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ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY UNIVERSITY

GRADUATE SCHOOL
MECHANICAL ENGINEERING DEPARTMENT

INVESTIGATION OF THE EFFECTS OF DIFFERENT PARAMETERS OF PHASE CHANGE MATERIAL ON HEAT TRANSFER FOR WASTE HEAT RECOVERY SYSTEMS

TURAN GÜNEŞ

MASTER OF SCIENCE

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TÜRKİYE CUMHURİYETİ
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ÖZET

ATIK ISI GERİ KAZANIM SİSTEMLERİ İÇİN FAZ DEĞİŞTİRİCİ MALZEMELERİN FARKLI PARAMETRELERİNİN ISI TRANSFERİNE ETKİSİNİN İNCELENMESİ

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Artan enerji talepleri ve sınırlı kaynaklar sanayide enerji depolama sistemlerinin tasarlanmasına olan ilgiyi arttırmıştır. Enerji depolama sorunun çözümünde Gizli Isı Depolama (GID) sistemleri umut vadeden çözüm tekniği olabilir. Gizli ısı depolama sistemi olarak Faz Değiştiren Malzemeler (FDM) düşük işletme sıcaklıklarında yüksek enerji depolama kapasitesi, kimyasal kararlılık ve düşük buhar basınç özellikleriyle iyi bilinen bir çözüm tekniğidir. Bu özellikler, faz değiştiren malzemeleri elektronik soğutma, atık ısı geri kazanım ve bunun gibi birçok alanda gelecek vadeden enerji depolama malzemeleri yapmaktadır. Bu çalışmanın amacı rejeneratif bir ısı değiştiricisinde faz değiştiren malzeme kullanarak ısı transfer etkinliğini farklı parametrelere göre sayısal olarak incelenmesidir. Çalışmada kullanılan parametreler; sıcak akışkan 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 (SP70, RT100, RT60). Hesaplamalı akışkanlar dinamiği (HAD) analizi için ANSYS Fluent yazılımı kullanılmıştır. Sonuç olarak, sıcak akışkanın Reynolds sayısı Re=400-1600 aralığında artması FDM'nin ısı depolama veriminde %17,2 artışa sebep olmuştur. Sıcak akışkanın giriş sıcaklığı 40°C'den 80°C'ye kademeli olarak artması FDM'nin ısı depolama veriminde %15,8 artışa sebep olmuştur. Ayrıca diğer FDM tipleri arasında RT60 en yüksek ısı depolama performansı göstermiştir. Bu çalışmadan elde edilen verilerle, ısı transfer etkinliği daha yüksek ısı değiştiricilerin tasarlanabilmesi ve farklı türdeki faz değiştiren malzemeler kullanarak daha verimli enerji depolama sistemlerinin tasarlanabileceği değerlendirilmiştir.

Anahtar Kelimeler: Faz değiştiren malzeme, ısı transferi, rejeneratif ısı değiştiricisi, termal enerji depolama.

ABSTRACT

INVESTIGATION OF THE EFFECTS OF DIFFERENT PARAMETERS OF PHASE CHANGE MATERIAL ON HEAT TRANSFER FOR WASTE HEAT RECOVERY SYSTEMS

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Increasing energy demands and limited resources have increased interest in designing energy storage systems for industries. Latent Heat Storage (LHS) systems could be promising solution technique for energy storage problem. Phase Change Materials (PCMs) as a LHS system is a well-known solution technique due to high energy storage capacity, chemical stability and low vapor pressure properties at low operating temperatures. These properties have made PCMs promising energy storage materials for many applications such as electronic cooling, waste heat recovery and many different fields. The aim of this study is numerically investigate heat transfer effectiveness of a regenerative heat exchanger using PCMs for different parameters. The parameters used in the study were determined as hot fluid Re number (Re=400, 800, 1200, 1600); hot fluid inlet temperature ($T_{hot,inlet}$=40, 60, 70, 80°C) and different PCMs types (SP70, RT100, RT60). ANSYS Fluent software has been used for computational fluid dynamics (CFD) analysis. The results indicate that increasing Reynolds number of the hot fluid gradually in range of Re=400-1600 caused an increase of 17.2% in efficiency of heat storage of PCM material. Increasing inlet temperature of the hot fluid gradually from 40°C to 80°C caused an increase of 15.8% in the efficiency of heat storage of PCM material. Furthermore, among different types of PCMs, RT60 has performed the highest heat storage performance. It has been evaluated that, with the data obtained from this study, heat exchangers with higher heat transfer effectiveness can be designed and more efficient energy storage systems can be designed by using different types of phase change materials.

Keywords: Heat transfer, phase change material, regenerative heat exchanger, thermal energy storage.

to my very dear family…

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LIST OF ABBREVIATIONS

TES : Thermal energy storage
TCES : Thermochemical energy storage
PCM : Phase change material
LHS : Latent heat storage
Re : Reynolds
DC : Data center
HPC : High performance computer
CFD : Computational fluid dynamics
LHTES : Latent heat thermal energy storage

LIST OF SYMBOLS

$T_{hot,in}$: Hot fluid inlet temperature

T_m : Melting temperature

h : Phase change enthalpy

T_l : Temperature in the liquid phase

c_p : Specific heat

m : The mass of the storage media

C_p : The heat capacity of the storage media

ΔT : The change in temperature of the storage media

H_l : The latent heat associated with any phase change of the storage media

ΔH_{rxn} : The heat of reaction of the chemical transformation

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

1. INTRODUCTION

Energy has always been as important as basic needs since the beginning of humanity. Today, the energy demand owing to increasing population cannot be met with limited resources of the world. There is not sufficient production to meet the energy demand. The development of technology and industry has increased the need for energy. The energy needs are mostly provided from fossil sources. Since limited fossil energy sources and their negative environmental impacts, researchers study new energy sources to meet the demand. The research for renewable energy sources has aroused interest since the destructive effects of oil-based energy sources. Sustainable and renewable energy usage will not only help mitigate the harmful gases and environmental waste released as a result of fossil fuel consumption but also prevent future effects such as global warming.

In order to achieve high efficiency in the utilization of renewable energy and ensure its integration into the energy system, there is a need for Thermal Energy Storage (TES) technology. Thermal energy storage enables the storage of renewable energy for a certain time. Regarding the excessive demand for energy consumption, thermal energy storage systems gain importance. Thermal energy, also known as heat energy, has numerous application fields across various industries and daily life. Here are some common applications of thermal energy:

- Heating and Cooling: One of the most widespread uses of thermal energy is for heating buildings and homes during colder months. Heating systems such as boilers, furnaces, and radiators utilize thermal energy to warm the air or water. On the other hand, cooling systems like air conditioners and refrigerators remove heat from an ambient, providing a cooling effect.
- Power Generation: Thermal energy is widely employed in power plants to generate electricity. Fossil fuel power plants burn coal, oil, or natural gas to produce heat, which is then used to convert water into steam. The steam drives a turbine connected to a generator, generating electrical energy. Additionally, concentrated solar power plants use mirrors to concentrate sunlight and generate thermal energy to produce electricity.
- Industrial Processes: Many industrial processes rely on thermal energy consumption. For example, in manufacturing processes, thermal energy is used for smelting, forging, heat treating, and annealing processes. It is also utilized in industries such as food

processing, chemical production, and textiles for heating, drying, sterilization, and other thermal treatments.

- Cooking and Food Preparation: Thermal energy is essential for cooking and food preparation in both residential and commercial needs. It is used in stoves, ovens, grills, and other cooking appliances to process foods.
- Transportation: Thermal energy is utilized in various modes of transportation. Internal combustion engines in automobiles and airplanes burn fuel to produce thermal energy, which is then converted into mechanical energy for drive force. Thermal energy is also used in nuclear powered vehicles and some forms of railway transportation.
- Water Heating: Thermal energy is commonly used to heat water for domestic and commercial purposes. Water heaters, which are powered by electricity, gas, or solar energy, utilize thermal energy to raise the temperature of water for bathing, washing clothes, and other applications.
- Waste Management: Thermal energy plays a role in waste management processes. Incineration plants burn waste materials at high temperatures, converting them into heat energy. This heat energy can be used to generate electricity.

These are just a few examples of the applications of thermal energy. Its versatility and abundance make it a valuable resource in various sectors of our daily life and industrial processes.

This study aims to observe the feasibility of recovering energy, which is in increasing demand day by day but limited in availability, through the utilization of waste heat in systems. Therefore, the ongoing research promote the use of latent heat storage methods. The research conducted in this study was performed by using the ANSYS Fluent program. Various parameters were considered as variables in the analysis. Different types of phase change materials, different Reynolds number of the hot fluid flow, waste heat temperature values, and different types of hot fluid flow were varied for the analysis. In the first analysis, in order to analyze the effect of different hot fluid inlet temperatures, the temperatures were set as T_{in}= 40, 60, 70, 80 °C while the PCM was RT60 and Re=1200. In the second analysis, the effect of different Reynolds numbers (Re= 400, 800, 1200, 1600) in the heat exchanger was analyzed with the RT60 material at a hot fluid inlet temperature of T_{in}= 60. In the third analysis, in order to determine the effect of different types of PCMs, RT60, RT100 and SP70 were used while T_{in}=60 °C and Re=1200.

Analyzing of heat transfer performance of a double-pipe heat exchanger containing phase change materials was performed by using the ANSYS Fluent program. The purpose of the analysis is to observe the use of phase change materials in heat exchangers by observing the effect of the determined parameters on the system. In this thesis study, combined effect of different inlet temperatures, Reynolds numbers and different types of phase change materials were examined on heat transfer performance of a double-pipe heat exchanger.

1.1. Thermal Energy and Types of Thermal Energy Storage Systems

Thermal energy, in academic terms, refers to the internal energy of a system arising from the motion and interaction of its particles at the microscopic level. It is a form of energy associated with the temperature of a substance or system. The thermal energy of a substance or system is directly related to the kinetic energy of its particles, such as atoms or molecules, as they move and vibrate.

Thermal energy can be transferred between objects or systems through various mechanisms, namely conduction, convection, and radiation. When two objects or systems are in contact with different temperatures, heat transfer occurs, leading to the exchange of thermal energy until thermal equilibrium is reached.

Understanding and analyzing thermal energy is crucial in various scientific fields, including thermodynamics, heat transfer, and other engineering fields. It plays a fundamental role in studying and designing systems such as temperature control systems, energy conversion, and heat management. The main techniques of thermal energy storage systems are shown in Figure 1.1. (Al-Musaedi et al., 2022).

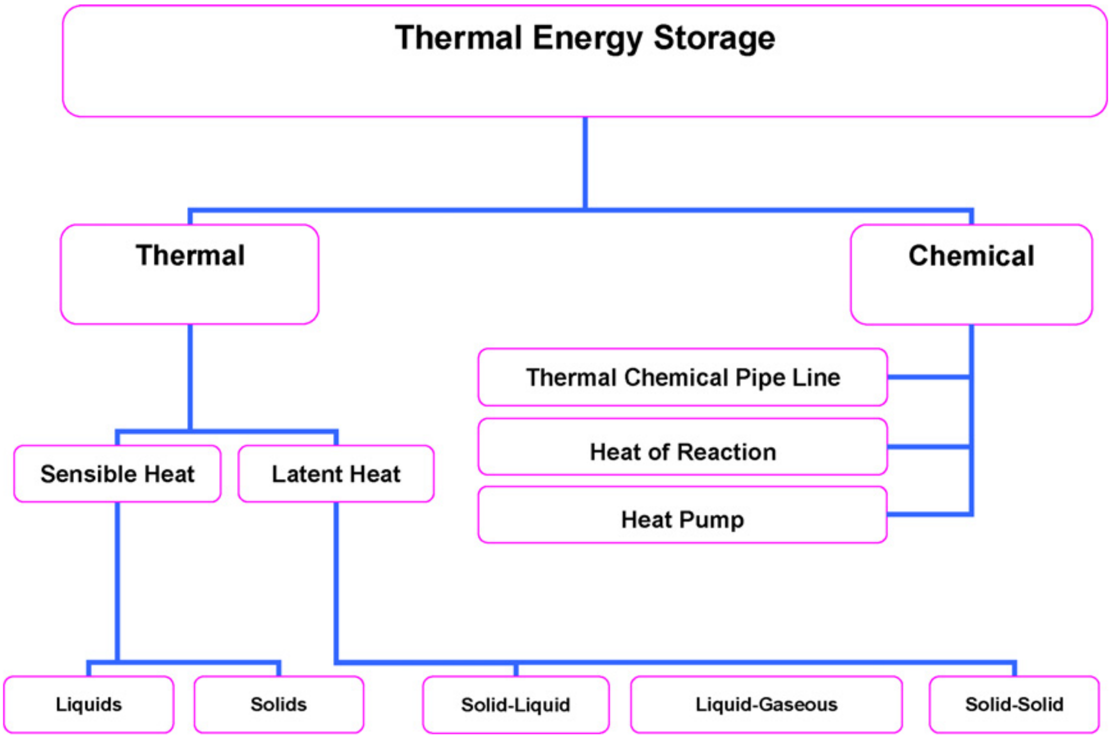


Figure 1.1. Different types of thermal energy storage systems (Sharma et al., 2009).

1.1.1. Thermochemical Heat Storage

Thermochemical heat storage is a method of storing thermal energy by utilizing chemical reactions that involve the absorption and release of heat. It involves storing energy in the form of chemical potential energy and then releasing it as heat when it is needed. The process typically consist of a reversible chemical reaction that can absorb or release heat energy. During the charging phase, the reaction absorbs thermal energy from a heat source, causing a chemical change and stores the energy. When the stored heat is required, the reaction is reversed, and the stored energy is released as heat. Thermochemical heat storage is a promising approach for efficient and effective thermal energy storage, offering potential solutions for meeting energy demands and enhancing the integration of renewable energy sources. The total stored energy can be defined by equation 1.1 (Fragnito et al., 2022).

$$\dot{Q} = mc_p\Delta T + mH_l + m\Delta H_{rxn} \tag{1.1}$$

m : The mass of the storage media

c_p: The heat capacity of the storage media

ΔT: The change in temperature of the storage media

H_l : The latent heat associated with any phase change of the storage media

ΔH_{rxn}: The heat of reaction of the chemical transformation

1.1.2. Sensible Heat Storage

The storage of energy by utilizing the heat storage capacity of a solid or liquid material is called sensible heat storage. By increasing the temperature of the material, the heat is stored in the form of sensible heat. The amount of stored thermal energy varies according to the temperature change, the specific heat of the environment and the amount of material. The amount of sensible heat storage is expressed with Equation 1.2.

$$\dot{Q} = mc_p(T_2 - T_1) \tag{1.2}$$

m: Amount of storage material

c_p: Specific heat

T_2: Final temperature

T_1: Initial temperature

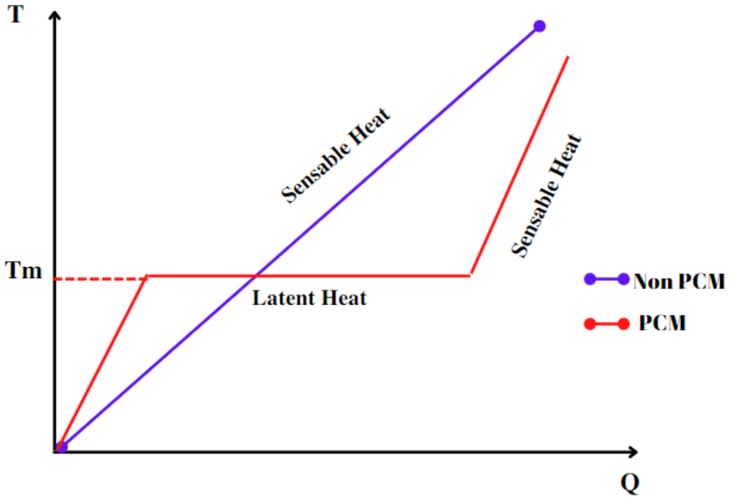


Figure 1.2. Latent and Sensible Heat Area.

It is shown in Figure 1.2. that the material, which is sensible heat storage is heat gain, expresses the stored heat as a result of the temperature change. The amount of stored sensible heat increases simultaneously with the temperature change. This method, used in thermal energy storage, is generally simpler and more cost-effective than other methods. Although sensible heat has the advantage of being an energy storage and recovery loop, it is a disadvantage that the volume of storage material requires a large volume.

1.1.3. Latent Heat Storage

Latent heat is generated heat during the phase change of a substance. Phase change is defined as the change in the phase of matter as a result of the change in the internal energy of a substance whose temperature is increased or decreased. The materials used in latent heat storage are called Phase Change Materials (PCMs). The heat in the system or the environment causes the internal energy of the material to change greatly. The latent heat resulting from the phase change of the storage material at a certain temperature can be stored. Therefore, phase change materials which have high latent heat potential are preferred for certain temperature ranges. Types of phase change to store heat occurs as solid-solid, solid-liquid, liquid-gas and solid-gas phase change as shown in Figure 1.3. In the solid-solid phase change, the substance transforms into a crystalline structure and stores heat without a change in substance. Liquid-vapor exchange is not suitable for heat storage because of the high-pressure storage problem that occurs as a result of gaseous phase change. The amount of latent heat that emerges as a result of solid-solid phase change is low.

Therefore, phase change processes such as solid-solid and solid-liquid are convenient for storing heat energy. The storage capacity of an LHS system with PCM is given as:

$$\dot{Q} = m\left[c_{ps}(T_m - T_s) + h + c_{pl}(T_l - T_m\right] \tag{1.3}$$

c_{ps}: Specific heat in solid phase

c_{pl}: Specific heat in the liquid phase

h: Phase change enthalpy

T_m: Melting temperature

T_s: Temperature in solid phase

T_l: Temperature in the liquid phase

The sensible and latent heating and cooling cycles that occur in thermal energy storage are shown in Figure 1.3.

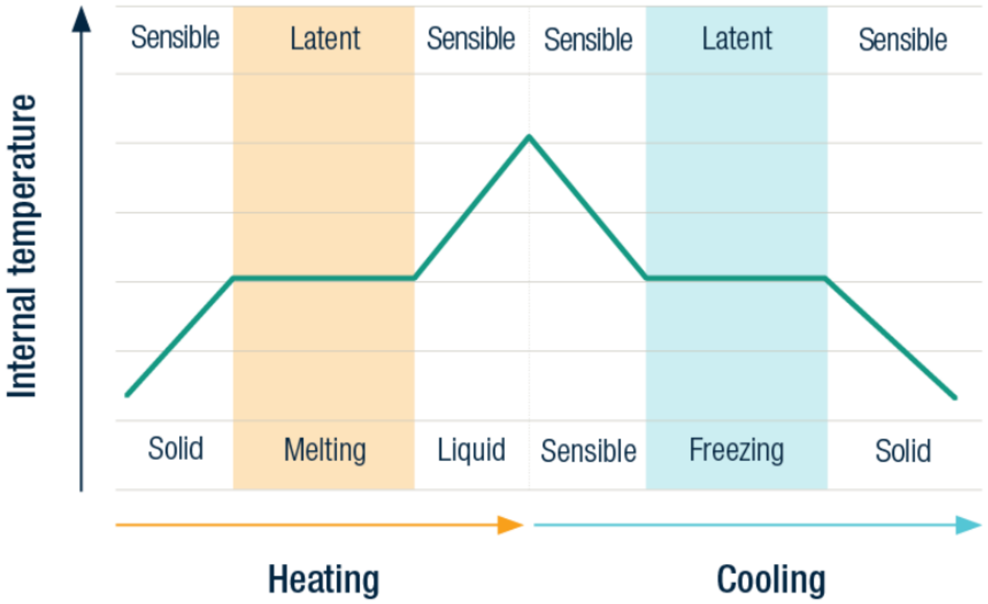


Figure 1.3. Latent Heat Phase Change (Sefidan et al., 2017).

During heat energy storage, phase change materials first absorb heat like other materials, and their temperature rises. However, unlike other materials, at the phase change temperature, the environment absorbs much more energy without temperature change. In an environment lower than the material temperature, it releases the latent heat in its body in the opposite direction.

1.2. Phase Change Materials

Phase change materials are substances that change phase in a certain temperature range and can store latent heat simultaneously. Phase change materials release a large amount of energy in the form of latent heat by freezing and absorb an equal amount of energy from the adjacent environment by melting. This phenomenon allows thermal energy storage. PCMs must have the properties shown in Table 1.1. to work efficiently in thermal energy storage systems.

Table 1.1. PCMs properties for thermal energy storage systems (Hathal et al., 2023).

Thermal Properties	➢ Suitable phase change temperature ➢ High latent heat of fusion ➢ Good heat transfer
Physical Properties	➢ Suitable phase balance ➢ Low vapor pressure ➢ Low volume change ➢ High density
Kinetic Properties	➢ Not excessive cooling ➢ Sufficient crystallization
Economy	➢ Be abundant ➢ Be cheap
Chemical Properties	➢ Not excessive cooling ➢ Suitable for building materials ➢ Non-toxic ➢ Not be flammable

General usage areas of phase change materials;

- Building and Construction: PCMs are used for thermal insulation, temperature regulation, and energy efficiency in buildings.
- Electronics and Thermal Management: PCMs are used for heat dissipation and thermal management in electronic devices.
- Energy Storage: PCMs are used for storing and releasing thermal energy in various energy storage systems, such as solar thermal energy storage and heat pumps.
- Textiles and Apparel: PCMs are used in fabrics and clothing for thermal comfort and temperature regulation.
- Transportation: PCMs are used in vehicles for temperature control and thermal management.

1.2.1. Classification of Phase Change Materials

Phase change materials are classified as solid-liquid, solid-solid, liquid-gas and solid-gas exchanged PCMs according to the phase transformation form. PCMs are also classified as organic, inorganic and eutectic phase change materials. The amount of heat generated in solid-solid phase change is less and the substance crystallizes. In liquid-gas phase changes, large pressure and large volume changes occur. Therefore, PCMs with solid-solid and liquid-gas phase changes are not efficient in heat storage. Studies have focused on materials with solid-liquid phase change with high heat storage capacity. The classification of phase change materials is shown in Figure 1.4.

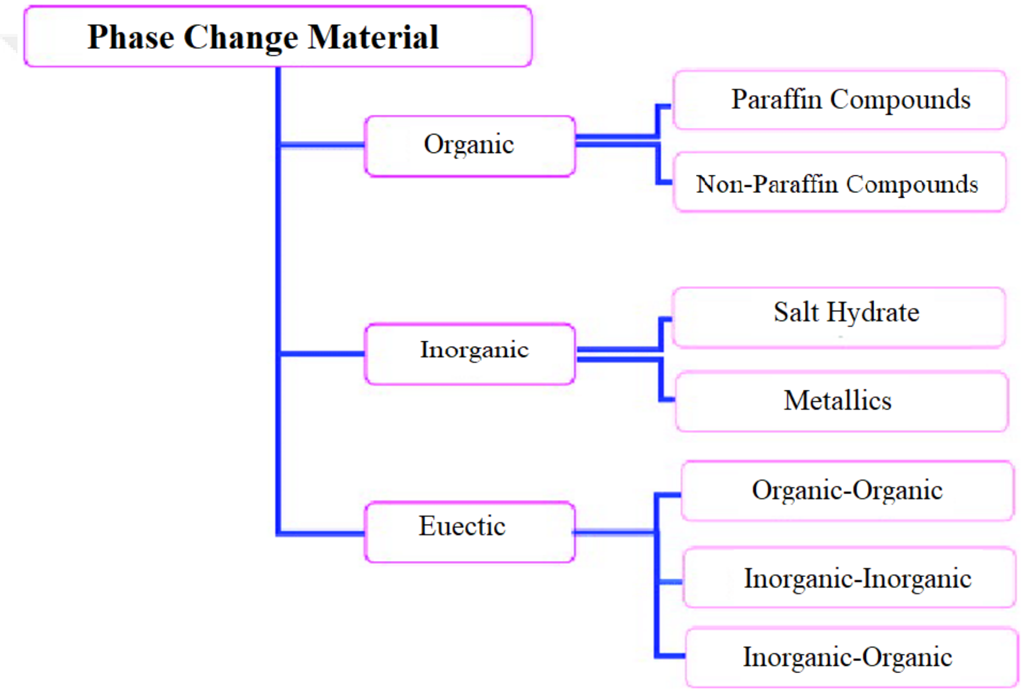


Figure 1.4. Scheme of phase change materials (Sharma et al., 2009).

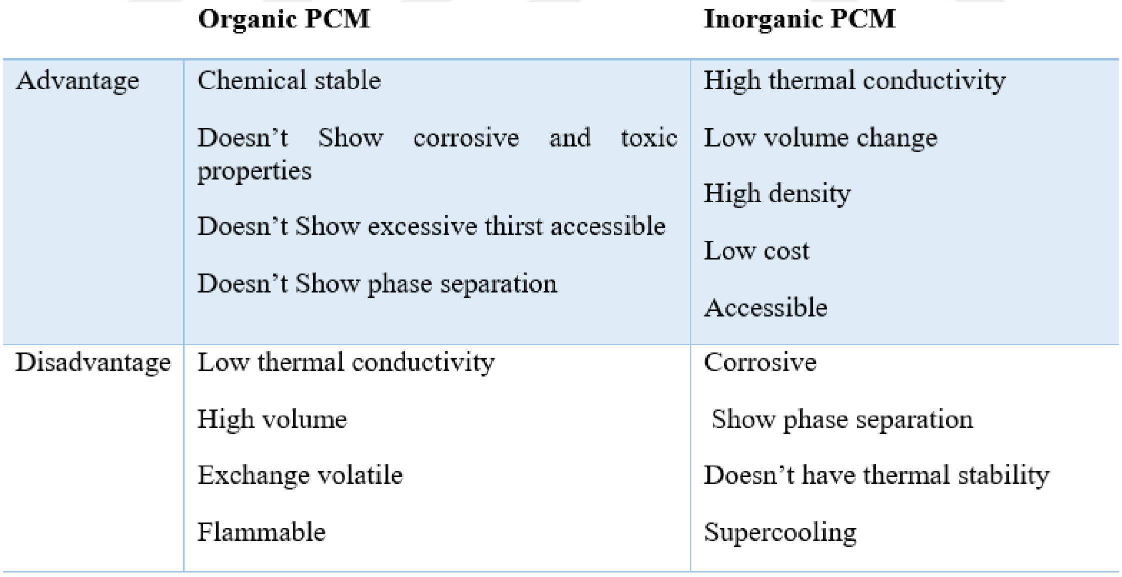
1.2.2. Advantages and Disadvantages of Phase Change Materials

Inorganic phase change substances consist of metals and salt hydrates. They are preferred in general applications due to their availability in nature and cost-effectiveness. During the phase change of salt hydrates, a high amount of heat transfer and phase separation occurs.

Eutectic phase change materials are formed as a result of the combination of two or more organic-organic, inorganic-organic or inorganic-inorganic components with the same melting temperature. Therefore, numerous eutectic materials can be produced.

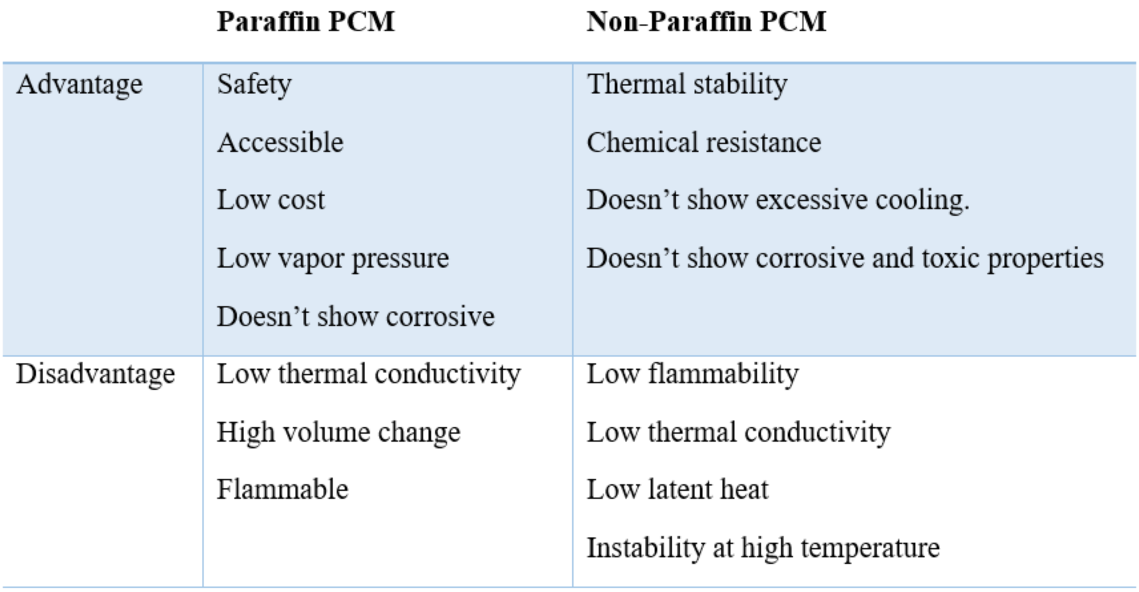
Organic phase change materials are hydrocarbons, which are found in large amounts in nature as a source and contain carbon and hydrogen. In general, they are divided into paraffin-based and non-paraffin-based organic substances. They have a high latent heat storage capacity. They are the most common phase change materials used in general applications. The advantages and disadvantages of organic and inorganic phase change materials are presented in Table 1.2. The advantages and disadvantages of paraffin-based and non-paraffin-based PCMs are given in Table 1.3. in order to see the difference of organic phase change materials (Koşan et al., 2018).

Table 1.2. Advantage and disadvantage of Organic and Inorganic PCMs (Koşan et al., 2018).



	Organic PCM	**Inorganic PCM**
Advantage	Chemical stable Doesn't Show corrosive and toxic properties Doesn't Show excessive thirst accessible Doesn't Show phase separation	High thermal conductivity Low volume change High density Low cost Accessible
Disadvantage	Low thermal conductivity High volume Exchange volatile Flammable	Corrosive Show phase separation Doesn't have thermal stability Supercooling

Table 1.3. Advantage and disadvantage of Paraffin and Non-Paraffin PCMs (Koşan et al. 2018).



	Paraffin PCM	**Non-Paraffin PCM**
Advantage	Safety Accessible Low cost Low vapor pressure Doesn't show corrosive	Thermal stability Chemical resistance Doesn't show excessive cooling. Doesn't show corrosive and toxic properties
Disadvantage	Low thermal conductivity High volume change Flammable	Low flammability Low thermal conductivity Low latent heat Instability at high temperature

Considering the types of phases changing materials and their properties, the material should be selected according to the system. The most important criterion is to choose the proper phase change material that will give the optimum result for the system.

1.3. Regenerative Heat Exchanger

A heat exchanger is a device or system designed to transfer heat energy from one fluid to another fluid, without any direct contact with each other. It allows heat transfer between the two fluids effectively while keeping them physically separated.

A regenerative heat exchanger is a type of heat exchanger where heat from the hot fluid is intermittently stored in a thermal storage medium before it is transferred to the cold fluid. It is operated by periodically switching the flow direction of the two fluids, allowing for efficient heat transfer. In a regenerative heat exchanger, two fluid streams with different temperatures flow through separate channels or passages. These channels are typically filled with a solid material, such as ceramic, metal, or a combination of materials with high thermal conductivity. The solid material acts as a thermal storage medium.

The working principle of a regenerative heat exchanger involves alternating cycles. During one cycle, the hot fluid flow passes through one set of channels, transferring its heat to the medium. The cold fluid flow simultaneously passes through another set of channels, absorbing heat from the medium. In the next cycle, the flow direction is reversed, and the roles of the hot and cold fluids are exchanged (Koşan & Aktaş, 2018).

The medium material in the regenerative heat exchanger acts as a heat reservoir, storing heat during one phase and releasing it during the other. This process performs heat transfer effectively between the two fluid flows with minimal temperature difference.

Regenerative heat exchangers are commonly used in various industrial applications, such as in thermal power plants, industrial furnaces, and waste heat recovery systems. These heat exchangers can enhance the overall energy efficiency of the systems by recovering and reusing heat energy.

Regenerative heat exchangers present several important advantages and play a significant role in various applications. Here are some key reasons for their importance:

Improved Energy Efficiency: Regenerative heat exchangers can improve energy efficiency by recovering and reusing heat instead of be wasted. They enable the heat transfer between two fluid flows with minimal temperature difference, for efficient heat exchange. This phenomenon results in reduced energy consumption and lower operating costs in systems where heat recovery is essential.

Waste Heat Recovery: Regenerative heat exchangers are particularly substantial in waste heat recovery (WHR) applications. WHR power plants utilize the waste heat generated by industrial processes or exhaust gases from cement plants, iron and steel plants and other heavy industries. Using regenerative heat exchangers contribute to energy conservation and sustainability by harnessing the waste heat.

Thermal Storage: The matrix material used in regenerative heat exchangers acts as a thermal storage medium. It can store excess heat during one phase of the cycle and release it during the other phase when it is needed. This capability enable heat exchangers to utilize more heat transfer and can manage heat energy supply and demand.

Compact Design: Regenerative heat exchangers can be designed to be compact and lightweight compared to some other heat exchanger types. This superiority makes them suitable for different applications where space is limited, such as in mobile or portable systems.

Versatility: Regenerative heat exchangers can be adapted to various fluid types, different temperature rages, and flow rates, making them versatile in different industrial processes and applications. Regenerative heat exchangers can be customized to meet specific requirements and integrated into existing systems without major modifications.

Reduced Environmental Impact: Regenerative heat exchangers contribute to reducing the environmental impact of industrial processes by improving energy efficiency and enabling waste heat recovery. Using these heat exchangers lead to lower greenhouse gas emissions and decrease reliance on fossil fuels.

Regenerative heat exchangers allow the establishment of less costly systems in terms of their applicability in many areas in the industry and the energy savings they provide.

2. LITERATURE REVIEW

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 phase change materials (PCMs) offer a large variety of commercial and residential applications like industrial waste heat management, electronic thermal management, batteries thermal management, photovoltaic thermal systems, building energy saving and so on. 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 literature, Fragnito et al. (2022) 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. (2020) 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, Phase Change Materials (PCMs) can be employed to prevent temperature fluctuations inside buildings under cooling conditions, leading to energy savings.

Hathal et al. (2023) 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. (2018) 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. (2018) 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. (2018) 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 (50ºC, 60ºC and 70ºC). The same result was observed as the number of fins (6, 9, 12 and 15), which is another parameter, increased.

Lia et al. (2019) conducted a comprehensive experimental study was to store waste heat generated from a steel sintering machine using phase change materials (PCMs) and utilize the stored thermal energy to provide electrical support to the system. Selecting appropriate PCM type reduced energy consumption from 103 kJ/kg to 1 kJ/kg, the daily fuel requirement of the system decreased by 0.06 tons. This application demonstrated the integration of waste heat recovery into industrial systems using phase change materials.

Ljungdahl et al. (2022) 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. (2013) conducted an analysis of the performance of a heat exchanger using phase change material (PCMs) 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%.

Medrano et al. (2009) conducted experimental research on phase change materials (PCMs) in five different heat exchangers to enable heat recovery through their latent heat properties, supporting increasing energy demands. Paraffin RT35 was chosen as the PCM, and the temperature range for the system was selected as 35-40°C. The experimental setup included double-pipe finned, double-pipe with graphite matrix, double-pipe, compact, and plate heat exchanger configurations. When the phase change temperature of the PCMs was combined with an increased temperature difference between the inlet hot water and the system, from 15°C to 25°C, it was observed that the solid-liquid phase change time decreased, while the duration of heat storage increased. When examining the average heat power values, the double-pipe with graphite matrix, double-pipe finned, and compact heat exchangers outperformed the others, indicating their potential for practical applications.

Nithyanandam et al. (2014) examined the optimization of encapsulated phase change materials (PCMs) 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.

Osterman et al. (2015) examined the performance of heating and cooling systems in large energy-consuming buildings by storing thermal energy using phase change materials (PCMs) 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.

Rana et al. (2022) 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. (2016) 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. (2018) aimed to increase the thermal conductivity of 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 their weak 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.

3. MATERIALS AND METHODS

Engineering research is conducted using analytical, experimental, and numerical methods. The most valid results are obtained from experimental methods, and experimental findings are used as a benchmark for comparative purposes in numerical studies. Experimental methods may not be feasible in every field initially due to the cost of conducting the experiment, its applicability, and design constraints. Numerical methods employed in engineering problem-solving include finite element, boundary element, finite difference, and finite volume methods. The most commonly used numerical method is the finite volume method.

A Computational Fluid Dynamics (CFD) analysis process consists of the following steps. In this report, all these items will be examined in detail based on the project.

- 3D design
- Material definition
- Division of the design into smaller parts (meshing)
- Definition of boundary conditions
- Solution process
- Examination of results

For the CFD analysis process, analyses were performed using the ANSYS-Fluent software. The section on theoretical foundations and literature review may include various subheadings.

In this study, a numerical analysis was conducted using the ANSYS Fluent 16.2 software to evaluate the performance of phase change materials (PCMs) in heat exchangers, considering their limited application field. Prior to performing the numerical analysis, certain assumptions were made to simplify the analysis. These assumptions are as follows:

- The PCM is assumed to be isotropic and homogeneous.
- The phase change process is considered to be isothermal.
- Heat transfer occurs through conduction and natural convection.
- During the liquid phase change, the movement of PCM is assumed to be laminar, transient, and incompressible.

3.1. Model Geometry

The first step in the CFD analysis process is the three-dimensional design stage. In this stage, all factors that would affect the flow need to be taken into consideration.

The following Figure 3.1. includes the three-dimensional design for the heat exchanger.

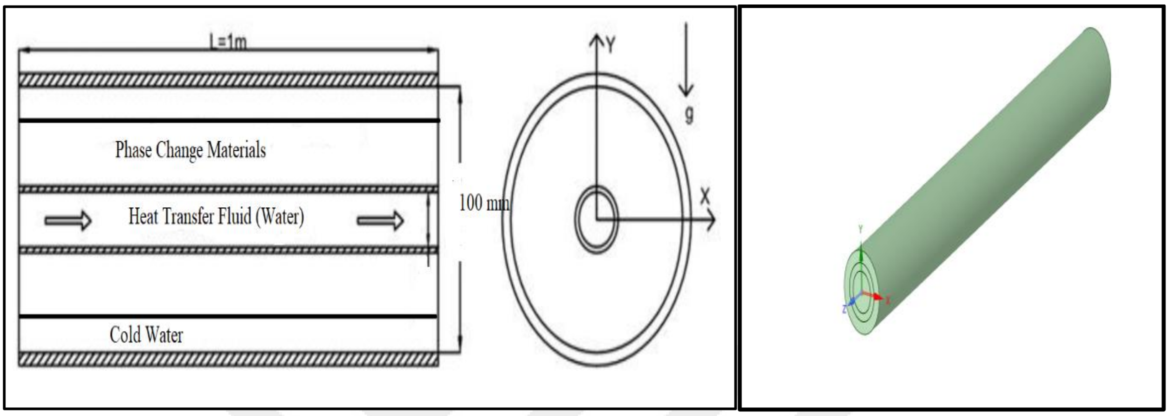


Figure 3.1. 2D and 3D geometry model.

For the analysis, the dimensions of the tube were calculated to be 50 mm, 70 mm, and 100 mm, starting from the inner diameter. The length of the tube was taken as 1 meter.

3.1.1. Mesh Independence Study

Mesh structure of the numerical model was intensified solid-liquid interface boundary layers. For independence study of numerical model, 5 different mesh model has been created and the models analyzed according to average temperature of the fluid in the heat exchanger. In numerical models, the number of cells was increased and examined for five different mesh structures, and it was determined that the average temperature value did not change after mesh number of 800000 and the results were independent of the mesh structure. Numerical model results were obtained according to this mesh structure. The mesh independence of the numerical model according to mesh number and average temperature is presented in Figure 3.2.

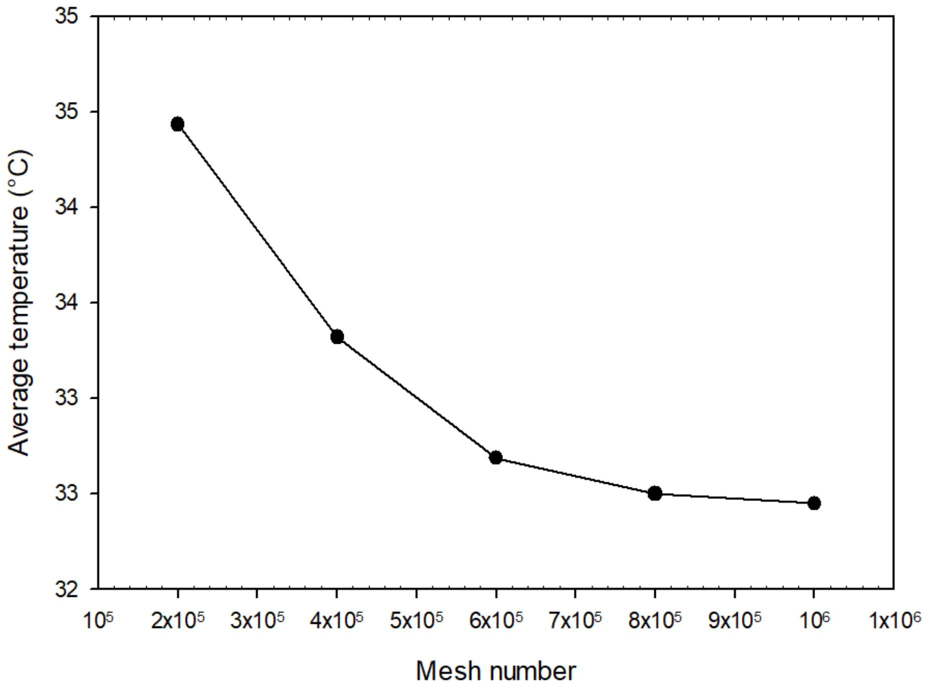


Figure 3.2. The mesh independence of the numerical model according to mesh number and average temperature.

3.1.2. Validation of the Numerical Study

The numerical model results were compared with results of the experimental study which was performed without PCM in the heat exchanger. The maximum error between numerical and experimental results was determined as 11%. It has been confirmed that the numerical model was good agree with experimental set-up. The difference between numerical and experimental data is presented in Figure 3.3.

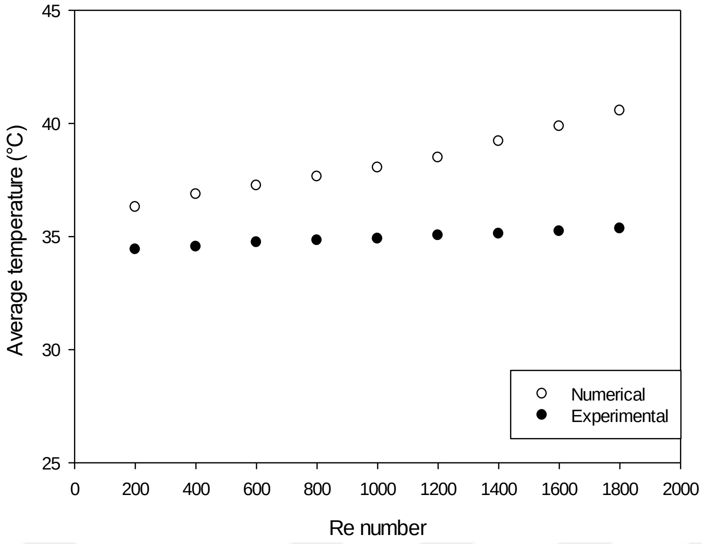
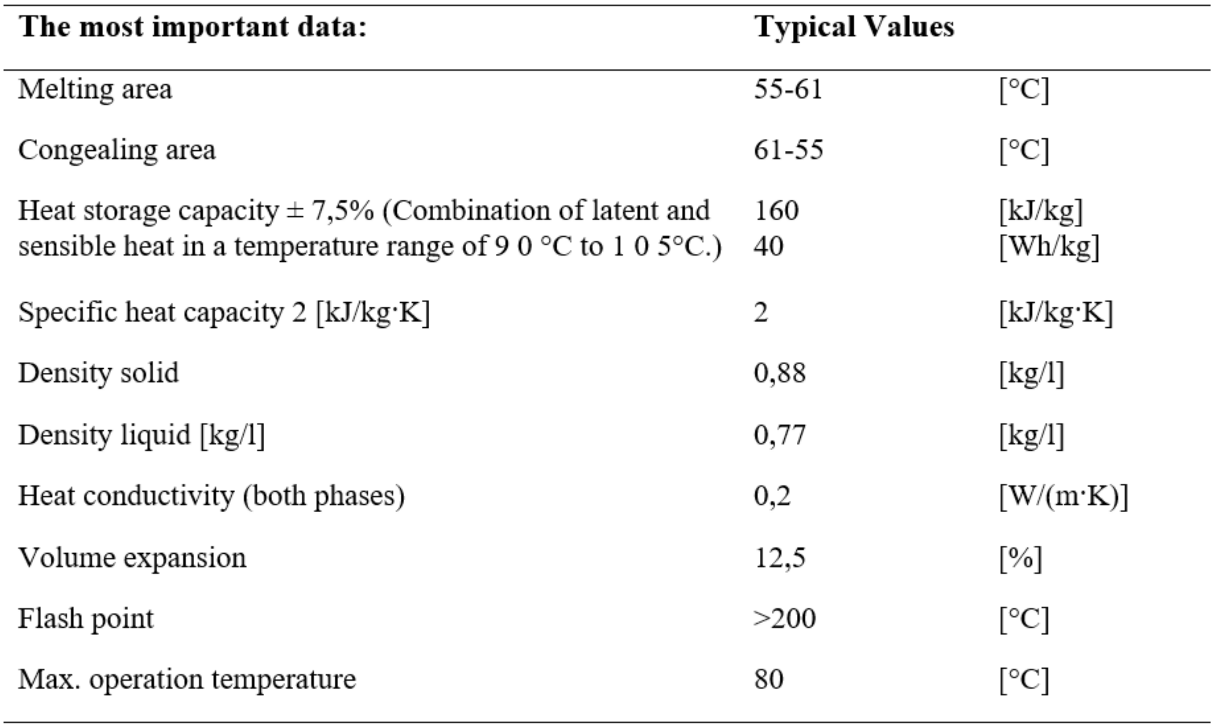


Figure 3.3. The difference between numerical and experimental data.

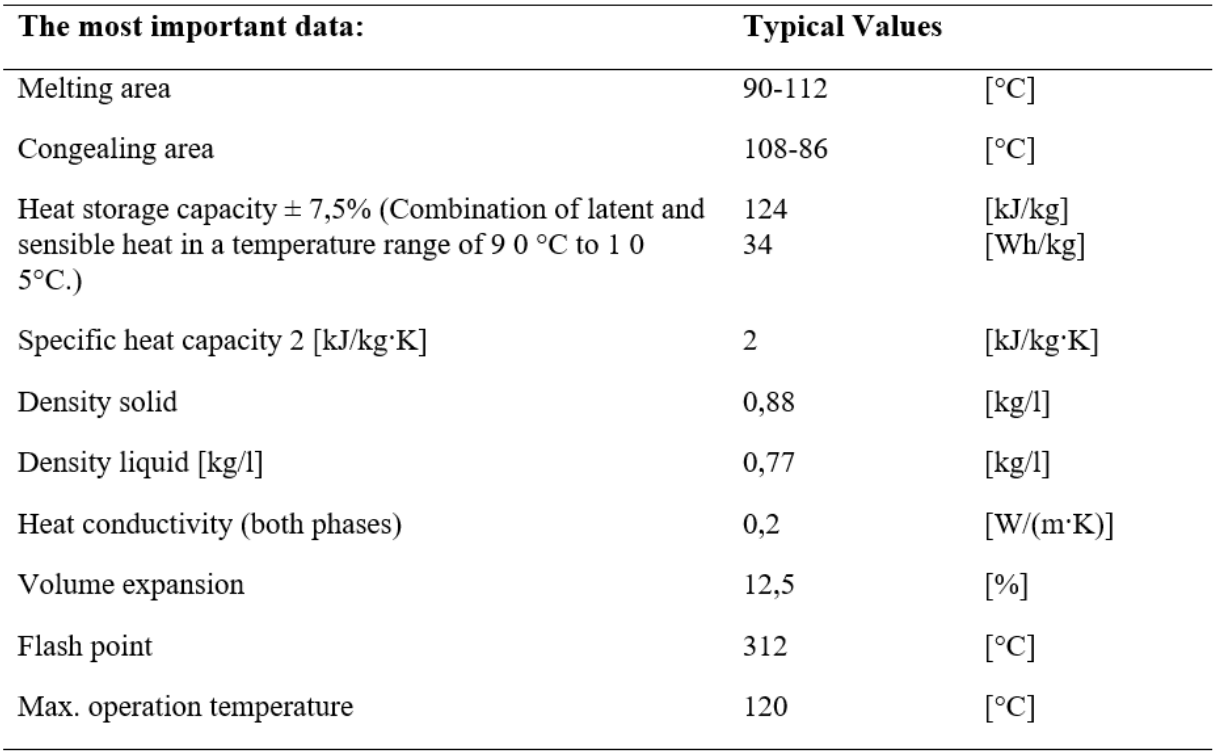
When considering phase change materials, it has been observed that organic-based materials are the most suitable for our analysis and suitable for use in latent heat storage processes. Since the analysis properties of these organic materials are not available, ready-made encapsulated products with predetermined thermal properties were used for our analysis. Considering the investigation in waste heat storage, material selection was made taking into account the system's inlet temperature. The selected material properties are shown in Table 3.1, 3.2, and 3.3.

Table 3.1. Properties of RT60 material



The most important data:	**Typical Values**	
Melting area	55-61	[°C]
Congealing area	61-55	[°C]
Heat storage capacity ± 7,5% (Combination of latent and sensible heat in a temperature range of 9 0 °C to 1 0 5°C.)	160 40	[kJ/kg] [Wh/kg]
Specific heat capacity 2 [kJ/kg·K]	2	[kJ/kg·K]
Density solid	0,88	[kg/l]
Density liquid [kg/l]	0,77	[kg/l]
Heat conductivity (both phases)	0,2	[W/(m·K)]
Volume expansion	12,5	[%]
Flash point	>200	[°C]
Max. operation temperature	80	[°C]

Table 3.2. Properties of RT100 material.

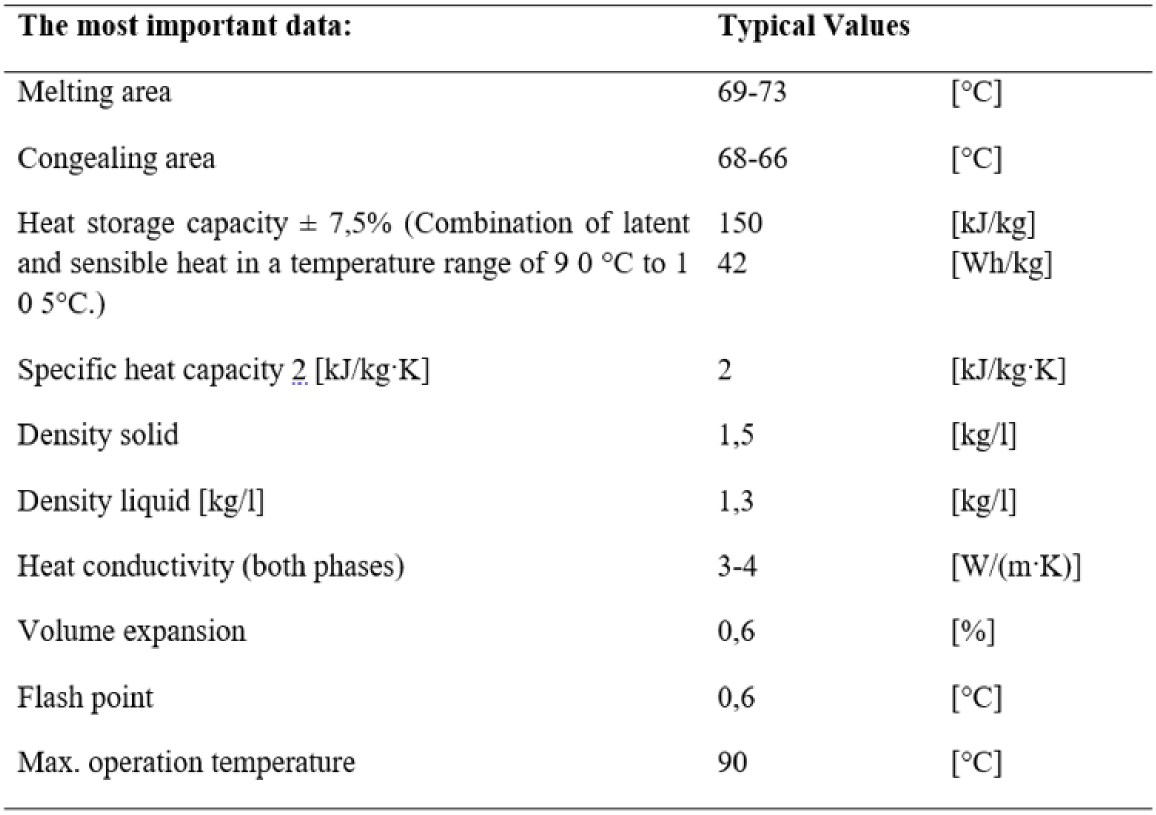


The most important data:	**Typical Values**	
Melting area	90-112	[°C]
Congealing area	108-86	[°C]
Heat storage capacity ± 7,5% (Combination of latent and sensible heat in a temperature range of 9 0 °C to 1 0 5°C.)	124 34	[kJ/kg] [Wh/kg]
Specific heat capacity 2 [kJ/kg·K]	2	[kJ/kg·K]
Density solid	0,88	[kg/l]
Density liquid [kg/l]	0,77	[kg/l]
Heat conductivity (both phases)	0,2	[W/(m·K)]
Volume expansion	12,5	[%]
Flash point	312	[°C]
Max. operation temperature	120	[°C]

The RT category of Phase Change Materials (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 thermal energy within a relatively consistent temperature range. Depending on their unique melting points, these PCMs can be employed for diverse heat storage applications at varying temperatures. 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.

RT products encompass a broad temperature span, ranging from approximately -10 °C to 90 °C (14 °F to 194 °F). Moreover, there are high-capacity RT variants, such as Rubitherm RT5 HC, tailored for specific temperature ranges. RTHC products exhibit an enhanced latent heat capacity of around 25-30% compared to traditional RT materials and possess a narrower temperature range for phase transition. These PCMs offer advantages even in situations where space is limited. In addition, RT materials can be combined with compact storage modules (CSM) or macro encapsulation. Furthermore, RT materials serve as the building blocks for our bonded or microencapsulated PCM solutions.

Table 3.3. Properties of SP70 material.

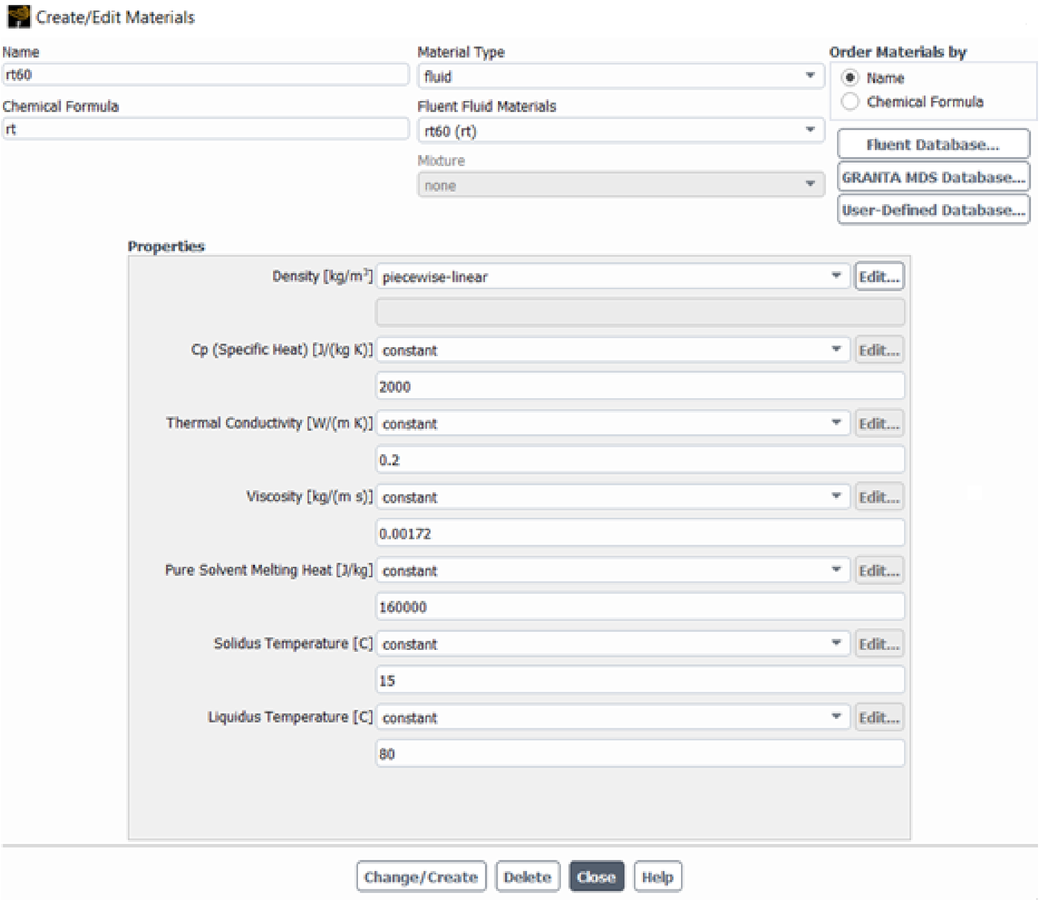


The most important data:	Typical Values	
Melting area	69-73	[°C]
Congealing area	68-66	[°C]
Heat storage capacity ± 7,5% (Combination of latent and sensible heat in a temperature range of 9 0 °C to 1 0 5°C.)	150 42	[kJ/kg] [Wh/kg]
Specific heat capacity 2 [kJ/kg·K]	2	[kJ/kg·K]
Density solid	1,5	[kg/l]
Density liquid [kg/l]	1,3	[kg/l]
Heat conductivity (both phases)	3-4	[W/(m·K)]
Volume expansion	0,6	[%]
Flash point	0,6	[°C]
Max. operation temperature	90	[°C]

Rubitherm SP products are formulated as Phase Change Materials (PCMs) utilizing combinations of saltwater mixtures and additives, which act as latent heat storage media. These PCMs undergo phase transitions between solid and liquid states, enabling the efficient release and storage of significant thermal energy. While the melting temperatures of SP materials may differ slightly from RT materials, typically by just 1 K, this temperature variation is minimal.

Another commonly mentioned issue with inorganic PCMs is cycle stability. In order to ensure the stability, some SP materials undergo up to 10000 cycles of operation. By doing so, we can eliminate aging effects.

The properties of the selected phase change materials are defined in the ANSYS Fluent program as shown in Figure 3.4. as an example.



Name: rt60

Chemical Formula: rt

Material Type: fluid

Fluent Fluid Materials: rt60 (rt)

Mixture: none

Order Materials by: ● Name ○ Chemical Formula

Properties

Density [kg/m^3]	piecewise-linear	
Cp (Specific Heat) [J/(kg K)]	constant	2000
Thermal Conductivity [W/(m K)]	constant	0.2
Viscosity [kg/(m s)]	constant	0.00172
Pure Solvent Melting Heat [J/kg]	constant	160000
Solidus Temperature [C]	constant	15
Liquidus Temperature [C]	constant	80

Figure 3.4. Identification of material properties to the system.

In the CFD scenario solved using the finite volume method, the most influential factor in determining the results is the mesh structure elements. The water volume is divided into equal small volumes to create nodes and elements. Using these nodes, results are obtained through various iterative method steps. Having a larger number of nodes creates more iterations, resulting in greater stability in the results. However, beyond a certain number of elements, the results do not show significant variation due to the condition of being "independent of the mesh structure." This is defined as a waste of time. On the other hand, having lesser nodes than required will result in the formation of coarse mesh structures, leading to faster solving but less accurate results. In this case, errors can occur in the results. When constructing the mesh structure, it is important to balance the number of elements. In this study, a mesh number of 808537 was used on the model geometry to achieve the most accurate results. The mesh image is shown in Table 3.5.

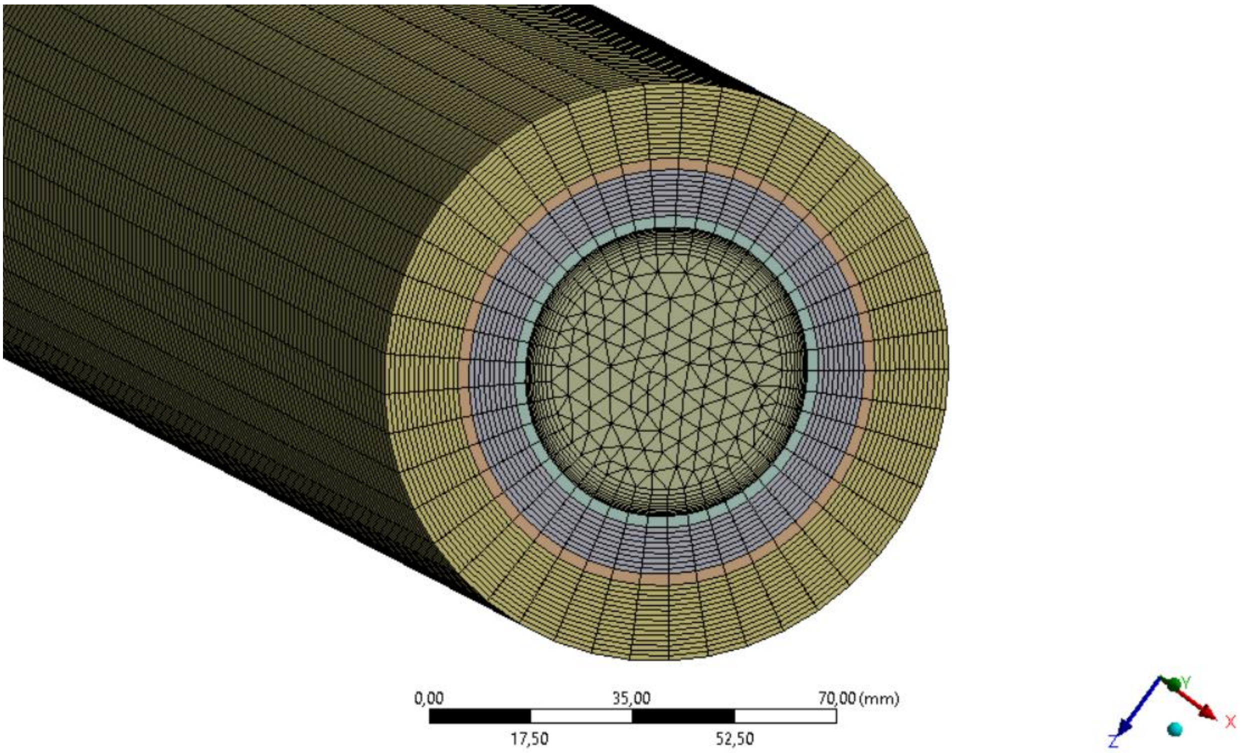


Figure 3.5. Mesh model of the geometry.

3.2. Mathematical Formulation and Numerical Analysis

After creating the mesh structure, the solver settings for numerical analysis are defined using the Fluent (Set-up) module of the ANSYS program. Material information, physical properties, and inlet/outlet conditions for hot and cold water are defined. To calculate phase change in PCM, Solidification/Melting is selected in the system. Boundary conditions are specified. Once the set-up process is completed, the program is run. After the analysis, the obtained results are examined numerically and visually in the result section of the program. The analysis is performed for a transient state.

The boundary conditions and the continuity, momentum, and energy equations used in the analysis are expressed by the following mathematical formulas.

Continuity equation:

$$\frac{1}{r}\frac{\partial(ru_r)}{\partial r}+\frac{1}{r}\frac{\partial(u_\theta)}{\partial\theta}+\frac{\partial(u_z)}{\partial z}=0 \tag{3.1}$$

Momentum equation:

In the r-direction:

$$p\left(\frac{\partial(u_r)}{\partial t}+u_r\frac{\partial(u_r)}{\partial r}+\frac{u_\theta}{r}\frac{\partial(u_r)}{\partial\theta}-{u_\theta}^2+u_z\frac{\partial(u_r)}{\partial z}\right)=-\frac{\partial P}{\partial r}+pg_r+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right)-\frac{u_r}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial\theta}-\frac{2}{r^2}\frac{\partial u_\theta}{\partial\theta}+\frac{\partial^2 u_r}{\partial z^2}\right] \tag{3.2}$$

In the -θ direction:

$$p\left(\frac{\partial u_\theta}{\partial t}+u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial\theta}+\frac{u_\theta u_r}{r}+u_z\frac{\partial u_\theta}{\partial z}\right)=-\frac{1}{r}\frac{\partial P}{\partial\theta}+pg_\theta+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_\theta}{\partial r}\right)-\frac{u_\theta}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial\theta^2}+\frac{2}{r^2}\frac{\partial u_r}{\partial\theta}+\frac{\partial^2 u_\theta}{\partial z^2}\right] \tag{3.3}$$

In the z-direction:

$$p\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial\theta}+u_z\frac{\partial u_z}{\partial z}\right)=-\frac{\partial P}{\partial z}+pg_z+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial\theta^2}+\frac{\partial^2 u_z}{\partial z^2}\right] \tag{3.4}$$

Energy equation:

$$\frac{\partial T}{\partial t}+u_r\frac{\partial T}{\partial r}+\frac{u_\theta}{r}\frac{\partial T}{\partial\theta}+u_z\frac{\partial T}{\partial z}=\frac{\dot{q}_g}{c_p}+\alpha\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T}{\partial\theta^2}+\frac{\partial^2 T}{\partial z^2}\right]+\frac{\varphi}{pc_p} \tag{3.5}$$

The boundary conditions of the model are expressed in Table 3.4.

Table 3.4. 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	$\frac{\partial T}{\partial z}=0$

The formulas used to determine the heat transfer rate and heat transfer effectiveness, as well as the value of logarithmic mean temperature difference, are expressed by the following equation.

Logarithmic mean temperature difference:

$$\Delta T_1 = T_{h,in} - T_{c,out} \tag{3.6}$$

$$\Delta T_2 = T_{h,out} - T_{c,in} \tag{3.7}$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \tag{3.8}$$

The heat transfer rate in the heat exchanger is given by:

$$\dot{Q} = UA_s\Delta T_{lm} \tag{3.9}$$

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

$$C_c = \dot{m}_c c_{pc} \tag{3.10}$$

$$C_h = \dot{m}_h c_{ph} \tag{3.11}$$

$$\Delta T_{max} = T_{h,in} - T_{c,in} \tag{3.12}$$

$$\dot{Q}_{max} = C_{min}\Delta T_{max} \tag{3.13}$$

$$\varepsilon = \frac{\dot{Q}_{act}}{\dot{Q}_{max}} = \frac{Actual\ heat\ transfer\ rate}{Maximum\ heat\ transfer\ rate} \tag{3.14}$$

4. RESULTS AND DISCUSSION

In this section, numerical results were obtained for three different parameters. In the first stage, three different types of phase change materials were selected, and analysis was performed with $T_{hot,in}$=60°C and Re=1200 to observe the effect of material diversity on heat transfer. In the second stage, the RT60 material was selected, and the Reynolds number was varied as Re=400, 800, 1200, and 1600 at $T_{hot,in}$= 60°C to investigate the effect of different Reynolds number on the system. Finally, in order to investigate the effect of different inlet temperatures, $T_{hot,in}$ was varied as 40°C, 60°C, 70°C, and 80°C while Re=1200 and RT60 material was selected as PCM.

4.1. Heat Transfer Performance of Different PCMs

The analysis was determined to observe the behavior of the selected phase change material when water passes through the tube at 60°C and Reynolds number Re=1200 (laminar flow). 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. Considering the differences in thermal conductivity of the selected materials, it is expected to observe the effect of thermal conductivity on heat conduction and heat storage when these parameters are taken into account.

As regards different types of phase change materials, the heat transfer effectiveness were calculated as 78.59% for SP70, 75.78% for RT100, and 81.3% for RT60. The stored energy by the PCM was determined as Q=292.26 W for RT60, Q=312.83 W for RT100, and Q=456.19 W for SP70. The temperature contours and velocity vectors for the RT60 material for different PCMs are shown Figure 4.1., 4.2., 4.3., 4.4., 4.5. and 4.6.

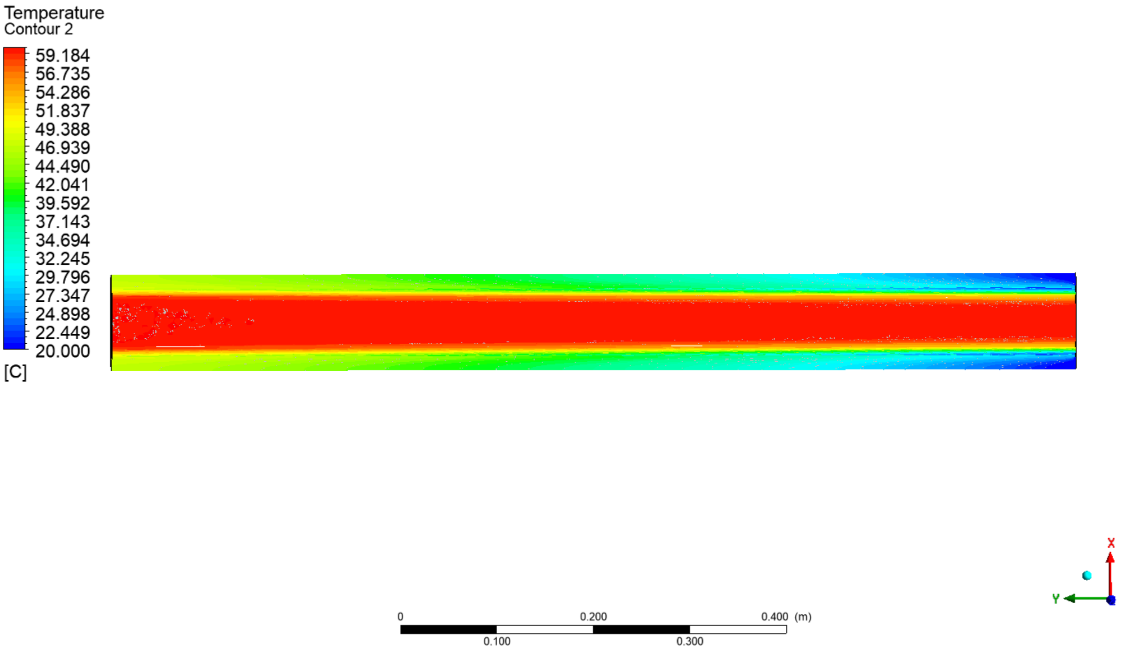


Figure 4.1. The temperature contours for the RT60 material.

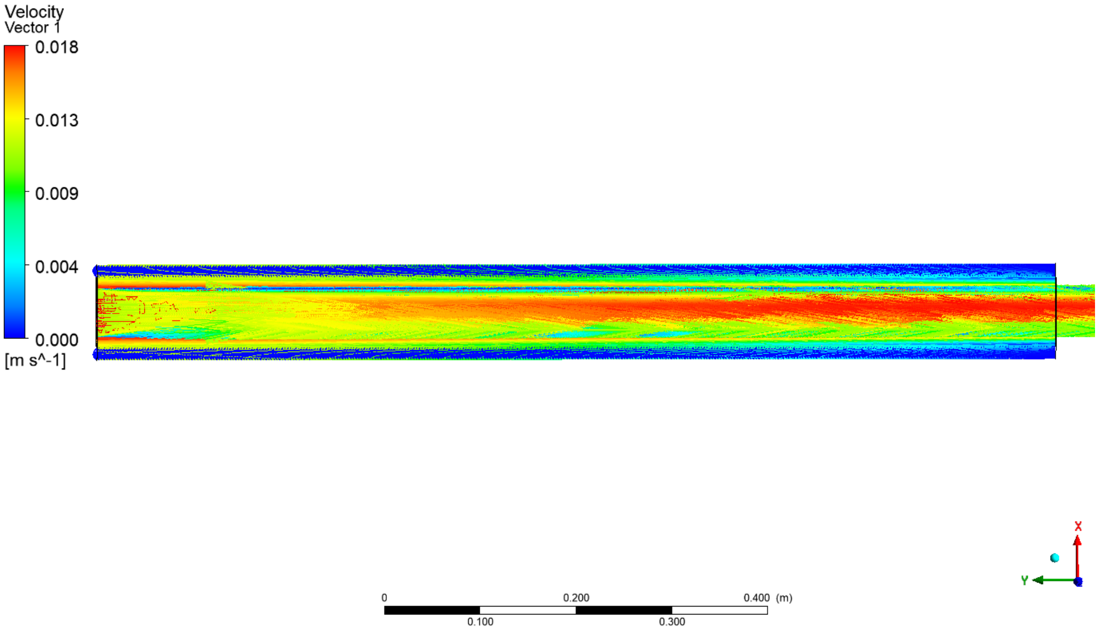


Figure 4.2. The velocity vectors for the RT60 material.

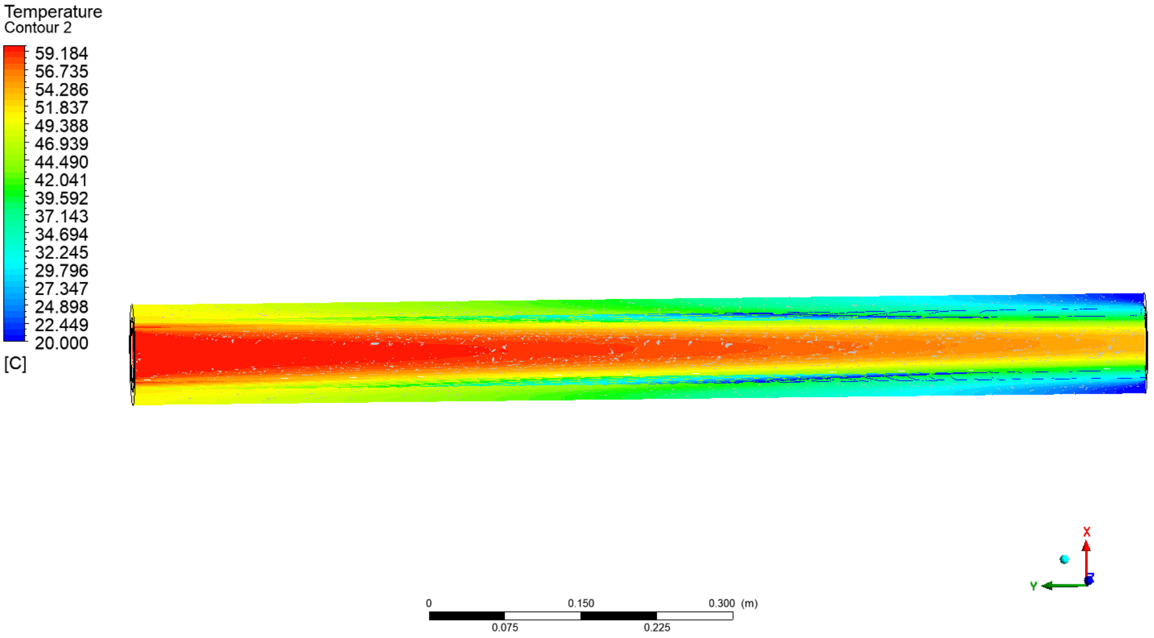


Figure 4.3. The temperature contours for the SP70 material.

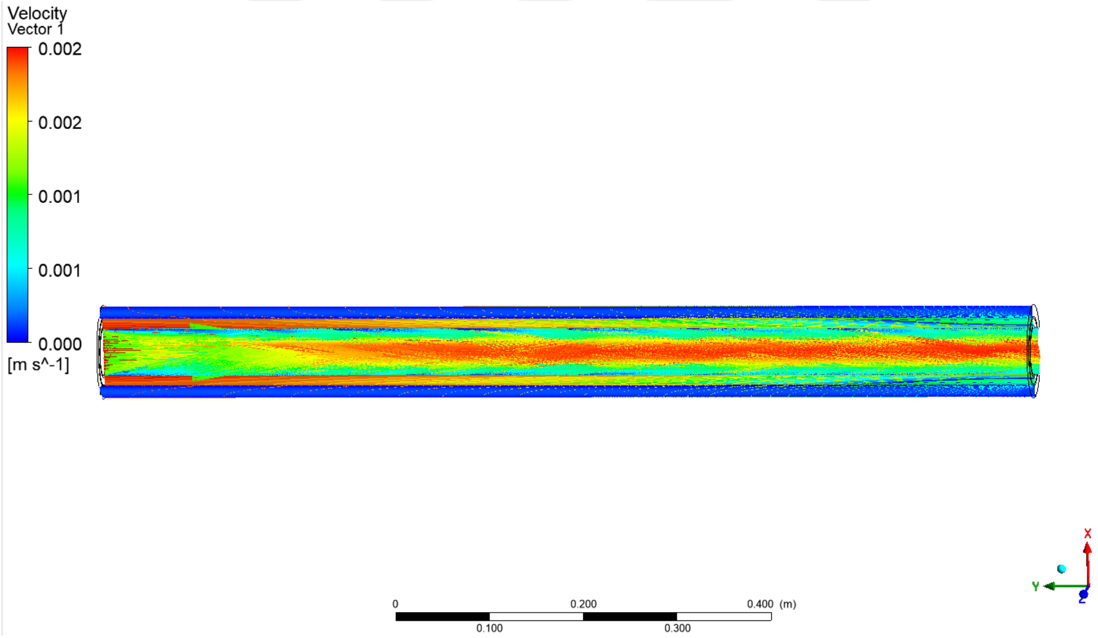


Figure 4.4. The velocity vectors for the SP70 material.

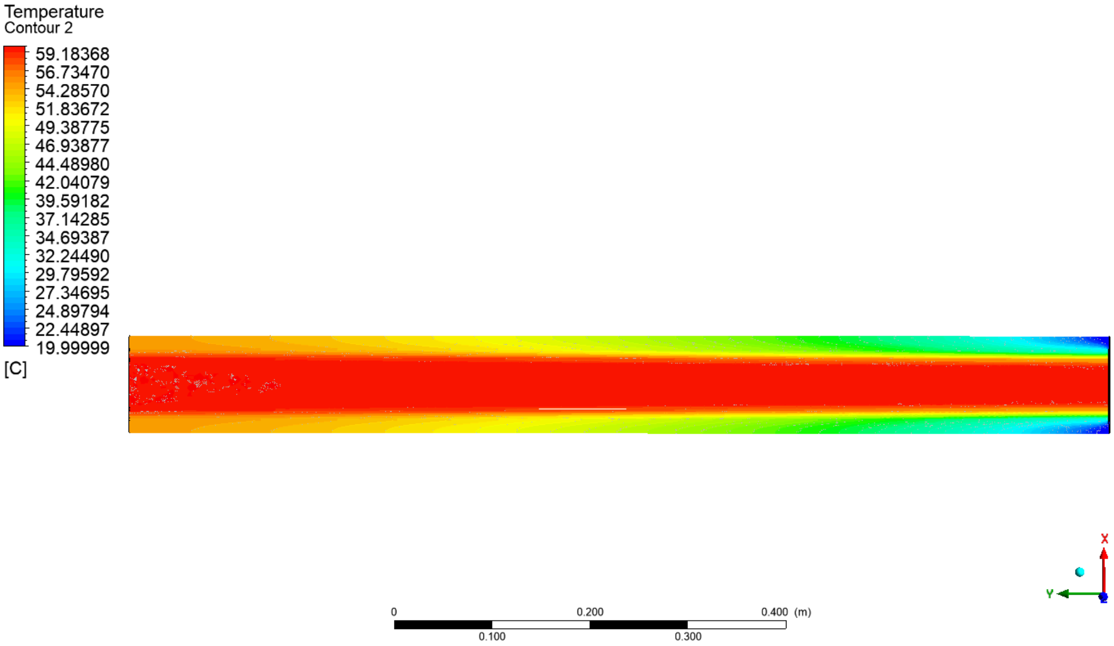


Figure 4.5. The temperature contours for the RT100 material.

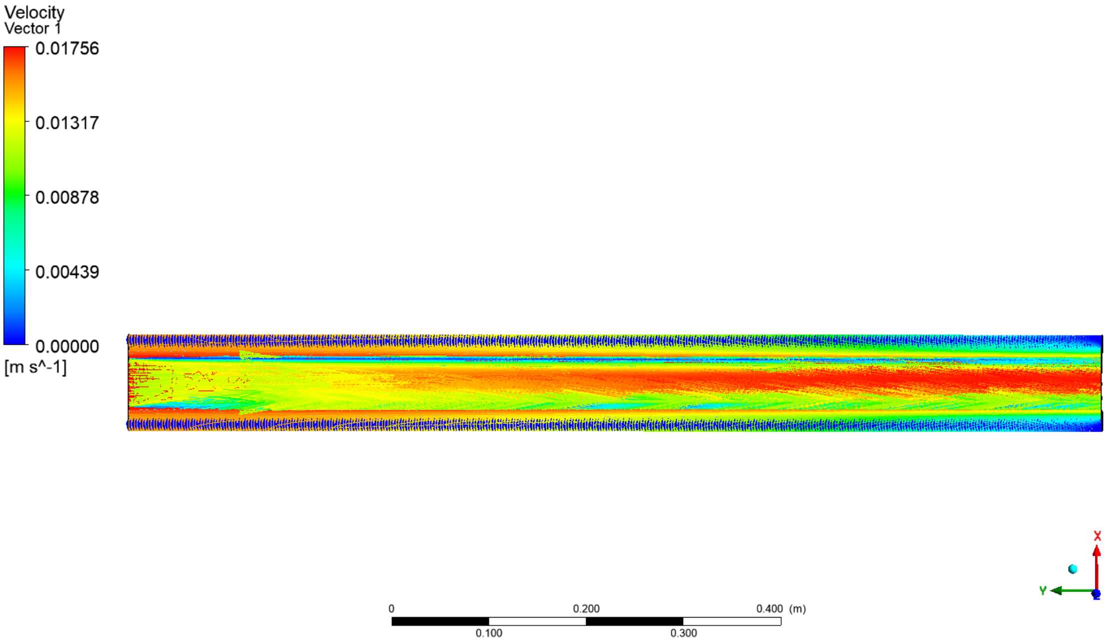


Figure 4.6. The velocity vectors for the RT100 material.

Considering the findings obtained from analysis, it can be observed that the materials RT100 and SP70, which have different material types, exhibit similar temperature changes. Additionally, their capability in heat storage and thermal conductivity are similar between hot water and cold water. Heat transfer effectiveness of the heat exchanger for different PCM types is presented in Figure 4.7.

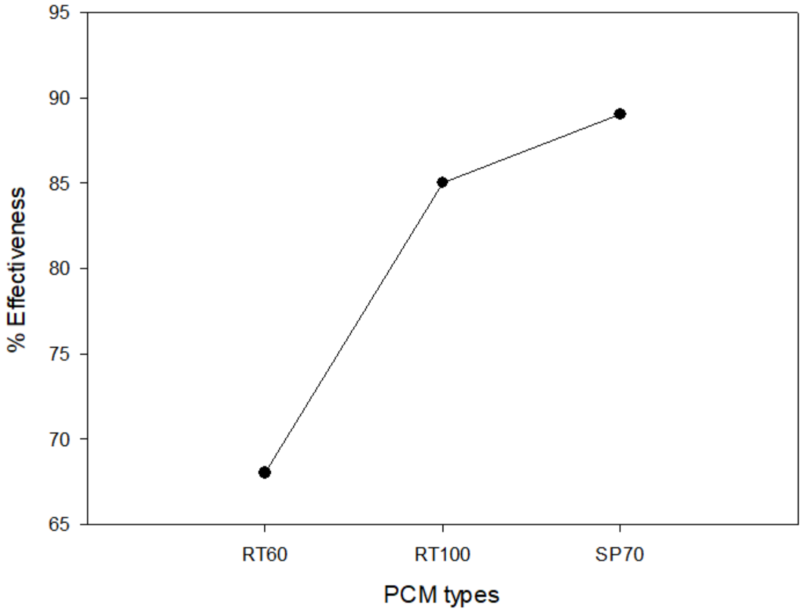


Figure 4.7. Heat transfer effectiveness of the heat exchanger.

4.2. The Effect of Different Reynolds Number

In this stage, the RT60 material is used to determine effect of different Reynolds number on heat transfer performance under laminar flows at 60°C. In order to investigate the effect of laminar flow conditions for waste heat recovery system which is operated under low flow velocities. Therefore, 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. The goal of the procedure is to achieve maximum energy storage and energy transfer by increasing Reynolds number gradually.

As regard different Reynolds numbers, the heat transfer effectiveness were calculated as 64.02% for Re=400, 73.9% for Re=800, 78.5% for Re=1200, and 81.19% for Re=1600. The stored energy by the PCMs was determined as Q=135.23 W for Re=400, Q=223.73 W for Re=800, Q=292.02 W for Re=1200, and 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 4.8., 4.9., 4.10., 4.11., 4.12., 4.13., 4.14. and 4.15.

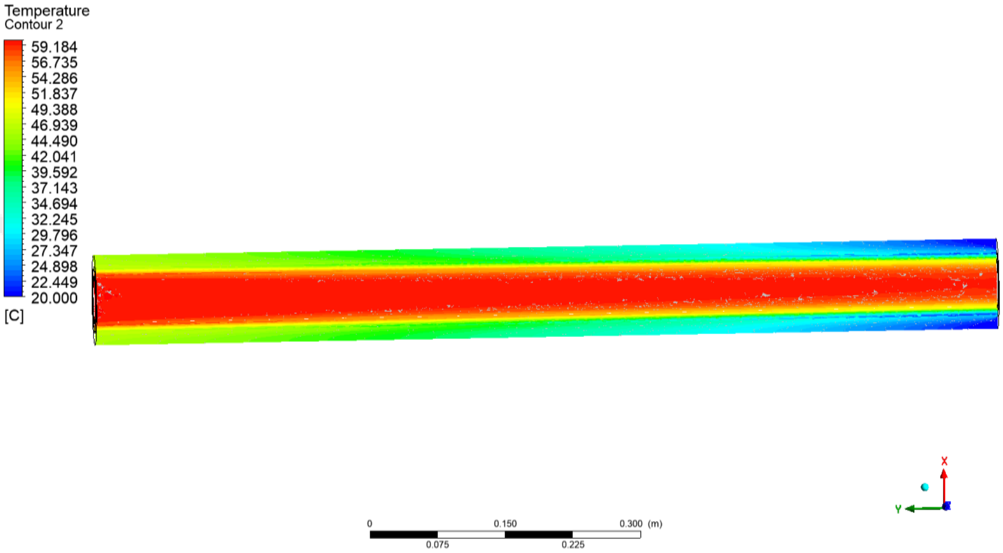


Figure 4.8. The temperature contours for the RT60 material for Re=400.

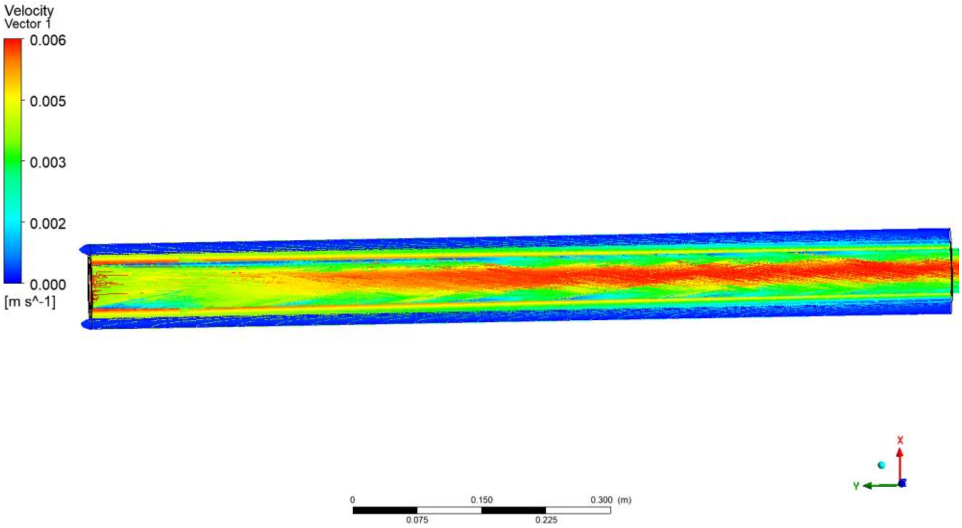


Figure 4. 9. The velocity vectors for the RT60 material for Re=400.

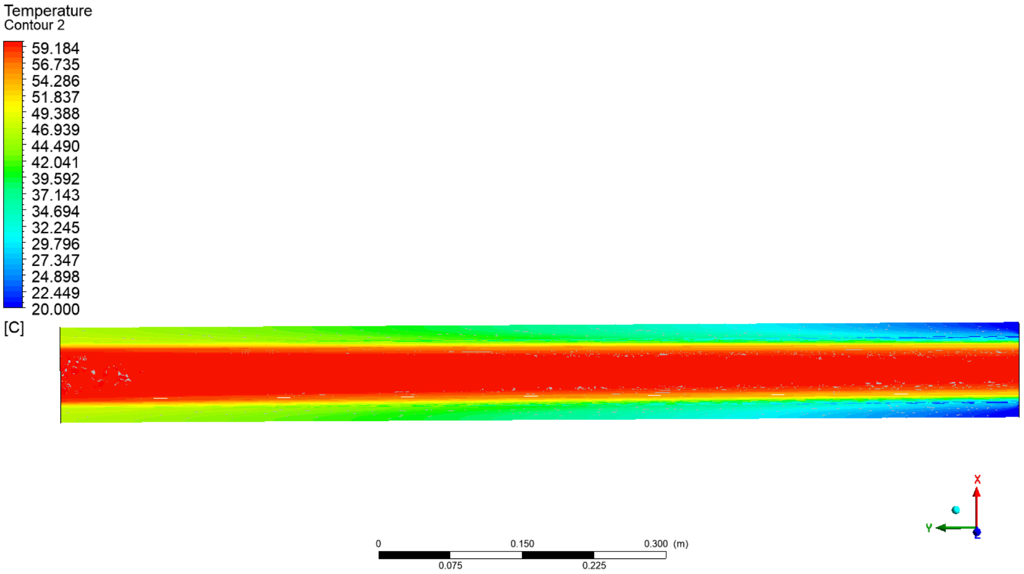


Figure 4.10. The temperature contours for the RT60 material for Re=800.

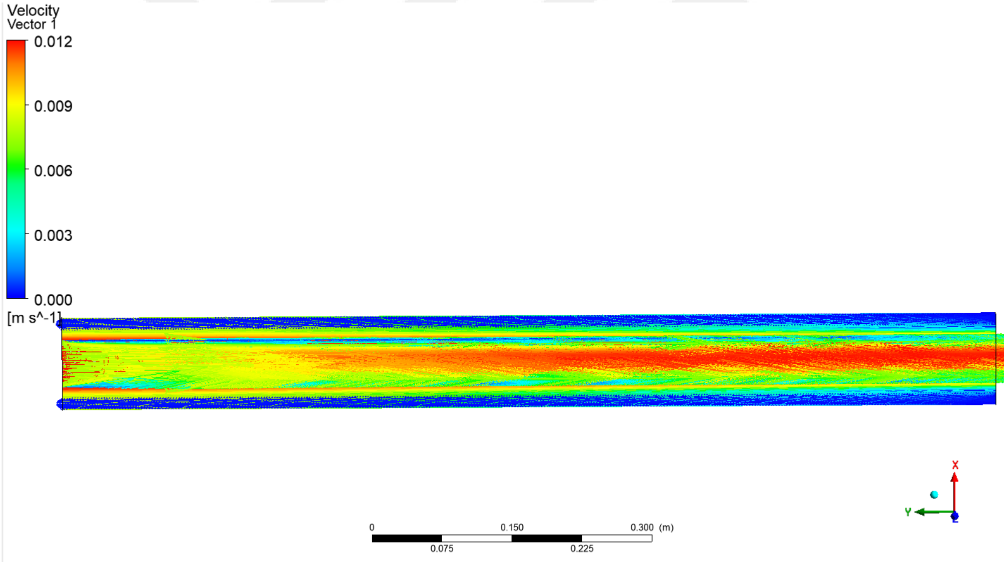


Figure 4.11. The velocity vectors for the RT60 material for Re=800.

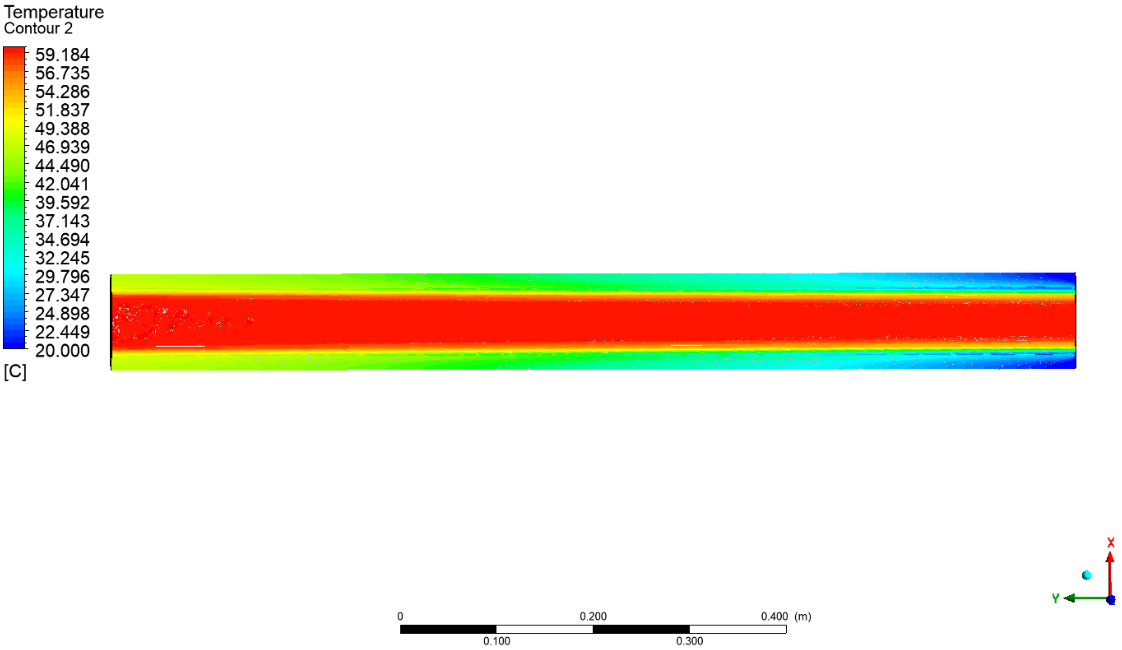


Figure 4.12. The temperature contours of the RT60 material for Re=1200.

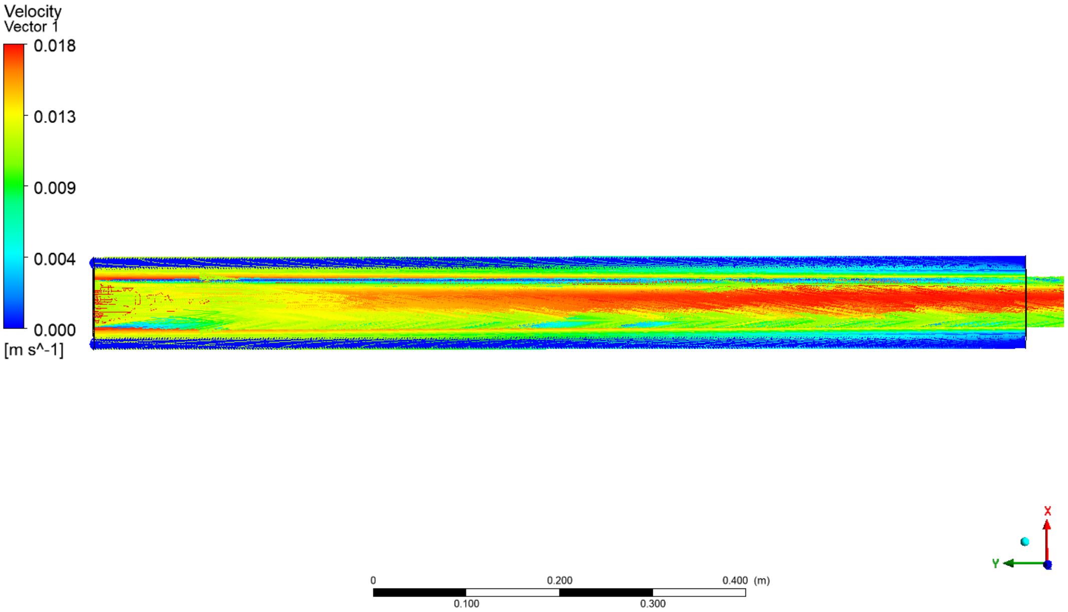


Figure 4.13. The velocity vectors of the RT60 material for Re=1200.

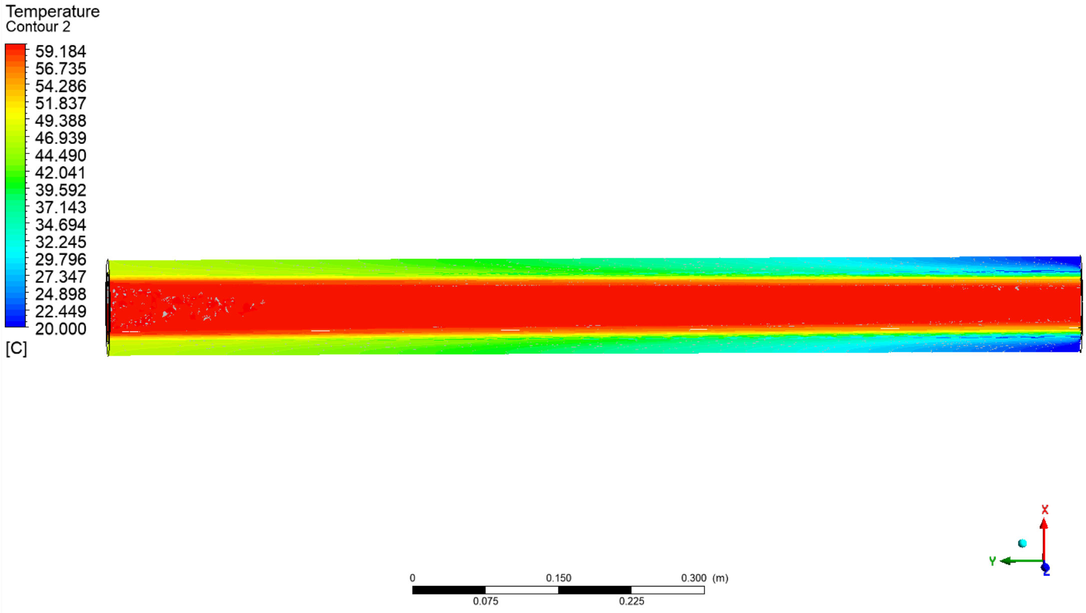


Figure 4.14. The temperature contours of the RT60 material for Re=1600.

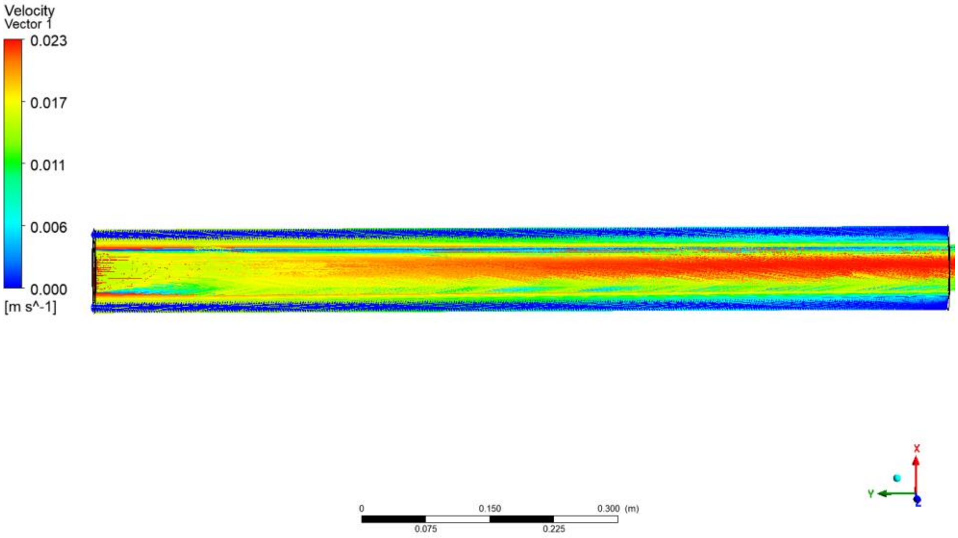


Figure 4.15. The velocity vectors of the RT60 material for Re=1600.

It has been determined that increasing Reynolds number of the fluid caused increase in heat transfer effectiveness. Effect of increasing Reynolds number on the heat transfer effectiveness is shown in Figure 4.16.

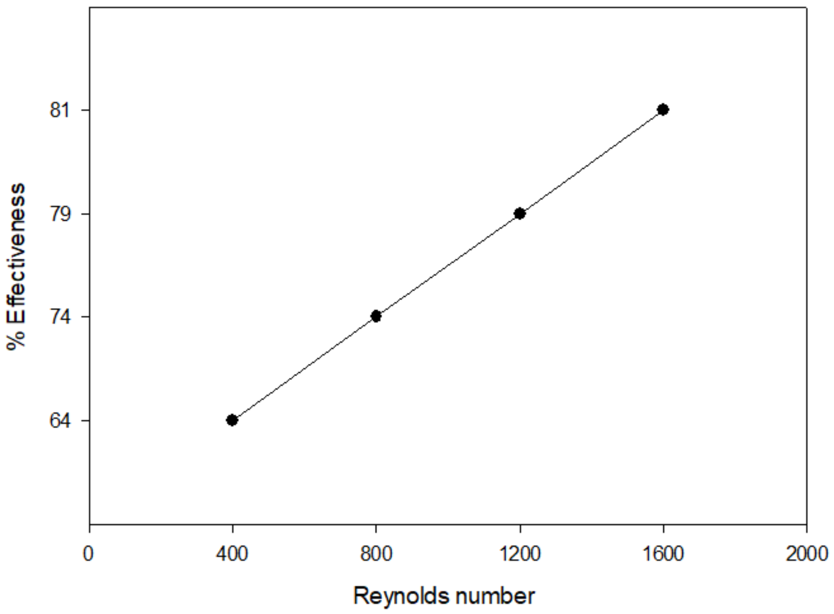


Figure 4.16. Heat transfer effectiveness for different Reynolds numbers.

4.3. The Effect of Different Inlet Temperatures

Effect of different inlet temperatures ($T_{hot,in}$=40, 60, 70, and 80°C) of the hot fluid is investigated for RT60 material with 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. The hot fluid inlet temperature has been selected in the range of 40-80°C, considering the temperature of the rejected heat. To better understand the effect of temperature increase, an increment from 40°C to 60°C was applied, and subsequent intervals were analyzed with equal increments.

It has been determined that the heat transfer effectiveness is 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. The temperature contours of the RT60 material for different inlet temperatures at Re=1200 are shown in Figure 4.17., 4.18., 4.19., 4.20., 4.21., 4.22., 4.23.and 4.24.

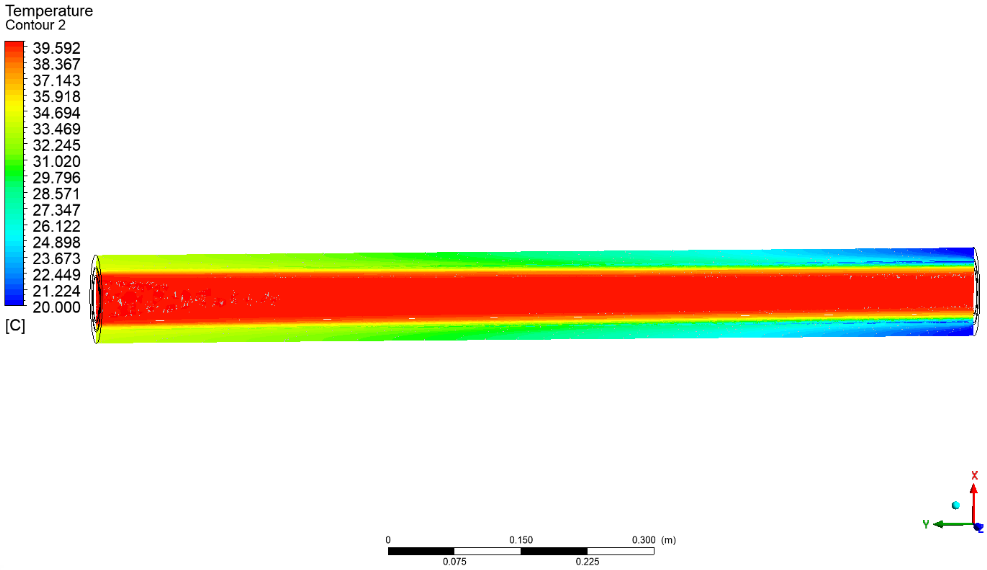


Figure 4.17. The temperature contours of the RT60 material for $T_{hot,in}$ = 40°C.

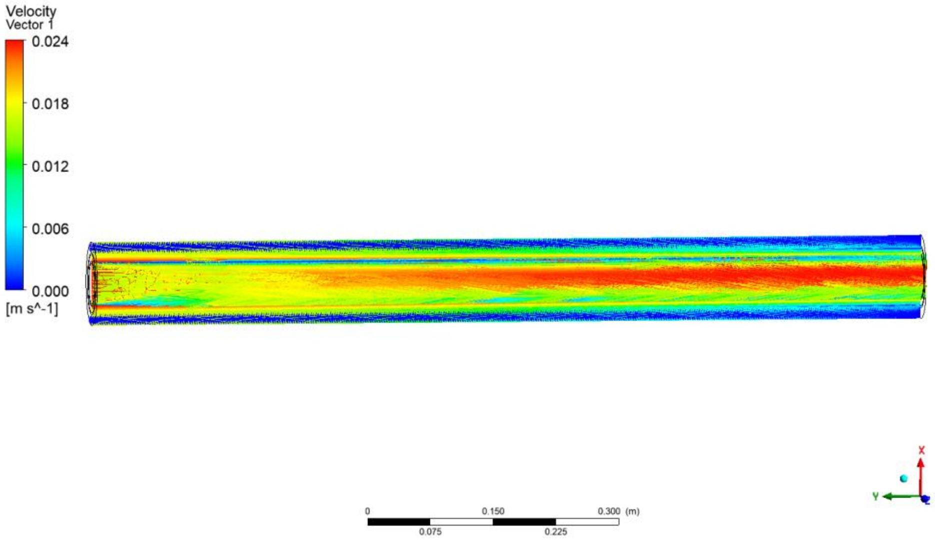


Figure 4.18. The velocity vectors of the RT60 material for $T_{hot,in}$ = 40°C.

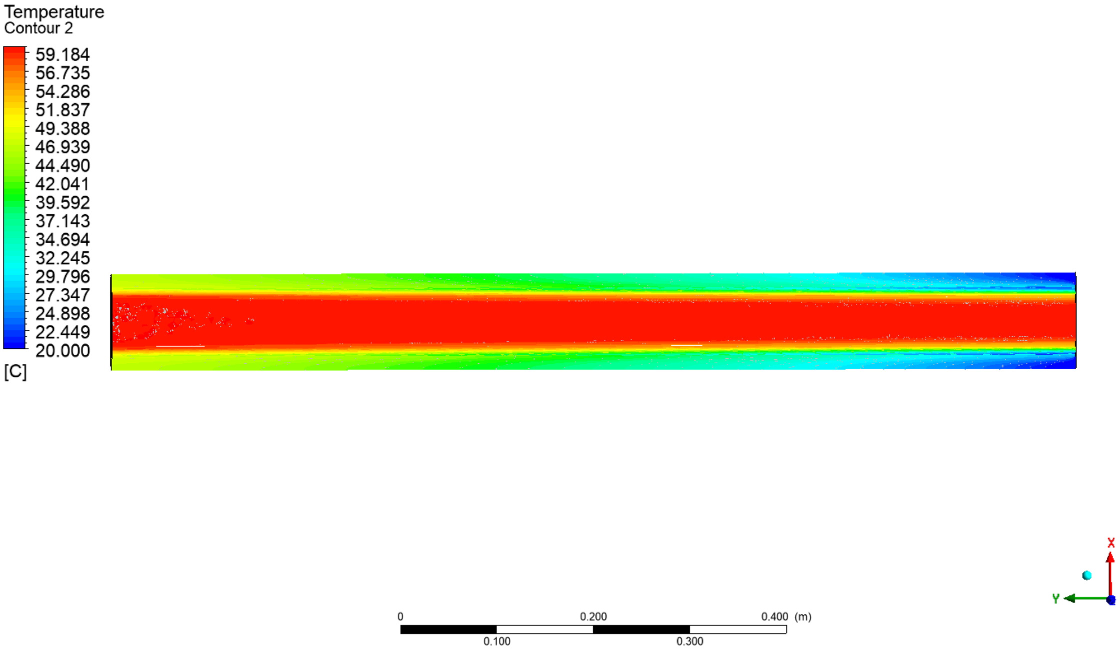


Figure 4.19. The temperature contours of the RT60 material for $T_{hot,in}$ = 60°C.

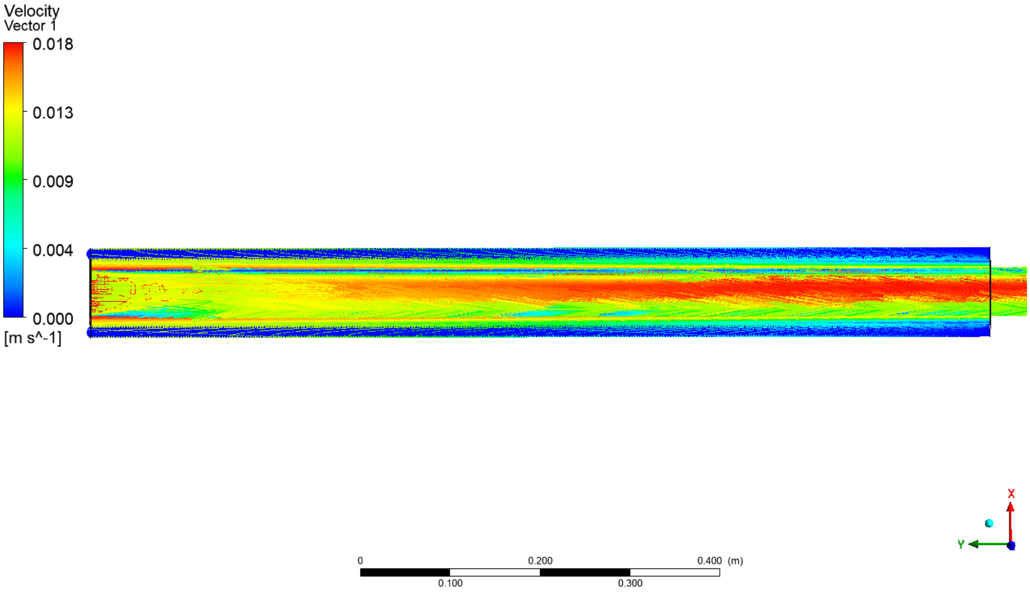


Figure 4.20. The velocity vectors of the RT60 material for $T_{hot,in}$ = 60°C.

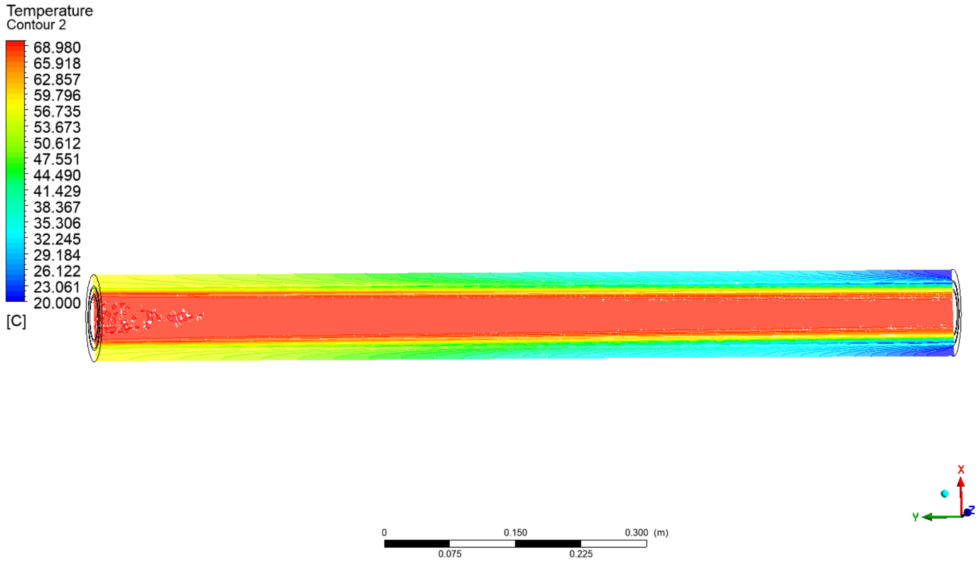


Figure 4.21. The temperature contours of the RT60 material for $T_{hot,in}$=70°C.

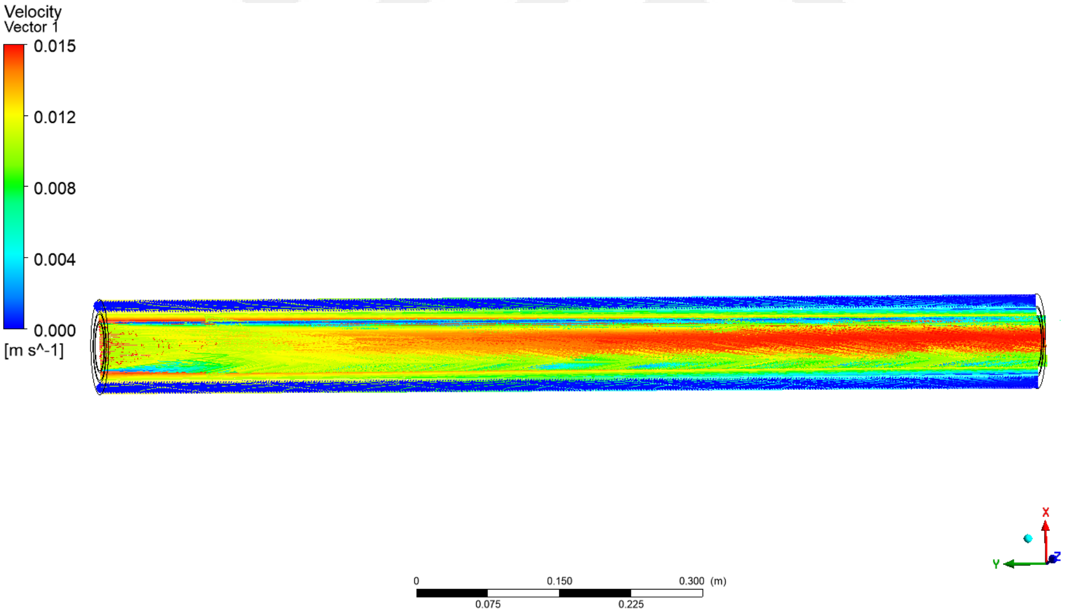


Figure 4.22. The velocity vectors of the RT60 material for $T_{hot,in}$=70°C.

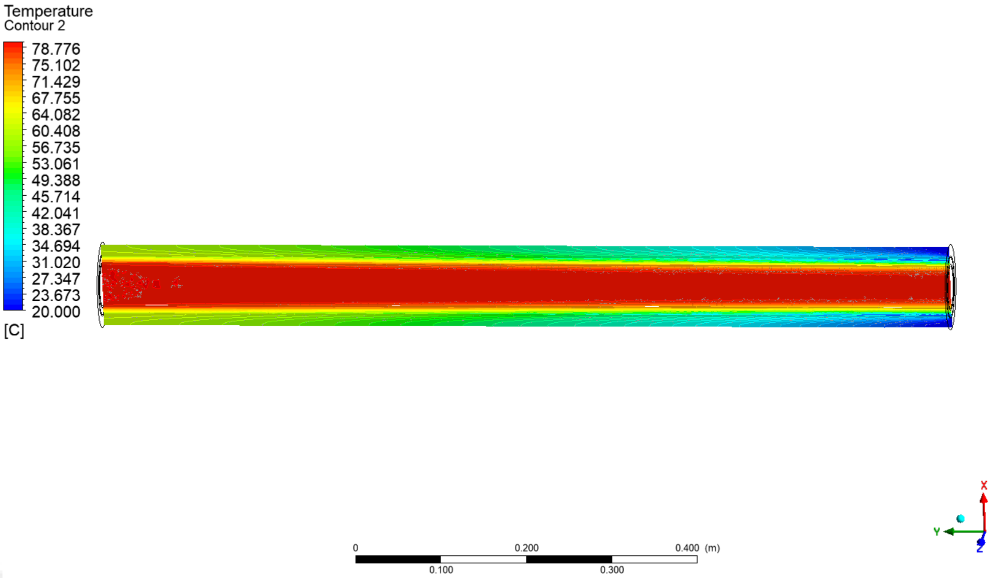


Figure 4.23. The temperature contours of the RT60 material for $T_{hot,in}$=80°C.

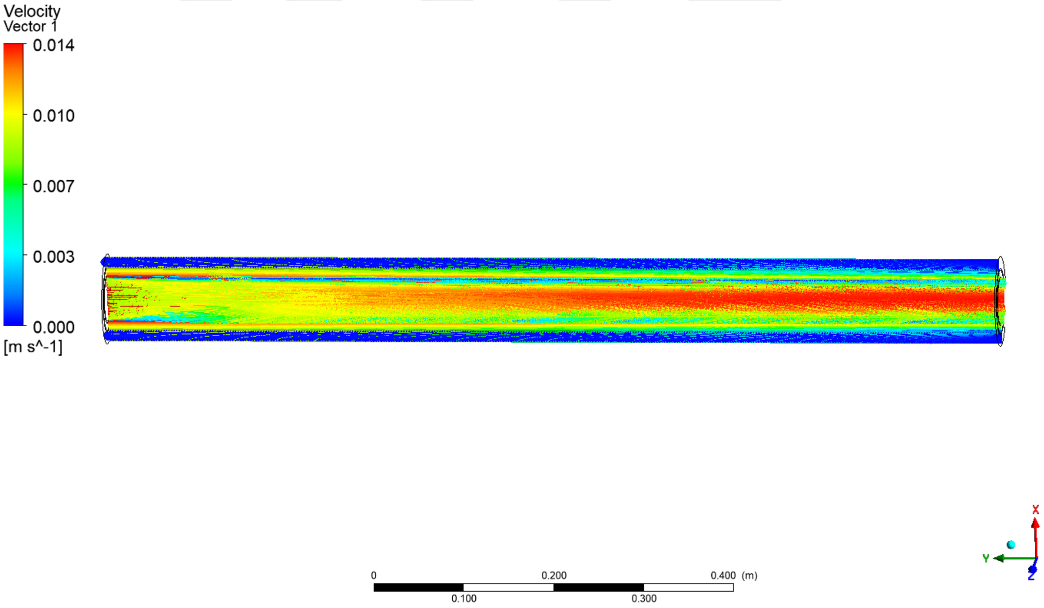


Figure 4.24. The velocity vectors of the RT60 material for $T_{hot,in}$=80°C.

It has been evaluated that inlet temperature of the hot fluid plays a significant role in the heat transfer effectiveness of the heat exchanger. The effect of the hot inlet temperature of the fluid in the heat exchanger is shown in Figure 4.25. As a result of the analysis, the reason for the 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.

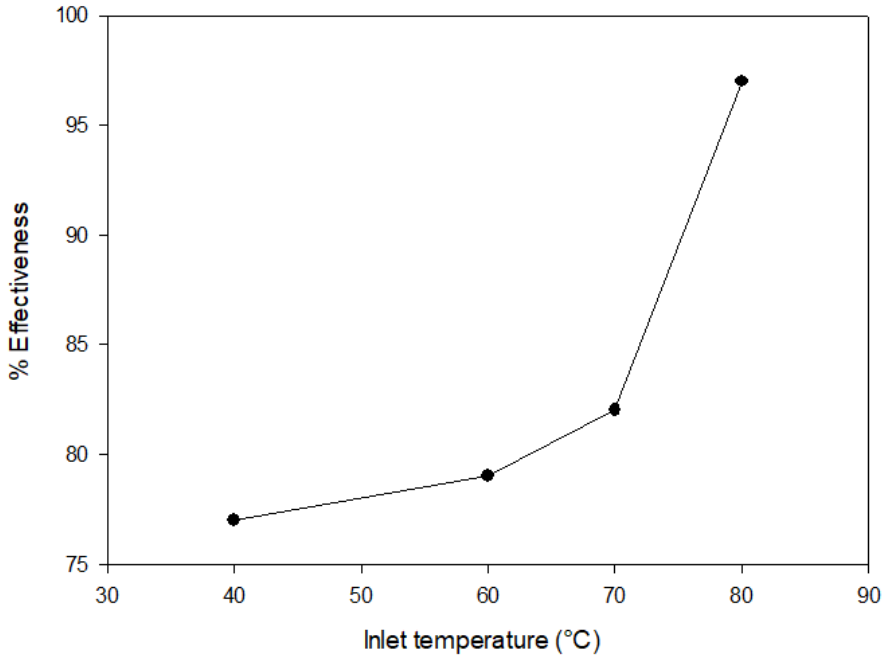


Figure 4.25. Heat transfer effectiveness of different inlet temperatures.

5. CONCLUSION

The aim of this thesis is to investigate the usage of phase change materials (PCMs) in waste heat recovery systems, which is not widely implemented yet but holds great potential. Waste heat recovery minimizes heat loss in systems and allows for the utilization of heat when it is needed through regenerative heat exchangers. Therefore, in this study, a regenerative heat exchanger was studied, and the analysis was conducted using the ANSYS Fluent program. Literature studies have mainly focused on the use of PCMs for thermal insulation and isolation purposes in buildings. Unlike literature studies, this study specifically analyzes the direct integration of waste heat recovery into the system using phase change materials.

Variable parameters in the analysis:

- For three different material types (RT60, RT100, and SP70), at a temperature of 60°C, for laminar flow conditions (Re=1200).
- For different Reynolds numbers (400, 600, 1200, 1600) with RT-60 material at $T_{hot,in}$=60°C.
- For different inlet temperatures of the fluid (40°C, 60°C, 70°C, and 80°C) with RT-60 material for Re=1200.

According to the results of the study,

- In the analysis conducted using different types of phase change materials, the heat transfer effectiveness were calculated as 78.59% for SP70, 75.78% for RT100, and 81.3% for RT60. The stored energy by the PCM was determined as Q=292.26 W for RT60, Q=312.83 W for RT100, and Q=456.19 W for SP70. RT60 showed the best heat transfer performance compared to other PCM types.
- Through the analysis conducted with varying Reynolds numbers using the selected material RT60, the heat transfer effectiveness were calculated as 64.02% (Re=400), 73.9% (Re=800), 78.5% (Re=1200), and 81.19% (Re=1600). The energy stored by the PCMs was determined as Q=135.23 W for Re=400, Q=223.73 W for Re=800, Q=292.02 W for Re=1200, and Q=348.15 W for Re=1600. It is determined that the fluid flow with Re=1600 has 17.2% more heat transfer effectiveness than the fluid flow with Re=400. Gradually increasing Reynolds number caused increase in heat transfer effectiveness.

- It has been observed that the heat transfer effectiveness is 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. Additionally the PCMs energy storage amounts were determined as Q=180.84 W for 40°C, Q=292.26 W for 60°C, Q = 332.15 W for 70°C, and Q = 364.38 W for 80°C. The fluid flow at $T_{hot,in}$=80°C temperature has 20.6% more heat transfer effectiveness than the fluid flow at $T_{hot,in}$=40°C. Increasing inlet temperature of the fluid caused increase in heat transfer effectiveness of the heat exchanger.

6. RECOMMENDATIONS

In order to develop heat exchangers, there are many active and passive methods in literature. The prominence of energy saving has made passive methods more important than active methods. Some of the passive methods are extended surfaces, geometrical modifications, use of phase change materials, nanofluids, vortex generators, different geometric designs. In this thesis study, different types of PCMs have been used with the combined effect of different Reynolds number and different inlet temperatures. For the future scope, in heat exchangers, different types of PCMs with nanofluids, hybrid and ternary hybrid nanofluids, fluids with ferromagnetic nanoparticles under magnetohydrodynamics (MHD) effect can be studied to design more effective heat exchangers. Furthermore, eco-friendly organic nanofluids can also be studied with different conditions in turbulent flow.

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