Development and Evaluation of a CFD Model to Simulate Thermal Performance of Phase Change Material (PCM) Based Energy Storage Systems

Hafiz Muhammad Adeel Hassan
Abstract

Waste heat can be recovered and used in different processes to increase energy efficiency and reduce CO\(_2\) emissions. It has become an attractive area of research for scientists and several techniques are being investigated and practiced to recover, store and use waste heat. Thermal Energy Storage is one of the modern techniques that is used to store and use waste heat. Energy can be stored in both sensible and latent forms of heat. Latent heat storage is the most efficient way of storing thermal energy as it provides higher storage density and lower temperature differential between storing and releasing heat. The materials that are used for latent energy storage are termed as Phase Change Materials (PCMs).

This thesis work investigates the feasibility of a latent heat storage and heat exchanger performance based on phase change material to recover heat at elevated temperatures. The heat transfer study is done by using state of the art commercial CFD tool. Different model geometries of the Thermal Storage equipped with Shell and tube heat exchanger were built with different pipe configurations.

The 1st type of model is a set of three 2D models built in COMSOL Multiphysics. These models constitute a cross section of a small portion of heat exchanger having four 10 mm outer diameter pipes immersed in PCM. Fins were mounted on the pipes to enhance the area for heat transfer and hence the heat transfer rate in modified models. Simulations were carried out for melting and solidification of PCM with these 2D models. After analyzing the results, a 3D model of the small block was created to get more realistic results and analyze the effect of pipe diameter on melting and solidification of PCM.

The results of 2D models show the effect of fins on heat transfer rates. The model with eight fins on each pipe shows the best results as compared to other two models. The melting and solidification rates are nearly half for eight fin model as compared to the model without fins. The four fin model shows moderate results but better than the model without fins. The comparison of the results for different diameter pipes in 3D model shows that heat transfer rate increases for increasing diameters of the pipe with same flow rate in the case of melting.
# Table of Contents

Abstract ................................................................................................................................. 2
Abbreviations .......................................................................................................................... 6
Nomenclature .......................................................................................................................... 7
Acknowledgements ................................................................................................................ 8
1 Introduction .......................................................................................................................... 9
  1.1 Background ..................................................................................................................... 9
  1.2 Objectives ...................................................................................................................... 9
  1.3 Methodology ................................................................................................................ 10
  1.4 Literature Review ....................................................................................................... 10
    1.4.1 Thermal Energy Storage ......................................................................................... 10
    1.4.2 Applications of Thermal Energy Storage .............................................................. 10
    1.4.3 Heat Exchangers used for PCM ........................................................................... 11
    1.4.4 Properties of Phase Change Materials .................................................................. 11
2 Heat Transfer in Phase Change Materials .......................................................................... 13
  2.1 The Stefan Problem ...................................................................................................... 13
    2.1.1 Techniques to Solve Stefan problem ................................................................... 13
  2.2 The Enthalpy Formulation Method ............................................................................... 14
  2.3 Heat Storage capacity of the PCM Container ............................................................... 16
3 Model Geometries ............................................................................................................. 17
  3.1 Work in COMSOL ...................................................................................................... 17
    3.1.1 Model parameters and conditions ....................................................................... 17
    3.1.2 Model-1 (2D) ....................................................................................................... 17
    3.1.3 Model-2 (2D) ....................................................................................................... 18
    3.1.4 Model-3 (2D) ....................................................................................................... 19
    3.1.5 3D model ............................................................................................................. 19
4 Results and Conclusions ................................................................................................. 21
  4.1 Model-1 (2D) ............................................................................................................ 21
    4.1.1 Melting/ Charging of PCM ................................................................................. 21
    4.1.2 Solidification/ discharging of PCM ..................................................................... 21
  4.2 Modified models (2D) ............................................................................................... 22
    4.2.1 Melting/ charging of the PCM ........................................................................... 22
    4.2.2 Solidification/ discharging of PCM ..................................................................... 23
  4.3 3D model ...................................................................................................................... 24
    4.3.1 Melting/ charging ............................................................................................... 24
    4.3.2 Solidification/ discharging .................................................................................. 25
  4.4 Discussion on results and Conclusions ...................................................................... 25
4.5 Future work Recommendations ........................................................................27
Bibliography .............................................................................................................28
Appendix-1: Physiochemical Properties of Erythritol.................................................29
Appendix-2: Model Parameters and Initial Conditions..............................................30
Appendix-3: CFD images of Melting Comparison for 2D models.................................32
Appendix-4: CFD Images of Temperature distribution for melting of PCM in 2D models........36
List of Figures

Figure 3-1 No fin model ..................................................................................................................18
Figure 3-2 Four fin model of the Heat Exchanger........................................................................18
Figure 3-3 Eight fin model of the Heat Exchanger.................................................................19
Figure 3-4 3D model geometry for heat exchanger..............................................................20
Figure 4-1 Phase Indicator diagram for PCM Melting............................................................21
Figure 4-2 Phase Indicator diagram for PCM solidification......................................................22
Figure 4-3 Phase indicator comparison for PCM melting.........................................................23
Figure 4-4 Phase indicator comparison for PCM solidification ................................................23
Figure 4-5 Phase indicator comparison for PCM melting for different diameters......................24
Figure 4-6 Phase indicator comparison for PCM solidification for different diameters..............25
Figure 4-7 Comparison of heat storage capacities/unit volume for 2D models .........................36
Abbreviations

PCM  Phase Change Material
CFD  Computational Fluid Dynamics
TES  Thermal Energy Storage
LHS  Latent Heat Storage
LHTES Latent Heat Thermal Energy Storage
HTF  Heat Transfer Fluid
Nomenclature

\( Q \) \hspace{1cm} \text{Amount of energy stored} \hspace{1cm} [J] \\
\( T_i \) \hspace{1cm} \text{Initial temperature} \hspace{1cm} [K] \\
\( T_m \) \hspace{1cm} \text{Melting temperature} \hspace{1cm} [K] \\
\( m \) \hspace{1cm} \text{Mass of heat storage material} \hspace{1cm} [kg] \\
\( C_p \) \hspace{1cm} \text{Specific heat} \hspace{1cm} [J/kg. K] \\
\( X_m \) \hspace{1cm} \text{Fraction of PCM melted} \hspace{1cm} - \\
\( h_m \) \hspace{1cm} \text{Heat of fusion per unit mass} \hspace{1cm} [J/kg] \\
\( T_f \) \hspace{1cm} \text{Final temperature} \hspace{1cm} [K] \\
\( C_{p,\text{solid}} \) \hspace{1cm} \text{Average specific heat between} \hspace{1cm} T_i \hspace{1cm} \text{and} \hspace{1cm} T_m \hspace{1cm} [J/kg. K] \\
\( C_{p,\text{liquid}} \) \hspace{1cm} \text{Specific heat between} \hspace{1cm} T_m \hspace{1cm} \text{and} \hspace{1cm} T_f \hspace{1cm} [J/kg. K] \\
\( \lambda \) \hspace{1cm} \text{Latent heat of melting} \hspace{1cm} [J/kg] \\
\( \rho \) \hspace{1cm} \text{Density of the PCM} \hspace{1cm} [kg/m}^3] \\
\( k_s \) \hspace{1cm} \text{Thermal conductivity of solid PCM} \hspace{1cm} [W/m. K] \\
\( k_l \) \hspace{1cm} \text{Thermal conductivity of liquid PCM} \hspace{1cm} [W/m. K] \\
\( t \) \hspace{1cm} \text{Time} \hspace{1cm} [s] \\
\( X(t) \) \hspace{1cm} \text{Boundary between liquid-solid interfaces} \hspace{1cm} - \\
\( H \) \hspace{1cm} \text{Total volumetric enthalpy} \hspace{1cm} [J/m}^3] \\
\( k_{eq} \) \hspace{1cm} \text{Equivalent thermal conductivity} \hspace{1cm} [W/m. K] \\
\( \alpha \) \hspace{1cm} \text{Thermal diffusivity of the PCM} \hspace{1cm} [m}^2/s] \\
\( \eta \) \hspace{1cm} \text{Fraction of PCM melted} \hspace{1cm} - \\
\( Q_{\text{storage}} \) \hspace{1cm} \text{Heat stored during charging of PCM} \hspace{1cm} [J] \\
\( Q_{\text{release}} \) \hspace{1cm} \text{Heat released during discharging} \hspace{1cm} [J] \\
\( F_{\text{fluid}} \) \hspace{1cm} \text{Flow rate of heat transfer fluid} \hspace{1cm} [m}^3/s] \\
\( h_0 \) \hspace{1cm} \text{Heat transfer coefficient} \hspace{1cm} [W/m}^2. K] \\
\( T_a \) \hspace{1cm} \text{Outside surface temperature of the} \hspace{1cm} \text{container} \hspace{1cm} [K] \\
\( T_0 \) \hspace{1cm} \text{Room temperature} \hspace{1cm} [K] \\
\( m_{\text{fluid}} \) \hspace{1cm} \text{Mass of the heat transfer fluid} \hspace{1cm} [kg] \\
\( \eta_{\text{storage}} \) \hspace{1cm} \text{Heat storage efficiency} \hspace{1cm} - \\
\( \eta_{\text{release}} \) \hspace{1cm} \text{Heat discharging efficiency} \hspace{1cm} -
Acknowledgements

I would like to express my sincere gratitude and appreciation to my master thesis supervisor Dr. Jeevan Jayasuriya for his continuous support and motivation. His kind guidance and encouraging attitude throughout the period of the project helped me to carry out this research work and transform my work into a successful thesis.

I would also like to thank my colleagues specially Mr. Faheem Mushtaq for helping me in learning COMSOL Multiphysics. He supported my approach to the modeling software by improving my knowledge and skills in COMSOL and helped me a lot whenever I needed.

Also at the end, I want to say thanks my family including my parents, brothers and my wife for being a constant source of prayers and courage for me throughout the period of my studies and especially during my thesis research work.
1 Introduction

Managing the use of energy, now a days, is crucial for industrial and domestic societies because of its less availability then its demand. Also the increasing use of energy has been associated with a number of serious problems that represent major global hazards such as global warming, which is the biggest cause of climate disorder. Among these issues, there are some questions regarding fossil fuels which have become quite significant such as: Energy Security, Energy Intensity, and Energy Efficiency. Energy Security has become the most significant one because of ever depleting fossil fuels. Also the intensity of fossil fuels in not the same everywhere on planet earth. There are regions of rich reserves and also some areas which can only import fuels for their use. There is a considerable need for sustainable ways that can pay their share in the production of energy and also are efficient enough to meet the environmental, economic as well as technological requirements. Some solutions to these issues have been proposed such as: to look forward towards Renewables, Synthetic Fuel production, fuel reforming and processing based on thermochemical methods e.g. Ethanol and Hydrogen production from different methods.

1.1 Background

A considerable amount of research is carried out all over the world to find out new energy resources. Beside the search of new resources, the energy available in the current resources can be utilized more efficiently to make maximum possible use of it. One of the methods is Thermal Energy Storage (TES) i.e. storing the Heat energy in the form of sensible or latent heat of suitable materials and then using it at the time of requirement. The term Thermal Energy Storage refers to the phenomenon of storing heat energy in the material as change in internal energy of the material as sensible heat or latent heat. The storing of heat in a material is called “Charging” and the extraction of heat from the material is called “Discharging” (Sharma, 2009)

The materials that store thermal energy as latent heat are called Phase Change Material (PCMs). To use PCM as heat storing medium, certain thermal, physical and chemical properties of the PCM must be carefully studied such as: suitable phase-transition temperature, high latent heat of transition (especially on volume bases), high density, small volume change, low vapor pressure, long-term chemical stability and compatibility with materials of construction. High thermal conductivity is the key that is responsible for charging and discharging of the energy storage. (Sharma, 2009)

The heat storage in the form of latent heat works when the material (PCM) exhibits a change in its phase e.g. from solid to liquid or liquid to gas absorbing certain quantity of heat. The heat is released when the material undergoes the same phenomenon i.e. transition in the phase but in opposite directions means from liquid to solid releasing considerable amount of heat. Latent heat storage takes the advantage over sensible heat storage because it gives high energy storage density as compared to sensible heat storage at constant temperature e.g. a certain mass of ice (water) takes almost 80 times as much energy to melt as it is required to raise the temperature of same mass of water to 1 °C. (Dutil, 2010)

1.2 Objectives

The aim of this thesis work is to investigate numerically the heat exchanger performance which is based on latent heat storage using phase change material. The heat transfer study is a part of a project of storing and transferring heat from industry to district heating system for heating purpose by conveying it through a heat transfer container/ vessel equipped with heat exchanger based on phase change material (PCM). Following are the key objectives of this research:

- Design a numerical model for PCM based heat exchanger (shell and tube heat exchanger with water in tubes and PCM in shell) to analyze the heat transfer by using state of the art computational fluid dynamics (CFD) Tool.
- Study the heat transfer in phase change materials (indirect method) by investigating the charging/ discharging rates i.e. melting and solidification rates of PCM in a shell and tube heat exchanger model developed in commercial CFD Tool.
- Optimize the heat storage capacity of the vessel/ container by making a compromise between Energy and Power rates.
1.3 Methodology

The methodology to approach the problem started with a detailed literature study of heat transfer and latent heat storage (LHS) systems. In this phase; scientific papers, journals, books and related articles have been studied to get thorough knowledge of the heat exchange and the storage system. The types of PCMs and the thermal, physical and chemical properties of the material have also been studied. Then two types of heat exchanger models were generated and studied in COMSOL Multiphysics. 1st type of models were 2D models with three schemes. The simplified model was an 8x8 cm² cross section of a portion of heat exchanger containing 4 pipes of outer diameter 10mm each. Then modifications were done in the model and two new models were generated with same geometry but with 4 and 8 longitudinal fins on each pipe. Simulations for melting and solidification of the PCM storage were carried out for a time of 20000 seconds for each process. Results were reported and discussed. After this work, another model was generated for further study. This model was a 3D model with a single pipe with multiple loops in it. Simulations were carried out for the same course of time as in the previous types of models with different pipe diameters to investigate the effect of pipe diameter on the melting and solidification rates on the PCM storage. Results were reported and discussed after the completion of the study.

1.4 Literature Review

The literature study done for this research work is based on scientific papers, journals, books and related articles available on online libraries and material provided by the supervisor.

1.4.1 Thermal Energy Storage

In the recent years, Thermal Energy Storage has gained quite a bit attention specially the term Latent Heat Energy Storage. Because of its several advantages, scientist are paying attention to make it practically useful in the fields of building materials, domestic solar water heating, solar power plants waste heat recovering systems etc. For the case of LHS, thermal energy can be stored in the PCM as heat of fusion i.e. the heat evolved during solid to liquid transition. Latent heat storage of energy if one of the most efficient ways to store and use thermal energy. LHS uses specific materials which store energy during melting process (charging) and release energy during solidification process (Discharging). These materials are termed as Phase Change Materials (PCMs). Latent Heat Storage is more efficient than sensible heat storage because it provides more storage density and smaller temperature differentials between charging and discharging of PCM. The biggest drawback of using PCMs as heat storing medium is their low thermal conductivity. But this problem is overcome by applying several techniques by the help of which thermal conductivity of the PCM is increased to considerable amount. (Oya, 2012)

Latent Heat Thermal Energy Storage is very attractive and more useful technique of storing heat energy than sensible heat storage because for a given amount of energy it needs less weight and volume of the material as compared to sensible heat storage. Also LHS provides the luxury of storing heat of fusion at almost constant temperature which is the phase transition temperature of the PCM. The latent heat of the PCM is almost 50-100 times higher than sensible heat storage systems. (Nomura, 2013) (Sharma, 2007)

1.4.2 Applications of Thermal Energy Storage

Thermal Energy Storage can be used in both of its forms i.e. Cold storage and Heat storage in domestic as well as industrial communities in order to match supply and demand during peak hours. Following are the possible application areas of PCM in TES.

1.4.2.1 Solar Water Heating Systems

Solar water heaters have gained the attention in scientific societies because of their lower cost of construction and maintenance as well as simplicity in their fabrication. Using PCM as heat storage and providing media, the temperature of the solar water heaters can be maintained at desirable temperatures during night times. (LIU, 2012)

1.4.2.2 Residential Buildings

To use thermal energy Storage for residential applications was one the 1st application area that was taken into consideration by the scientists. In 1975, the use of PCM for PCM based thermal energy storage was reported in the literature by Telkes for heating and cooling of the buildings. Encapsulation of PCM in
walls, ceiling and floor makes the building quite energy efficient as PCM absorbs solar energy during daytime and stores it in the form of thermal energy which is extracted at the time of requirement. (LIU, 2012) (Zalba, 2003)

1.4.2.3 Solar Cookers
Phase change materials are used as heat providing medium in solar cookers to obtain longer cooking periods. In one of the studies on the use of PCM for solar cookers as box type solar cooker using magnesium nitrate hexahydrate (Mg(NO$_3$)$_2$·6H$_2$O) as a PCM for the heat storage to use the cooker during the non-sunshine hours. The overall efficiency of the cooker during discharging was found to be 3-4 times greater than the ordinary cookers. (LIU, 2012)

1.4.2.4 Other Applications
TES systems are integrated with other sources to provide the necessary heat energy during high demand for uninterrupted heat supply such as heat pump and heat distribution system, solar thermal power systems, and small domestic solar water heating systems. The use of cold thermal storage is widely used for different purposes e.g. vegetable cooling, pre-cooling of inlet air for gas turbine applications and temperature maintenance in a room where temperature sensitive equipment are in use. PCMs are also used for energy saving and management in greenhouses. (Zalba, 2003)

1.4.3 Heat Exchangers used for PCM
Generally PCMs have low thermal conductivity. In this case the efficiency of the heat exchangers becomes very important. The use of different configurations of the fins with certain parameters on the tubes in shell and tube type heat exchangers increases the heat transfer rate. (Zalba, 2003)

1.4.3.1 Concentric tube heat exchanger with axial fins
Scientists studied different types of Heat exchangers with different PCMs to investigate the mode as well as efficiency of heat transfer. In one of the experiments a concentric tube heat exchanger with axial fins was analyzed both numerically and experimentally and the solidification process of a PCM was studied. Results showed that the heat transfer through PCM was governed by conduction. (Medrano, 2009)

1.4.3.2 Shell and tube configuration of a heat exchanger
In another experiment, shell and tube configuration of a heat exchanger was used to study the melting (charging) and solidification (discharging) of a paraffin type PCM. In this configuration, heat transfer fluid was inside the tubes whereas the shell was filled with the PCM. (Medrano, 2009)

1.4.3.3 Heat exchanger tubes with radial fins
Another configuration in which heat exchanger tubes with radial fins, carrying heat transfer liquid, was used and the PCM was surrounding the tubes in the shell. Various types of techniques were implemented to depict the results. (Medrano, 2009)

Whatever the configuration is and the type of PCM, the main objective is to study the heat transfer properties of phase change material for charging (melting) and discharging (solidification) of the PCM and then on the bases of experimental and numerical results, implementation of the PCM with desired results for different practical uses. (Medrano, 2009)

1.4.4 Properties of Phase Change Materials
Latent Heat Storage materials have specific thermal, physical and chemical properties because of these properties they have become very attractive and useful and being used for particular applications. (Sharma, 2009)

1.4.4.1 Thermal Properties
In order to select a PCM for specific application, following thermal properties of the PCM must be carefully taken into account

- Suitable Phase Change Temperature in accordance with operating temperatures
- High Heat of Fusion
- High Heat Transfer capability (thermal conductivity should be as high as possible)
1.4.4.2 Physical Properties
Following are some important physical properties that are essential for a good PCM to have

- Suitable phase change equilibrium
- High Density
- Small volume change
- Low vapour pressure

The stability in the phase during the melting and freezing is important and high density per unit volume gives the optimized size of the heat storage container.

1.4.4.3 Chemical Properties
Certain chemical properties of the PCM are important for its selection and use in applications

- Chemical Stability for longer periods
- No affinity towards fire
- Non toxic
- Compatable with material of the container
2 Heat Transfer in Phase Change Materials

The phenomenon of heat transfer in LHS systems occurs when the phase change material changes its state from solid to liquid and vice versa by absorbing sufficient heat (latent heat of melting) at its melting temperature or evolves the same amount of heat when it solidifies. The capacity of heat storage for a latent heat storage system is given by: (Sharma, 2007)

\[ Q = \int_{T_i}^{T_f} mC_p dT + mX_m \Delta h_m + \int_{T_m}^{T_f} mC_p dT \]

\[ Q = m \left[ C_{p,\text{solid}} (T_m - T_i) + X_m \Delta h_m + C_{p,\text{liquid}} (T_f - T_m) \right] \]

Where \( Q \) is the amount of energy stored, \( T_i \) is the initial temperature, \( T_m \) is the melting temperature, \( m \) is the mass of heat storage material, \( C_p \) is the specific heat, \( X_m \) is the fraction of PCM melted, \( \Delta h_m \) is the heat of fusion per unit mass, \( T_f \) is the final temperature, \( C_{p,\text{solid}} \) is the average specific heat between \( T_i \) and \( T_m \), and \( C_{p,\text{liquid}} \) is the specific heat between \( T_m \) and \( T_f \). (Sharma, 2007)

2.1 The Stefan Problem

The study of heat transfer mechanism in latent heat storage systems has been an attractive topic for the researchers. Stefan, an American scientist, in 1889 studied the phenomenon of heat transfer during phase change and formulated and solved his problem. He gave the energy equation for the moving boundary at solid liquid interface which gives the energy conservation across the moving interface as:

\[ \lambda \rho \left( \frac{ds(t)}{dt} \right) = k_s \left( \frac{\delta T_s}{\delta t} \right) - k_l \left( \frac{\delta T_l}{\delta t} \right) \]

Where \( \lambda \) is the latent heat of melting, \( \rho \) is the density of the PCM, \( k \) is the thermal conductivity of the PCM, \( s \) is the energy given, \( T \) is the temperature and \( t \) is the time. (Sharma, 2007)

2.1.1 Techniques to Solve Stefan problem

The non-linear nature of the phase change systems and different thermophysical properties of the two phases at the moving interface makes it difficult to understand and predict the behavior of the system. Two common techniques to solve the Stefan problem are Numerical and Analytical approaches. In numerical techniques, there are two sub techniques quite useful in solving the moving boundary problems which are finite difference method and finite element method. For simple geometries and shapes, a time variant mesh approach offers a satisfactory solution with certain level of accuracy. For practical applications, the fixed mesh approach is used which gives simple and accurate solutions. In fix mesh approach, the latent heat of melting at the melting point is assumed to be added to the PCM’s specific heat. (Sharma, 2007)

When the solid-liquid interface starts to form at the start of the melting process, the melted and solid interface starts to travel away from the heating source. Because of the very poor thermal conductivity of the PCM especially in liquid phase, it is always required to enhance the heat transfer. The most common way to do so is to increase the effective area of heat transfer by applying fins which offer significant increase in the heat transfer but may lead to structural complexities and increase in non-heat storing medium within the heat storage container. The presence of moving boundary layer makes it complex to solve the problem as it requires the mass balance and heat balance at every point. The finite element technique is more useful in solving the phase change problems because it gives the advantage of solving complex thermochemical problems with complex boundary conditions. The Enthalpy Formulation
method is one of the sub methods of finite element method which is used mostly by the scientists to solve the moving boundary layer. This method takes enthalpy as a function of the temperature. (Nedjar, 2001) (Sharma, 2007)

V. Voller elaborated the Stefan problem of heat flow in one dimension. For the case of freezing/solidification, assuming that the heat transfer mode between heat source and PCM is only conduction, Fourier’s law for heat conduction gives separate equations for the two phases i.e. solid and liquid in one dimension. For the time \( t \leq 0 \) the liquid phase exists and the equation for the liquid phase is given as

\[
\frac{\partial}{\partial x} \left( k_l \frac{\partial T_l}{\partial x} \right) = \rho C_p, l \frac{\partial T_l}{\partial t} , \quad \text{for the condition } X(t) \leq x
\]

For solid phase

\[
\frac{\partial}{\partial x} \left( k_s \frac{\partial T_s}{\partial x} \right) = \rho C_p, s \frac{\partial T_s}{\partial t} , \quad \text{for the condition } 0 \leq x < X(t)
\]

Where \( k_s \) and \( k_l \) are the thermal conductivities of the material in solid and liquid phases respectively, \( X(t) \) is the liquid-solid interface at time \( t \) and \( x \) is the space covered in one direction. (Voller, 1980)

### 2.2 The Enthalpy Formulation Method

The enthalpy formulation method is very simple and useful method to solve Stefan problem. Its main advantage is that it has very simple governing equation and it automatically obeys the interface condition. Another advantage is that this method offers a mushy zone at the solid and melted interface. The mushy zone is a pattern of microstructures that is formed when the melted material solidifies. The energy conservation equation for the material undergoing a phase change in terms of its enthalpy and temperature is given as

\[
\frac{\partial H}{\partial t} + \nabla (uH) = \nabla (k(T))
\]

The convective term in the energy equation is dependent on the movement within the medium. To understand the movement in the medium, we need to solve the equations of continuity, motion and energy simultaneously, which makes it complex. In order to make the solution simple, assume constant thermophysical properties and then the equation reduces to

\[
\frac{\partial H}{\partial t} = \nabla (k_{eq}(\nabla T))
\]

Where \( H \) is the total volumetric enthalpy, \( T \) is the temperature and \( k \) is the thermal conductivity of phase of the PCM. This method is called enhanced conduction method which still takes the effects of the convective term. The term \( k_{eq} \) is defined by empirical equations and is a function of dimensionless numbers for different geometries. (Costa, 1996) (Kutateladze, 1966)

The volumetric enthalpy of the PCM is the sum of latent and sensible heats of the material given as: (Sharma, 2009)

\[
H(T) = h(T) + \rho f(T) \lambda
\]

Where \( \rho \) is the density of the PCM, \( f(T) \) is the temperature function that gives the fraction of PCM melted or solidified at a given temperature and \( \lambda \) is the latent heat of melting of the PCM. The term \( h(T) \) is given as:
\[ h = \int_{T_m}^{T} \rho C_p \, dT \]

Where \( T_m \) is the melting temperature and \( C_p \) is the specific heat of the PCM.

If the phase change is assumed to be isothermal, the fraction of the melted PCM at different locations is given as:

\[ f = \begin{cases} 
0, & \text{if } T < T_m \ (\text{solid}) \\
0 - 1, & \text{if } T = T_m \ (\text{mushy}) \\
1, & \text{if } T > T_m \ (\text{liquid}) 
\end{cases} \]

From above equations of enthalpies, we deduce the equations for the enthalpies of every phase as:

For solid state,

\[ H = \int_{T_m}^{T} \rho_s C_{p,s} \, dT', \quad \text{for } T < T_m \]

For phase transition (melting)

\[ H = \rho_l f \lambda \quad \text{for } T = T_m \]

Where \( f \) is the fraction of the PCM melted and \( \rho_l \) is the density of melted PCM.

For liquid state

\[ H = \int_{T_m}^{T} \rho_l C_{p,l} \, dT + \rho_l \lambda \]

Solving the above three equations to get the temperatures of every phase, we get

For solid state

\[ T = \frac{T_m + H}{\rho_s C_{p,s}}, \quad H < 0 \]

For solid-liquid interface

\[ T = T_m, \quad 0 \leq H \leq \rho_l \lambda \]

For liquid state

\[ T = \frac{T_m + (H - \rho_l \lambda)}{\rho_l C_{p,l}}, \quad H > \rho_l \lambda \]

Where \( T_m \) is the melting temperature.

The heat transfer equation for one dimensional problem can be obtained by using the equations for enthalpies as: (Costa, 1996)
\[ \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left( \alpha \frac{\partial h}{\partial x} \right) - \rho_l \lambda \frac{\partial f}{\partial t} \]

Where \( \alpha \) is the thermal diffusivity of the PCM and \( f \) is the fraction of PCM melted.

### 2.3 Heat Storage capacity of the PCM Container

The charging and discharging of the PCM is of vital importance for the optimization of the storage container. The heat storing and releasing capacities of the system can be calculated by using the below equations. (Kaizawa, 2007)

\[
Q_{\text{fluid,in}} = Q_{\text{fluid,out}} + Q_{\text{storage}} + Q_{\text{loss}}
\]

\[
Q_{\text{storage}} = Q_{\text{fluid,in}} - Q_{\text{fluid,out}} - Q_{\text{loss}}
\]

\[
Q_{\text{storage}} = \int_{0}^{t} \left\{ F_{\text{fluid}} \rho_{\text{fluid}} C_{p,\text{fluid}} (T_{\text{fluid,in}} - T_{\text{fluid,out}}) - A h_0 (T_a - T_0) \right\} dt
\]

Also

\[
Q_{\text{release}} = Q_{\text{fluid,out}} - Q_{\text{fluid,in}} + Q_{\text{loss}}
\]

\[
Q_{\text{release}} = \int_{0}^{t} \left\{ F_{\text{fluid}} \rho_{\text{fluid}} C_{p,\text{fluid}} (T_{\text{fluid,out}} - T_{\text{fluid,in}}) - A h_0 (T_a - T_0) \right\} dt
\]

The heat storage and release efficiencies can be calculated as:

\[
\eta_{\text{storage}} = \frac{Q_{\text{storage}}}{Q}
\]

\[
\eta_{\text{release}} = \frac{Q_{\text{release}}}{Q}
\]

Where \( Q_{\text{storage}} \) is the heat stored during charging of PCM, \( Q_{\text{release}} \) is the released heat during discharging \( F_{\text{fluid}} \) is the flow rate of heat transfer fluid is, \( A \) is the storage container surface area, \( h_0 \) heat transfer coefficient, \( T_a \) is the outside surface temperature of the container, \( T_0 \) is the room temperature, \( \eta_{\text{storage}} \) is the storage efficiency and \( \eta_{\text{release}} \) is the heat discharging efficiency.

The maximum heat storage capacity of the heat storage container is calculated by:

\[
Q_{\text{max}} = \int_{T_0}^{T_m} m_{\text{PCM}} C_{p,\text{PCM,solid}} (T_m - T_0) dT + \int_{T_{\text{m.p.}}}^{T_{\text{max}}} m_{\text{PCM}} C_{p,\text{PCM,Liquid}} (T_{\text{max}} - T_m) dT + \int_{T_0}^{T_{\text{max}}} m_{\text{fluid}} C_{p,\text{fluid}} (T_{\text{max}} - T_0) dT
\]

Where \( Q_{\text{max}} \) is the maximum heat capacity, \( m_{\text{PCM}} \) is the mass of PCM in kg, \( T_m \) is the melting temperature of PCM, \( T_{\text{max}} \) is the maximum temperature of the system and \( m_{\text{fluid}} \) is the mass of the heat transfer fluid.
3 Model Geometries

The heat exchanger used for the study in this project is shell and tube heat exchanger with heat transfer fluid (water in this case) is circulating in the tubes and PCM is packed in the shell. The material for the tubes is aluminum with a thermal conductivity value of 205 W/m.K. The advantage of using aluminum as material is that it has good thermal conductivity and lighter in weight and economical in price as compared to other materials with large thermal conductivities such as copper which has high thermal conductivity but heavy in weight and expensive. The models are built in 2D and 3D environment in COMSOL Multiphysics.

The heat transfer fluid used is water which is heated at high temperatures before entering into the heat exchanger for the case of charging of PCM where it transfers its heat to PCM. However in the case of discharging of PCM, the HTF is at moderate temperatures when it enters the heat exchanger to take the heat from the melted PCM.

The phase change material used for the study is 1, 2, 3, 4-Butanetetrol commonly known as Erythritol with chemical formula $C_4H_{10}O_4$. It is a middle temperature range PCM which melts at 117 °C. The physiochemical properties of Erythritol are given in Appendix-1:

3.1 Work in COMSOL

There are two types of models considered in this research to study the heat transfer during the phase change of erythritol. 1st type of models are built in 2D environment in COMSOL. There are three schemes considered in 1st type. In all the schemes, a small portion of the heat exchanger is assumed having an area of 8x8 cm$^2$ with 4 pipes. The simulation environment used for the analysis is Heat Transfer in Fluids in COMSOL Multiphysics which offers, by default, the ease of having two different phases for the material under phase change study. The Heat Transfer Module is based on the balance of energy in the system. The energy balance model originates from conduction, convection, latent heat, Joule heating and heat sources. The heat transfer equations are defined automatically by the dedicated physics interfaces for heat transfer and fluid flow. Physical properties such as thermal conductivity, heat capacity, density, and emissivity can be obtained from the built-in material library for solids and fluids in COMSOL. In addition, the module contains relations for the calculation of heat transfer coefficients for different types of convective heat transfer from a surface. For turbulent heat transfer, it also features relations that calculate the thermal conductivity in turbulent flow using the eddy diffusivity from turbulence models (sometimes referred to as turbulent conductivity). The energy equation used for analysis, by heat transfer in fluids, is given as:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla (k \nabla T) + Q$$

Where $Q$ is the external heat source and in case of our study, there is no external heating so this term is zero.

3.1.1 Model parameters and conditions

As the main objective of the research work is to devise a model of the heat exchanger which gives faster charging and discharging rates for the PCM. The type of heat exchanger considered is shell and tube. The material for the pipes is aluminum and heat transfer fluid is assumed to be water which flows through the pipes. In 1st type of models, 3 different pipe configurations are modeled for the study. First one is 4 pipes without any fins, second one is 4 pipes with 4 fins on each pipe and third one is 4 pipes with 8 fins on each pipe. The 2nd type of model is a 3D model with volume of 90x50x10 cm$^3$. Model parameters and Initial Conditions are given in Appendix-2.

A brief description of the models is given below with all the necessary assumptions that have been made to study the models.

3.1.2 Model-1 (2D)

The simplest model used is a cross section of a small portion of a shell and tube heat exchanger. The model geometry is built in COMSOL. The area of this small portion is 8x8 cm$^2$ having 4 pipes equally
spaced from each other and PCM is filled between the spaces as shown in the figure. The initial values and parameters for the model are given in Appendix-2.

Assumptions:
For the simplicity of the case, it is assumed that the pipes containing the HTF remain at constant temperature of 408.15 K for the case of charging and 333.15 K for the case of discharging. The walls of the system are perfectly insulated i.e. there is no heat loss to the surrounding. The effects of volumetric forces are negligible and the heat transfer mode is mainly conduction.

3.1.3 Model-2 (2D)
In this model the area of the system, number of pipes, positions of the pipes and diameters of the pipes are the same. The only modification that is done is the application of the fins on the pipes to enhance the heat transfer rate and reduce the time for charging/ discharging of the PCM. The fins are applied in longitudinal direction on the surface of the pipes such that the angle between every two fins in 90°.
Assumptions:
It is supposed that the pipe containing the HTF and the fins mounted on each pipe remain at constant
temperature of 408.15 K for the case of charging and pipes are at 333.15 °C for the case of discharging
whereas fins are at the same temperature as the PCM. The walls of the system are perfectly insulated i.e.
there is no heat loss to the surrounding. The effects of volumetric forces are negligible and the heat
transfer mode is mainly conduction.

3.1.4 Model-3 (2D)
In this model, all the parameters are the same as in 4-fin model. But the number of fins are increased from
4 to 8 in this model in order to study the increase in heat transfer with increase in number of fins. The
angle between every two fins is 45°. The model geometry with is given below:

![Figure 3-3 Eight fin model of the Heat Exchanger](image)

Assumptions:
All the assumptions are the same as taken for model-2 with 4 fins configuration.

3.1.5 3D model
The 3D model is 2nd type of heat exchanger model studied in this work. The model geometry was
generated in COMSOL. This model is a box type storage system having PCM stuffed inside and a single
pipe inside with multiple loops to circulate the HTF. Three configurations have been simulated having
11%, 12.4% and 15% volume of the pipes in the whole volume. The system having 11% volume has pipe
diameter of 4 cm, 124% volume system has pipe diameter of 4.24 cm and the system having volume of
15% has pipe diameter of 4.664 cm. The arc length of the bends in the pipe is calculated by the formula
given below. The parameters and initial conditions for the model are given in Appendix-2.

\[
Arc\ Length\ of\ the\ bend = 0.5\sqrt{16h^2 + w^2 + \left(\frac{w^2}{8h}\right)\left[\ln(4h + \sqrt{16h^2 + w^2}) - \ln(w)\right]}\]

Where \(w\) is the width of the bend or dome and \(h\) is the height of the dome.
Figure 3-4 3D model geometry for heat exchanger
4 Results and Conclusions

The research study has been carried out on different type of heat exchanger models including 2D and 3D. The results show the effects of modifications in the models on PCM melting and solidification processes. The investigation is done by 1st carrying out simulations on a simple model then making a comparison of the results for the simple model with modified models in 2D schemes. Whereas for 3D model, a comparison of three different pipe diameters has been made. The results for all the models are described below separately.

4.1 Model-1 (2D)

As the mentioned in the previous chapter, Model-1 is the simplest 2D model of 1st type which shows the cross sectional surface of a selected portion of a shell and tube heat exchanger. The results for both charging and discharging processes of PCM for model-1 are given below:

4.1.1 Melting/ Charging of PCM

The phase indicator diagram shown in the figure 4-1 explains the formation of the liquid phase with time.

![Figure 4-1 Phase Indicator diagram for PCM Melting](image)

We see from the figure that the formation of the liquid layer is nearly linear with time but the slope goes down slightly as the liquid phase dominates the solid phase in the system. This is because of the low thermal conductivity of the liquid PCM which is almost half of the solid PCM thermal conductivity value. At the end of 20,000 seconds 95% of the PCM melted.

4.1.2 Solidification/ discharging of PCM

The discharging or solidification of the PCM is the reverse phenomenon. The PCM becomes the heat source which transfers its already stored heat to the HTF in the pipes. Figure 4-2 indicates the formation of solid phase with time.
Due to very high thermal conductivity of the aluminum, the pipes which act as a sink for the heat in this case, receive the heat in shorter time as compared to PCM and the rate of heat transfer from PCM storage to the pipes is higher. The whole system of PCM solidifies at 7500 seconds and for the rest of the time, the heat is conducted from solid PCM to HTF which is assumed to be circulating in the pipes.

4.2 Modified models (2D)

Here some modifications were done in the model-1 as described in the previous chapter to increase the charging/discharging rates of the PCM. The effect of the use of the fins on charging and discharging rates of the PCM system are given below with comparison to the model-1 results. The CFD images for the melting process comparison for the three models corresponding to phase indicator diagrams are given in appendix-3 which show the melted layer movement with time and the heat flux.

4.2.1 Melting/charging of the PCM
Figure 4-3 (b) Phase indicator comparison for PCM melting
Figure 4-3 (a) and (b) show the comparison of the melting/charging rates of the PCM for all three schemes. With the help of graphs and CFD images, we can see that the melting rate is maximum for the model-3 with 8 fin configuration. Model-2 with 4 fins also has a better heat transfer rate as compared to model-1. The significant effect of fins application is quite evident. The system with 8 fins reaches to almost 98% phase formation near 11000 seconds whereas at the same time the system without fins just reaches to 68% melting of the PCM and the system with 4 fins reaches almost 92% conversion. Because of the use of the fins, the heat distribution and the heat flux increases in the system which results in rapid melting than the other models as can be seen from figure 4-3 (a).

4.2.2 Solidification/ discharging of PCM
A comparison of the PCM solidification for all the three models is given in figure 4-4.

Figure 4-4 Phase indicator comparison for PCM solidification
The graph for 8 fins model represented by blue line in figure 4-4 shows that the solid phase reaches to 100% concentration level at a time about 3200 seconds whereas at the same time we have 60% solid phase formation for the model without fins and almost 90% solid PCM for the case of 4 fin model. The model
without fins takes almost double time than 8 fin model to reach 100% solid formation (almost 7500 seconds).

4.3 3D model

The 3D model was made to study the effect of pipe diameter on the charging and discharging of PCM by giving a suitable flow rate to the HTF. The model parameters and initial conditions for the model are given in appendix-2. The total volume occupied by the pipe for diameter 4 cm is 11% of the whole volume, for diameter 4.24 cm is 12.4% and for 4.664 cm is 15%. Simulations were carried out for both melting and solidification of the PCM for a time of 20000 seconds for each case. The results of the work are given below:

4.3.1 Melting/charging

Figure 4-5 shows the phase transition from solid to liquid phase for all the three models with time. The model with diameter of 4.664 cm gives the highest rates of melting as compared to other two models. At the end of the process we have 85% of the system melted with diameter 4.664 cm and for other two models we see that the conversion reaches to 80%.

![Figure 4-5 Phase indicator comparison for PCM melting for different diameters](image)

Figure 4-5 Phase indicator comparison for PCM melting for different diameters
4.3.2 Solidification/ discharging

Figure 4-6 Phase indicator comparison for PCM solidification for different diameters

Figure 4-6 gives a comparison of the PCM solidification for the three cases. All the three models show the same rates for the solid phase formation in the start. The graphs of the models with pipe diameter 4.664 cm and 4.24 cm show almost the same rates till the end of the process without any considerable difference while the 3rd model with pipe diameter 4 cm varies from the trend of other models. At time 15000 seconds, we see that the solid phase formation for all the three models is nearly same i.e. 98%.

4.4 Discussion on results and Conclusions

In this thesis work, the study of charging and discharging of PCM based energy storage system has been done by using two types of models (2D & 3D) built in COMSOL Multiphysics. The PCM used in the study is a middle temperature range material with a fair range of thermal conductivities between solid and liquid phases. The optimization of the rates of charging and discharging of PCM system is done by simulating different configurations of the heat exchanger models.

The simplest model (model-1) gives quite ordinary results for melting and solidification of the PCM. The time taken by PCM to charge and discharge completely is very high. This is mainly because of very low thermal conductivities of the solid and liquid phases of the PCM. To overcome this disadvantage of low thermal conductivity, models were modified by the application of longitudinal fins. Fins offer an increase in surface area for heat transfer and the heat transfer rates are increased. Because of the use of the fins, the heat distribution and the heat flux increases in the system which result in rapid melting than the other models and more heat storage capacity as compared to other models. This modification shows significant increase in charging/ discharging rates. Figures 4-3 and 4-4 show the comparison of the three models for PCM charging and discharging. For the case of 8 fins model, the system melts and solidifies in almost half of the time taken by the model without fins. This is quite useful because it shortens the time to charge and discharge the PCM storage.

But we have increased the power rates on the expense of energy. Figure 4-7 shows a comparison of three models on the basis of heat storage capacity per unit volume. The increase in volume of non-heat storing medium i.e. volume of pipes and fins decreases the volume of PCM in the storage system.
Figure 4-7 is calculated for complete melting of the PCM. The time taken by the PCM to get melt for every case is mentioned in bar graph. The model with 8 fins shows the fastest melting rate i.e. it melts completely in 14000 seconds but if we see the graphs in figure 4-7. The model with 8 fins shows the least heat storage capacity per unit volume among the three models and the model without any fins shows the highest heat storage capacity per unit volume but it has the lowest melting rate. That means if we have to achieve higher melting rates, we have to compromise on heat storage capacity. If the time for charging the energy storage system is the main concern with sufficient amount of energy stored, then the model with 8 fins is recommended to be used but on the expense of energy. But if number of fins are increased in order to achieve faster results than the model with 8 fins, the volume of PCM will be reduced more that will result in less storage capacity which may go below the requirements.

A concluding discussion for 1st type of study (2D model study) is made by taking into account the disadvantages that could be related to this type of models. As the fins are made of aluminum in this case which is a ductile material with less stiffness value, in real case of operation, the fins may face the stresses due to volumetric expansion and contraction of the PCM during melting and solidification processes which may bend the angle of the fins or even damage the geometry. If all these considerations are taken as invalid, the model with 8 fins is recommended for achieving faster rates of melting and solidification in this type of heat exchanger.

There are certain things which were assumed during the analysis of 2D models study. The temperature of the pipes and the PCM was assumed to be constant for simplicity in the start of the processes. It was assumed that the HTF is circulating in the pipes at 408.15 K giving a perfect heat transfer to aluminum pipes and the pipes are also at 408.15 K. For the solidification process, it was assumed that the melted PCM got all the heat from HTF and is at 408.15 K. To get more realistic results, a further study with the simulations in a 3D environment was carried out. Suitable flow rate to the HTF was given and the effects of wall heat transfer between the HTF and the pipes were considered. Here a parametric study of the pipe diameter was done to see the effects of pipe diameter on heat transfer. Three types of models with different percentage of pipe volume to total volume were generated. The results show that the model with 15% of pipe volume (4.664 cm dia) gives the higher conversion rates than the other two models for melting and solidification processes.

After the study of heat transfer in PCM storage system for two different types of models, we draw some conclusions from the work. As in this type of heat transfer the limiting factors are the heat transfer area and the type of PCM material. By using erythritol as PCM material with low thermal conductivity values, the heat transfer area is the only parameter to be changed to increase heat transfer for the system. Therefore a heat storage system with shell and tube configuration having PCM in shell and HTF in pipes.
with diameter of 4.664 cm with eight longitudinal fins mounted on the pipes is recommended for achieving faster melting and solidification rates.

4.5 Future work Recommendations

As this research study is done with limited scope, there are some recommendations which may be adopted for future study in this field. A small heat storage system in the shape of a box can be modeled and analyzed in COMSOL Multiphysics with all the necessary dimension of a prototype of a storage container with all the piping. As 8 fins configuration is proposed, eight fins should be modeled. A suitable flow rate must be given for the optimum velocity to the HTF. Then a physical model of the storage with same dimensions and design parameters should be fabricated and experiments must be carried out for solidification and melting of erythritol. The results of the experimental study should be compared with the results of COMSOL modeling study.
Bibliography


Oya Teppei Thermal conductivity enhancement of erythritol as PCM by using graphite and nickel particles [Journal]. - 2012.


Waschull J. Investigation of Phase Change Materials for Elevated Temperatures [Journal].

Appendix-1: Physiochemical Properties of Erythritol

<table>
<thead>
<tr>
<th>State of Material</th>
<th>Melting Temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Thermal Conductivity (W/m.K)</th>
<th>Dynamic Viscosity (Pa.s)</th>
<th>Latent Heat of Fusion (kJ/kg)</th>
<th>Specific Heat capacity (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>117-119</td>
<td>1480</td>
<td>0.733</td>
<td>0.029</td>
<td>339</td>
<td>1350</td>
</tr>
<tr>
<td>Liquid</td>
<td>-</td>
<td>1300</td>
<td>0.326</td>
<td>0.016</td>
<td>-</td>
<td>2740</td>
</tr>
</tbody>
</table>

Physiochemical properties of Erythritol (Nomura, 2013)
Appendix-2: Model Parameters and Initial Conditions

2D model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Without fins</th>
<th>With 4 fins</th>
<th>With 8 fins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total area of the system</td>
<td>8x8 cm²</td>
<td>8x8 cm²</td>
<td>8x8 cm²</td>
</tr>
<tr>
<td>Number of pipes</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Inner diameter of the pipe</td>
<td>8 mm</td>
<td>8 mm</td>
<td>8 mm</td>
</tr>
<tr>
<td>Outer diameter of the pipe</td>
<td>10 mm</td>
<td>10 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>Number of fins on each pipe</td>
<td>-</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Height of each fin</td>
<td>-</td>
<td>5 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Thickness of each fin</td>
<td>-</td>
<td>1 mm</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Initial Conditions

For charging/melting of PCM

<table>
<thead>
<tr>
<th>Models</th>
<th>Without fins</th>
<th>With 4 fins</th>
<th>With 8 fins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Temperature of the PCM (solid)</td>
<td>333.15 K</td>
<td>333.15 K</td>
<td>333.15 K</td>
</tr>
<tr>
<td>Initial Temperature of the pipes containing HTF</td>
<td>408.15 K</td>
<td>408.15 K</td>
<td>408.15 K</td>
</tr>
<tr>
<td>Initial Pressure of the system</td>
<td>Atmospheric</td>
<td>Atmospheric</td>
<td>Atmospheric</td>
</tr>
<tr>
<td>Initial Temperature of the fins</td>
<td>-</td>
<td>408.15 K</td>
<td>408.15 K</td>
</tr>
</tbody>
</table>
For discharging/solidification of PCM

<table>
<thead>
<tr>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Temperature of the PCM (liquid)</td>
<td>408.15 K</td>
<td>408.15 K</td>
<td>408.15 K</td>
</tr>
<tr>
<td>Initial Temperature of the pipes containing HTF</td>
<td>333.15 K</td>
<td>333.15 K</td>
<td>333.15 K</td>
</tr>
<tr>
<td>Initial Pressure of the system</td>
<td>Atmospheric</td>
<td>Atmospheric</td>
<td>Atmospheric</td>
</tr>
<tr>
<td>Initial Temperature of the fins</td>
<td>-</td>
<td>333.15 K</td>
<td>333.15 K</td>
</tr>
</tbody>
</table>

**3D model**

Model parameters:
- Height of the box: 50 cm
- Length of the box: 90 cm
- Width of the box: 10 cm
- Length of the pipe: 39.5 cm
- Diameter of the pipe (i): 4 cm
- Diameter of the pipe (ii): 4.24 cm
- Diameter of the pipe (iii): 4.664 cm

**Initial Conditions:**

**For melting**
- Initial temperature of HTF: 408.15 K
- Initial temperature of PCM: 333.15 K
- Volumetric flow rate of HTF: 0.0005 m³/s
- Final Pressure of HTF: Atmospheric

**For solidification**
- Initial temperature of HTF: 333.15 K
- Initial temperature of PCM: 408.15 K
- Volumetric flow rate of HTF: 0.0005 m³/s
- Final Pressure of HTF: Atmospheric
Appendix-3: Comparison of melting rates for 2D models

Following figures show the comparison of the melting phase formation with time for the 2D models. The black arrows show the direction of total heat flux. The images are taken after 1 hour, 2 hours, 3 hours and 4 hours of melting process.

Melting of PCM after 1 hour (3600 seconds)
Melting of PCM after 2 hours (7200 seconds)
Melting of PCM after 3 hours (10800 seconds)
Melting of PCM after 4 hours (14400 seconds)
Appendix-4: Temperature distribution for melting of PCM in 2D models

Melting of PCM after 1 hour (3600 seconds)
Melting of PCM after 2 hours (7200 seconds)
Melting of PCM after 3 hours (10800 seconds)
Melting of PCM after 4 hours (14400 seconds)