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Investigation of the Effect of Different Parameters of Phase Change Materials on Heat Exchanger Performance

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Abstract

Technological improvements and increasing energy demand necessitate energy efficient designs for heat transfer systems. The storage and reuse of heat energy plays an important role in the development of energy-efficient systems. Phase change materials (PCMs) are crucial components which increase energy efficiency in heat exchangers as can be applied to many systems. In this study, the heat transfer performance of different types of phase change materials in a regenerative heat exchanger was investigated according to different parameters. Reynolds number depending on the hot fluid velocity (Re=400, 800, 1200, 1600), hot fluid inlet temperature ($T_{sıcak,giriş}$=40, 60, 70, 80°C), and different types of phase change materials (RT60, RT100, and SP70) are the parameters used in this study. ANSYS Fluent software was used for computational fluid dynamics analysis. As a result, it has been determined that when the Reynolds number of the hot fluid in the heat exchanger was increased in the range of Re=400-1600, the heat transfer effectiveness increase of 17%; when the hot fluid inlet temperature was increased in the range of $T_{hot,inlet}$=40-80°C, the heat transfer effectiveness increase of 21%. As regards the effect of different types of phase change materials, the heat transfer effectiveness was 81% for RT60, 79% for SP70 and 76% for RT100. It has been evaluated that, with the results obtained from this study, heat exchangers with higher heat transfer effectiveness and higher energy storage capacity can be designed.

Keywords: Phase change material, heat exchanger, heat transfer effectiveness, Reynolds number

Faz Değiştiren Malzemelerin Isı Değiştiricisi Performansına Etkisinin, Farklı Parametreler İçin İncelenmesi

Öz

Teknolojik ilerlemeler ve artan enerji talebi, ısı transfer sistemlerinde enerji tasarruflu tasarımları gerekli kılmaktadır. Enerji tasarruflu sistemlerin geliştirilmesinde, ısı enerjisinin depolanması ve tekrar kullanılabilmesi önemli bir rol oynamaktadır. Faz değiştiren malzemeler (FDM), birçok sisteme

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uygulanabildiği gibi ısı değiştiricilerinde de sistemin enerji veriminde önemli artış sağlayan bir bileşendir. Bu çalışmada, rejeneratif bir ısı değiştiricisinde farklı tipteki faz değiştiren malzemelerin ısı transfer performansı farklı parametrelere göre incelenmiştir. Çalışmada kullanılan parametreler; sıcak akışkan hızına bağlı Reynolds sayısı (Re=400, 800, 1200, 1600), sıcak akışkan giriş sıcaklığı ($T_{sıcak,giriş}$=40, 60, 70, 80°C) ve farklı tipteki faz değiştiren malzemelerdir (RT60, RT100 ve SP70). Hesaplamalı akışkanlar dinamiği analizi için ANSYS Fluent yazılımı kullanılmıştır. Sonuç olarak, ısı değiştiricisinde sıcak akışkanın Reynolds sayısı Re=400-1600 aralığında arttırıldığında ısı transfer etkinliğinde %17 artış; sıcak akışkan giriş sıcaklığı $T_{sıcak,giriş}$=40-80°C aralığında arttırıldığında ısı transfer etkinliğinde %21 artış tespit edilmiştir. Farklı tipteki faz değiştiren malzemelerin etkisi incelendiğinde ise; RT60 için ısı transfer etkinliği %81, SP70 için ısı transfer etkinliği %79 ve RT100 için ise ısı transfer etkinliği %76 olarak tespit edilmiştir. Bu çalışmadan elde edilen sonuçlarla, ısı transfer etkinliği ve enerji depolama kapasitesi daha yüksek ısı değiştiricilerin tasarlanabileceği değerlendirilmiştir.

Anahtar Kelimeler: Faz değiştiren malzemeler, ısı değiştiricisi, ısı transfer etkinliği, Reynolds sayısı

1. INTRODUCTION

Thermal energy storage (TES) systems have always played a critical role in industrial and domestic purposes in order to achieve cost effective and energy efficient systems. Heat exchangers are main components for heat transfer systems and thermal energy storage or energy transfer systems. There are many active and passive methods to improve the effectiveness of heat exchangers. Surface modifications, vortex generators, different types of baffles, various geometrical structures, nanofluids are some of passive methods [1]. Passive methods gain more importance than active methods due to their energy saving manners. As another passive method in heat exchangers, phase change materials are substances based on melting or solidification caused by the temperature difference of one or more materials, allowing energy to be stored and reused [2]. Phase-change materials (PCMs) have an important factor in the design of thermal systems due to their thermal energy control capability, chemical stability, high thermal energy storage capacity, sensitivity to small temperature changes [3].

Regenerative heat exchangers are used in many fields where required to be stored and reuse thermal energy. Different types of PCMs are used in regenerative heat exchangers as thermal energy storage and release medium. Phase change regenerative heat exchangers are used in many fields such as electronic devices [4-6], solar energy applications [7,8], waste heat recovery [9-11], thermal management systems [12], smart buildings [13-15]. In order to figure out the issue between energy demand and supply and improve the energy efficient systems, latent heat thermal energy storage (LHTES) systems based on PCMs offer a large variety of commercial and residential applications. The ability of absorbing heat, adjusting melting range and transferring stored heat of phase change materials make them applicable in many fields of heat transfer systems.

In the literature, Fragnito et. al. [16] examined the effect of using fractal fin structures in a latent heat exchanger on the weak thermal conductivity of phase change materials (PCMs). In the simulations, it was observed that the fractal fin heat exchanger reduced the melting time of PCM by 27.3% compared to a rectangular fin heat exchanger. Furthermore, the simulations showed that the optimized fractal fins resulted in a 35.6% decrease in melting time. The investigations concluded that the use of fractal-type fins with low thermal conductivity PCM in heat exchangers can reduce melting time and improve system efficiency. Faraj et. al. [17] conducted a literature study demonstrating the feasibility of thermal energy storage systems in buildings. The aim of the study was to show that in buildings with significant environmental impact, thermal comfort can be achieved by preserving the existing energy of heating and cooling systems. As a result of their research, it was noticed that using suitable structure and geometry, PCMs can be employed to prevent temperature fluctuations inside buildings under cooling conditions, leading to energy savings. Hathal et. al. [18] conducted a numerical and experimental research to demonstrate the effect of using phase change materials (PCMs) in thermal energy storage technologies. They added PCM types such as paraffin, salt hydrate, and a mixture of salt hydrates to thermal energy storage tanks. The composite PCMs used in the experiments provided greater contributions to energy storage. PCM materials can be used as an alternative for a sustainable energy system. In conclusion, the experiments showed that PCMs can play an active role in thermal energy systems. Konuklu et. al. [19] carried out an experimental study to increase energy efficiency and reduce waste heat. In the experimental study, the changes in ambient temperature were compared by insulating a container with phase change materials. As a result, it has been observed that it provides 5–10 % energy savings in cooling in summer and 10–20 % in winter compared to an uninsulated environment. Koukou et. al. [20] examined a latent heat thermal energy storage (LHTES) unit used in a cascaded heat exchanger, employing different phase change materials (PCMs) at low temperatures. All the organic PCMs used in the study exhibited a super-cooling effect directly affecting the heat dissipation of the LHTES unit. Koşan et. al. [21] analyzed the thermal behavior of the melting temperature, which is the latent heat storage limit of the phase change materials. The materials are the inner element of the heat exchanger, which is used effectively in thermal energy storage systems, at variable geometry and system inlet temperature. The analysis was carried out with the computer using ANSYS Fluent program. As a result, it was observed that the melting time of the phase change material decreased as the variable system inlet temperature increased (50℃, 60℃ and 70℃). The same result was observed as the number of fins (6, 9, 12 and 15), which is another parameter. Ljungdahl et. al. [22] investigated the potential of using phase change materials (PCMs) to support waste heat recovery in information systems and high-performance computing clusters. The cooling of data centers (DC) and high-performance computing (HPC) systems involves significant energy consumption. A study conducted in Denmark showed that PCM usage reduced electricity consumption by approximately 8.14% to 10.8%. However, the efficiency of latent heat storage varies seasonally depending on the temperature difference between the system and the environment. Despite these variations, it has been determined that PCM applications need for improvement and their current state is not efficient for use in advanced systems. Mat et. al. [23] conducted an analysis of the performance of a heat exchanger using phase change material as an alternative to improve the efficiency of solar energy systems. The analysis was carried out using a computer fluent software. The PCMs in the heat exchanger was analyzed with fins on the inside, outside, and on both sides. The analysis revealed that in the heat exchanger with internal and external finned triple pipes, the melting time was observed to decrease by 43%. Rana et. al. [24] examined the effect of heat transfer performance of increasing number of fins in a heat exchanger coated with phase change material. The study was conducted using two-dimensional computational fluid dynamics (CFD) simulations. CFD simulations were used to investigate the design of the heat exchanger. It was observed that the heat transfer performance increased when PCM was used at temperatures of 50°C and 60°C. The use of phase change materials in the system also reduced the melting time. Tomizawa et al. [25] conducted an experiment to investigate the reduction of generated heat for mobile phones using phase change materials (PCMs). The generated heat by mobile phones is typically dissipated through passive cooling methods. Due to the latent heat property of PCMs, they can reduce the rate of temperature increase. As a result, the encapsulated PCMs applied to mobile phones were found to decrease the rate of heat accumulation and achieve higher performance. Youssef et. al. [26] aimed to improve the thermal conductivity of various phase change materials (PCMs) for effective utilization in heat exchangers in their study. One of the factors influencing the preference for phase change materials in latent heat storage applications is its low thermal conductivity. In the analysis, heat exchangers with spiral wire tubes were designed and an indirectly solar-assisted heat pump was integrated. In order to validate the findings, a 3D CFD model of the PCM heat exchanger was created and compared with measurement results.

Osterman et. al. [27] examined the performance of heating and cooling systems in large energy-consuming buildings by storing thermal energy using phase change materials in order to reduce energy consumption. They selected the paraffin RT22HC material for the investigation. They built an office using plates filled with RT22HC as the experimental chamber. The heating and cooling performance of the office was observed throughout the year. Initially, the structure was analyzed as numerical model. Subsequently, an experimental setup was created. It was observed that using PCM resulted in an annual energy saving of approximately 142 kWh. Nithyanandam et. al. [28] examined the optimization of encapsulated phase change materials in thermal energy storage in their research. In the study, the capsule parameters were varied to achieve a targeted storage cost of less than $15/kWh and a storage charging time of less than 6 hours. The charging and discharging times of different PCM types were also examined in the study. Through numerical analysis, optimization was achieved by adjusting capsule dimensions, PCM quantities, PCM types, and flow types. The initially targeted optimal cost and charging time were obtained from a cylinder with a diameter of 15 mm, a height of 15 m, and a diameter of 11.25 m ($7.55/kWh and 7.42 hours). This study provided a model-based optimization for encapsulated thermal energy storage. Wang et al. [29] proposed a novel rotary regenerative heat exchanger filled with PCM capsules and examined it numerically with traditional one. The effects of using PCM capsules have lead better temperature distribution in the heat exchanger. Rajagopal and Velraj [30] investigated a PCM based a flat plate heat exchanger numerically and experimentally for cooling applications. It has been evaluated that decreasing inlet temperature of air in the heat exchanger cause a reduce in solidification time of PCM. Zhou and Zhao [31] investigated heat transfer properties of paraffin wax RT27 and calcium chloride embedded in graphite and open-cell metal foam experimentally. The results indicate that porous structure enhanced heat transfer rate of PCM medium. Jaworski [32] presented an experimental report on thermal performance of structure formed with PCM integrated with ventilation system in buildings. The set-up showed that warm air in day time can melt PCM and melted PCM can warm cool air by solidifying in night time. Kaizawa et. al. [33] investigated thermophysical characteristics of different sugar and sodium acetate trihydrate as PCMs. According to results, erythritol as a PCM showed the best performance among others due to good chemical stability and high decomposition point. Palmer et. al. [34] studied a structured fin configuration which reduce PCM melting time by enhancing flow dynamic in a triple tube heat exchanger. Findings showed that optimized fin structure in the triple tube heat exchanger can reduce melting time up to 57.4% and can improve heat energy storage capacity. The study also indicated that upper fins in the heat exchanger can provide better heat transfer performance that lower fins. Wang et. al. [35] studied the effects of melting time, storage capacity and heat transfer characteristics of PCMs integrated as copper metal foam composites. The experimental study showed that increasing copper proportion in the composite from 0% to 2.13% has decreased melting time of PCMs and has increased storage capacity and heat transfer rate of the system. The study also indicates that the best heat storage capacity for the copper metal foam composite was obtained at 2.13% proportion. Kittusamy et. al. [36] investigated to enhance thermal conductivity of phase change material (OM65) numerically and experimentally. In the study, three different models were composed with different nanographene particle proportions. The results indicated that reduction in melting time up to 37.5% for PCM models with nanographene was indicated when compared to base PCM model. Xu et. al. [37] conducted a numerical study to examine the effect of magnetic field on thermal storage capacity of nano enhanced phase change material formed with metal foam. Increasing volume fraction of nanoparticles in the composite material could improve melting time but has no remarkable effect on heat transfer. Sudhakaran et. al. [38] conducted a numerical study to evaluate the effects of material and thickness on thermal management performance for batteries. Among others, RT35 phase change material showed a promising performance. Soliman et. al. [39] evaluated heat transfer and energy storage performance of different PCMs for a PV system experimentally. The results ensured that RT44 material achieved the highest energy storage while RT25 showed the lowest temperature for PV system.

Different from the literature, this study numerically investigates heat transfer effectiveness and thermal energy storage capacity of different types of PCMs (RT 60, RT 100 and SP 70) as regards to Reynolds number and inlet temperature of hot fluid under laminar flow condition. Obtained results compared with experimental data which was performed with pure water in a heat exchanger.

2. MATERIAL AND METHOD

The RT category of PCMs manufactured by RUBITHERM consists of organic substances. These PCMs employ phase transition mechanisms, specifically the melting and solidification processes, to efficiently store and release substantial quantities of heat energy within consistent temperature range. Depending on their melting points, these PCMs can be employed for diverse heat storage applications for varying temperature ranges. PCMs demonstrate a noteworthy latent heat capacity within narrow temperature intervals, owing to their exceptional purity and specific compositions. Additionally, they possess chemical inertness and an unlimited lifespan. Physical properties of RT60 and RT100 products are presented in Table 1 and Table 2, respectively [40].

Table 1. Properties of RT60 material [40].

Properties	Values	Unit
Melting range	55-61	°C
Congealing range	61-55	°C
Heat energy storage capacity ± 7,5% (Combination of sensible and latent heat in temperature range of 90°C to 105°C.)	160 40	kJ/kg Wh/kg
Specific heat	2	kJ/kg·K
Density (solid)	0.88	kg/L
Density (liquid)	0.77	kg/L
Thermal conductivity (for both phases)	0.2	W/(m·K)
Volume expansion	12.5	%
Flash point	>200	°C
Operation temperature (max.)	80	°C

Table 2. Properties of RT100 material [40].

Properties	Values	Unit
Melting range	90-112	°C
Congealing range	108-86	°C
Heat energy storage capacity ± 7,5% (Combination of latent and sensible heat in temperature range of 90°C to 105°C.)	124 34	kJ/kg Wh/kg
Specific heat	2	kJ/kg·K
Density (solid)	0.88	kg/L
Density (liquid)	0.77	kg/L
Thermal conductivity (for both phases)	0.2	W/(m·K)
Volume expansion	12.5	%
Flash point	312	°C
Operation temperature (max.)	120	°C

Rubitherm SP products as PCMs utilizing combinations of saltwater mixtures and additives, which act as latent heat storage media. These PCMs undergo phase transitions between solid and liquid phases, enabling release and storage of significant thermal energy. The melting temperatures of SP materials may differ slightly from RT materials. Physical properties of SP70 are presented in Table 3.

Table 3. Properties of SP70 material [40].

Properties	Values	Unit
Melting range	69-73	°C
Congealing range	68-66	°C
Heat energy storage capacity ± 7,5% (Combination of latent and sensible heat in a temperature range of 90°C to 105°C.)	150 42	kJ/kg Wh/kg
Specific heat capacity	2	kJ/kg·K
Density (solid)	1.5	kg/L
Density (liquid)	1.3	kg/L
Thermal conductivity range (for both phases)	0.6	W/(m·K)
Volume expansion	3-4	%
Flash point	0.6	°C
Operation temperature (max.)	90	°C

CFD analysis were performed using ANSYS-Fluent software. Dimensions of model geometry of the regenerative heat exchanger was determined that 50 mm, 70 mm, and 100 mm as diameter of the tubes and 1000 mm as the length of the tubes. Schematic view of the model is shown in Figure 1 as two-dimensionally.

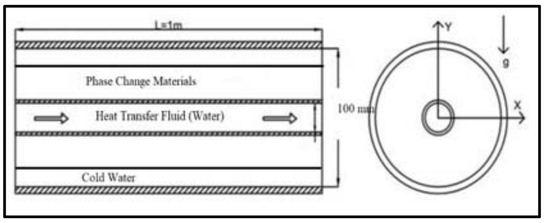

Figure 1. 2D schematic view of the regenerative heat exchanger

2.1. Mesh Independence Study

Number of cells of the numerical model was increased solid-liquid interface boundary layers. For the independence study of the numerical model, five different mesh model has been created and the models were analyzed according to average temperature of the hot fluid in the regenerative heat exchanger. The number of cells was increased, and numerical data examined for five different mesh model. It was determined that the average temperature value did not change significantly after 800000 cells. Variation of average temperature with respect to the number of cells is presented in Figure 2.

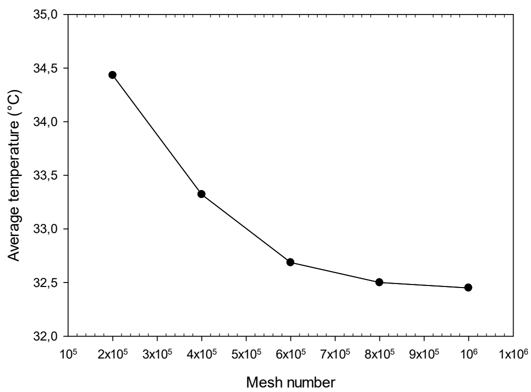

Figure 2. Variation of average temperature with respect to the number of cells

2.2. Validation of the Numerical Model

In order to verify the numerical model, the data obtained from the experimental study [41] in which pure water was used as hot and cold fluid in the heat exchanger were compared with the numerical model data. The maximum error between experimental and numerical data was determined as 11%. Therefore, it was determined that the numerical model good agree with the experimental study. Comparison of numerical data with experimental data is presented in Figure 3.

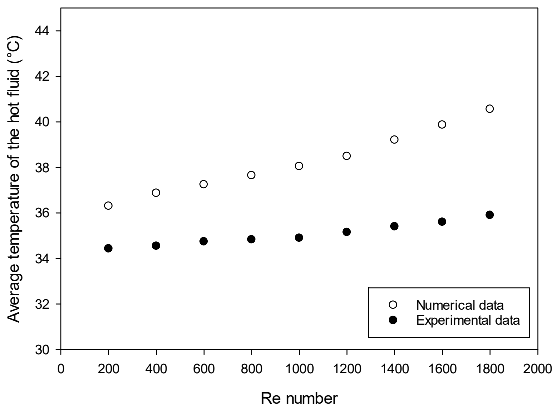

Figure 3. Numerical and experimental data

Mesh structure of the numerical model is shown in Figure 4.

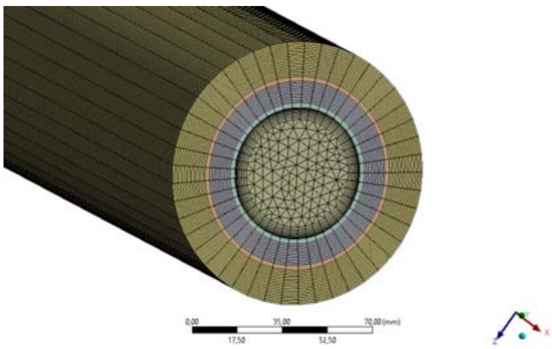

Figure 4. Mesh structure of the numerical model

2.3. Mathematical Formulations and Boundary Conditions

In order to determine heat transfer effectiveness of the numerical model, continuity, momentum, and energy equations are given below.

Continuity equation:

$$\frac{1}{r}\frac{\partial(ru_r)}{\partial r}+\frac{1}{r}\frac{\partial(u_\theta)}{\partial\theta}+\frac{\partial(u_z)}{\partial z}=0 \quad (1)$$

Momentum equation:
In the r-direction:

$$p\left(\frac{\partial(u_r)}{\partial t}+u_r\frac{\partial(u_r)}{\partial r}+\frac{u_\theta}{r}\frac{\partial(u_r)}{\partial \theta}-u_\theta{}^2+u_z\frac{\partial(u_r)}{\partial z}\right)= -\frac{\partial P}{\partial r}+pg_r+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right)-\frac{u_r}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial \theta}-\frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}+\frac{\partial^2 u_r}{\partial z^2}\right] \quad (2)$$

In the θ-direction:

$$p\left(\frac{\partial u_\theta}{\partial t}+u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{u_\theta u_r}{r}+u_z\frac{\partial u_\theta}{\partial z}\right)= -\frac{1}{r}\frac{\partial P}{\partial \theta}+pg_\theta+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_\theta}{\partial r}\right)-\frac{u_\theta}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2}+\frac{2}{r^2}\frac{\partial u_r}{\partial \theta}+\frac{\partial^2 u_\theta}{\partial z^2}\right] \quad (3)$$

In the z-direction:

$$p\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial \theta}+u_z\frac{\partial u_z}{\partial z}\right)=-\frac{\partial P}{\partial z}+pg_z+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial \theta^2}+\frac{\partial^2 u_z}{\partial z^2}\right] \quad (4)$$

Energy equation:

$$\frac{\partial T}{\partial t}+u_r\frac{\partial T}{\partial r}+\frac{u_\theta}{r}\frac{\partial T}{\partial \theta}+u_z\frac{\partial T}{\partial z}=\frac{\dot{q}_g}{c_p}+\alpha\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T}{\partial z^2}\right]+\frac{\varphi}{pc_p} \quad (5)$$

The boundary conditions of the numerical model presented in Table 1.

Table 1. The boundary conditions of the numerical model

	U(m/s)	V(m/s)	W(m/s)	T (K)
Hot Fluid Inlet	$U=U_{inlet}$	V=0	W= 0	$T=T_{hot,in}$
Cold Fluid Inlet	U=0	$V=V_{in}$	W=0	$T=T_{cold,in}$
Hot Fluid Outlet	$\frac{\partial U}{\partial x}=0$	$\frac{\partial V}{\partial x}=0$	$\frac{\partial W}{\partial x}=0$	$\frac{\partial T}{\partial x}=0$
Cold Fluid Outlet	$\frac{\partial U}{\partial z}=0$	$\frac{\partial V}{\partial z}=0$	$\frac{\partial W}{\partial z}=0$	$\frac{\partial T}{\partial z}=0$
Body	U=0	V=0	W=0	$\frac{\partial T}{\partial z}=0$

Heat transfer rate in the regenerative heat exchanger is determined as;

$$\dot{Q}=UA_s\Delta T_{lm} \quad (6)$$

Logarithmic mean temperature difference:

$$\Delta T_1=T_{h,in}-T_{c,out}$$
$$\Delta T_2=T_{h,out}-T_{c,in} \quad (7)$$
$$\Delta T_{lm}=\frac{\Delta T_1-\Delta T_2}{\ln(\Delta T_1/\Delta T_2)}$$

A_s is the heat transfer surface area and U is the overall heat transfer coefficient. Heat transfer effectiveness (ε) is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate.

3. RESULTS AND DISCUSSION

The analysis was performed in the heat exchanger as counter-flow arrangement. Pure water as hot fluid in the inner tube and cold water in the outer tube were arranged with PCMs in the annular tube. Different Reynolds numbers (Re=400, 800, 1200, 1600), different inlet temperatures ($T_{hot,in}$=40, 60, 70, 80°C) and different PCMs (RT60, RT100, SP70) were determined as parameters.

3.1. The Effects of Reynolds Number

In order to investigate the effects of different Reynolds number on heat transfer performance, the PCM in the regenerative heat exchanger was determined as RT60; and inlet temperature of the hot fluid was determined as 60°C under laminar flow condition. The Reynolds number is varied as 400, 800, 1200, and 1600 for the examination due to investigate the effect of flow characteristics under laminar flow conditions to achieve maximum energy storage and energy transfer. Heat transfer effectiveness was calculated as 64.02% for Re=400, 73.9% for Re=800, 78.5% for Re=1200, and 81.19% for Re=1600. Energy storage capacity of the PCM were determined as $\dot{Q}$=135.23 W for Re=400, $\dot{Q}$=223.73 W for Re=800, $\dot{Q}$=292.02 W for Re=1200, and $\dot{Q}$=348.15 W for Re=1600.

The temperature contours and velocity vectors for the RT60 material at 60°C for different Reynolds number are shown in Figure 5 and Figure 6, respectively.

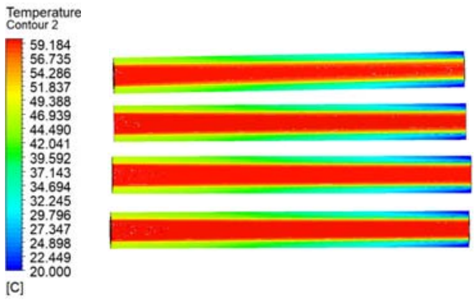

Figure 5. The temperature contours of the RT60 material for different Reynolds numbers (From top to bottom, Re=400, 800, 1200, 1600)

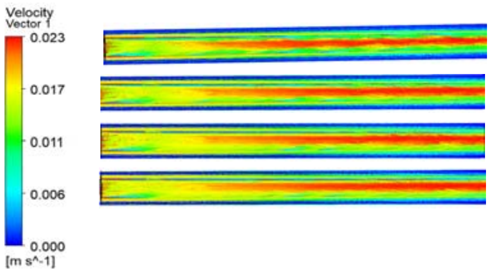

Figure 6. The velocity vectors of the RT60 material for different Reynolds numbers (From top to bottom, Re=400, 800, 1200, 1600)

Increasing Reynolds number in range of Re=400-1600 yields an increase of 17% in heat transfer effectiveness. Effect of Reynolds number on heat transfer effectiveness is presented in Figure 7 graphically.

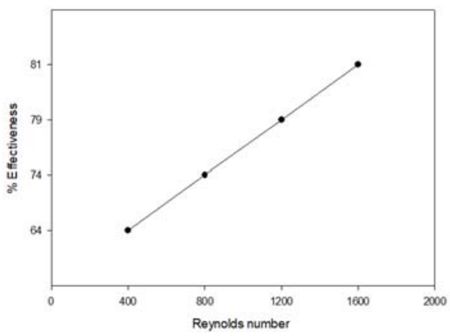

Figure 7. Effect of Reynolds number on heat transfer effectiveness

3.2. The Effects of Inlet Temperature

The effect of different inlet temperatures ($T_{hot,in}$=40, 60, 70, and 80°C) of the hot fluid on heat transfer performance was investigated for RT 60 material and constant Reynolds number (Re=1200). The hot fluid inlet temperature in the heat exchanger is determined in the range of 40-80°C for waste heat recovery systems which is operated for low temperature conditions. Heat transfer effectiveness of the heat exchanger was determined 76.97% for $T_{hot,in}$=40°C; 78.59% for $T_{hot,in}$=60°C; 81.7% for $T_{hot,in}$=70°C and 97.54% for $T_{hot,in}$=80°C. Increasing inlet temperature of the hot fluid leads an increase in heat transfer effectiveness.

The temperature contours and velocity vectors for the RT60 material at Re=1200 for different inlet temperatures are shown in Figure 8 and Figure 9, respectively.

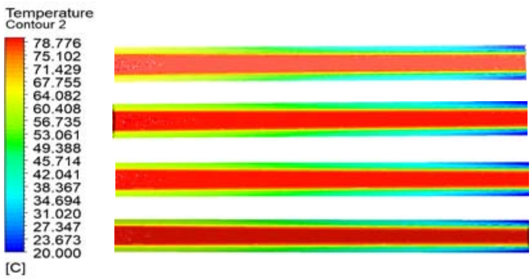

Figure 8. The temperature contours of the RT60 material for different inlet temperatures (From top to bottom, $T_{hot,in}$=40, 60, 70, 80°C)

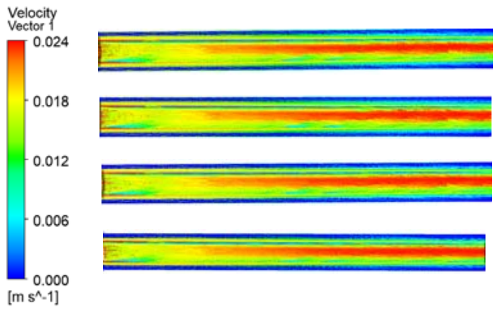

Figure 9. The velocity vectors of the RT60 material for different inlet temperatures (From top to bottom, $T_{hot,in}$=40, 60, 70, 80°C)

It was determined that increasing inlet temperature from 40°C to 80°C leads an increase in heat transfer effectiveness by 20%. It is obtained that the reason for the sudden increase in efficiency after 70°C is due to the phase-changing material used reaching its maximum operating temperature of 80 °C, and the transition of RT60 into a completely liquid state. The effect of inlet temperature of the hot fluid on heat transfer effectiveness is presented in Figure 10.

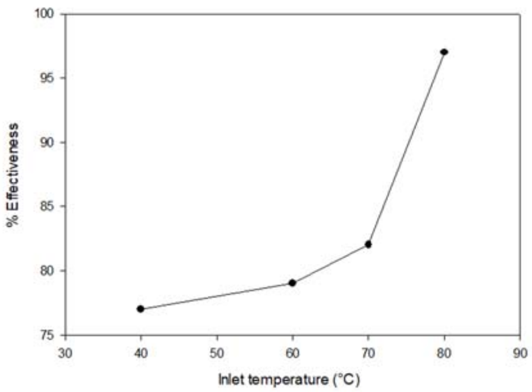

Figure 10. The effect of inlet temperature of the hot fluid on heat transfer effectiveness

3.3. The Effects of Different PCMs

Different PCM types as RT100, SP70 and RT60 were used in the heat exchanger at 60°C and Re=1200. The selected phase-changing materials were chosen within appropriate operating temperature ranges for the system. SP70, RT100, and RT60 types of materials were chosen to observe the working outcomes of organic and inorganic materials. Heat transfer effectiveness of the PCMs were determined as 75.78% for RT100, 78.59% for SP70 and 81.3% for RT60. Energy storage capacities of the PCMs were determined as $\dot{Q}$=292.26 W for RT60, $\dot{Q}$=312.83 W for RT100, and $\dot{Q}$=456.19 W for SP70. The temperature contours and velocity vectors for the PCMs are shown in Figure 11 and Figure 12, respectively.

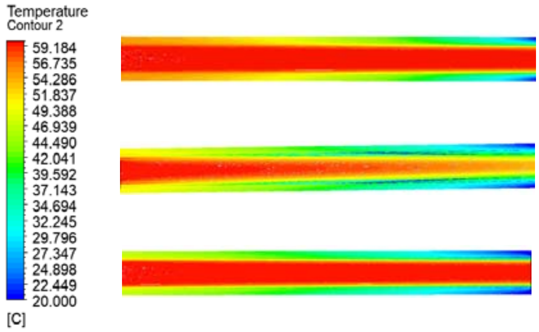

Figure 11. The temperature contours of the PCMs (From top to bottom, RT100, SP70, RT60)

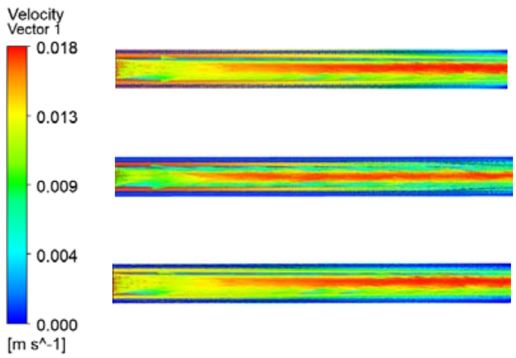

Figure 12. The velocity vectors of the PCMs (From top to bottom, RT100, SP70, RT60)

Heat transfer effectiveness of the heat exchanger for different PCM types is presented in Figure 13.

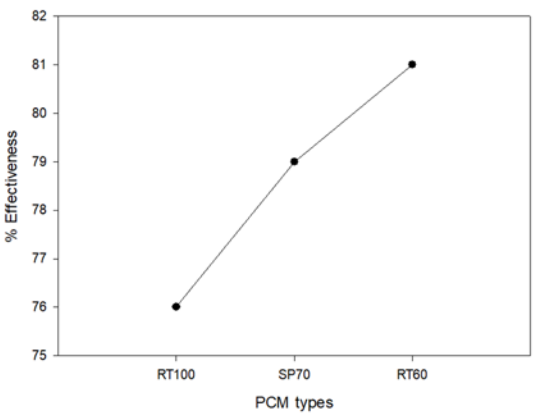

Figure 13. Heat transfer effectiveness of different PCMs

4. CONCLUSION

In this study, different types of PCMs were investigated numerically in a regenerative heat exchanger with different Reynolds number and different inlet temperatures. As a result;

a. Increasing Reynolds number of hot fluid in range of Re=400-1600 yields an increase in heat transfer effectiveness by 17%. Increasing the Reynolds number caused an increase in the hydrodynamic boundary layer and a decrease in the thermal boundary layer.
b. Increasing Reynolds number in laminar flow as Re=400-1600 yields an increase in energy storage capacity of regenerative heat exchanger.
c. Increasing the inlet temperature of the hot fluid from 40°C to 80°C shows an incremental increase in heat transfer effectiveness, resulting in an overall increase of 20%.
d. For constant inlet temperature and Reynolds number, RT 60 shows the best heat transfer performance among others. However, SP 70 shows the best energy storage capacity among others.
e. It has been determined that obtained data from this study, regenerative heat exchangers which have better heat transfer performance and higher energy storage capacity can be designed with lesser cost.

Abbreviations

TES	: Thermal energy storage
PCM	: Phase change material
LHS	: Latent heat storage
CFD	: Computational fluid dynamics
LHTES	: Latent heat thermal energy storage
$T_{hot,in}$	: Hot fluid inlet temperature
$T_{cold,in}$	: Cold fluid inlet temperature
$T_{hot,out}$	: Hot fluid outlet temperature
$T_{cold,out}$	: Cold fluid outlet temperature
T_m	: Melting temperature
c_p	: Specific heat
ΔT_{lm}	: Logarithmic mean temperature difference
A_s	: Surface of the area
$\dot{Q}_{act}$	: Actual heat transfer rate
$\dot{Q}_{max}$	: Maximum heat transfer rate

Subscripts

f	: fluid
p	: particle
nf	: nanofluid
fr	: freezing point
m	: mass

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