulation studies.

• In this study, in which only the melting times of PCMs were examined, the solidification process time that will occur due to transferring the heat stored by PCMs to water by passing cold water through the inner pipe can also be investigated.

• The analysis performed in the current study will be useful for researchers to decide on pipe material selection, especially in experimental studies with heat exchangers. It is thought that this study will be useful in deciding on the most efficient material selection when designing similar systems.

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