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PCM Based Waste Heat Recovery System to Damp Thermal Power Fluctuations

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Abstract- Energy that is wasted and lost to the environment is called waste heat. Different heat recovery technologies can be used to recover it. Hot combustion gases from many sources, such as internal combustion engine exhaust, thermal power plants, cement factories, etc., are the primary source of waste heat. A waste heat recovery system is one that uses a heat exchanger to recover energy from high-temperature process outputs and move it to a different area for a useful purpose. This usually results in an increase in the system's thermal efficiency. This lowers the pollution in the environment while simultaneously increasing system efficiency. A thermal energy storage system (TES) is one way to recover energy. TES primarily falls into two categories: sensible heat storage and latent heat storage. The waste heat thermal power fluctuations are the biggest obstacle to energy storage. Energy recovery power systems' functionality and viability from an economic standpoint are severely impacted by these oscillations. Phase change material (PCM) serves as both a heat transfer medium and a fluctuation damping device in this work. The shell and tube heat exchangers were designed using a variety of tube sizes and orientation. The optimal arrangement was simulated to improve melting time and energy storage. To determine the ideal melting time, this study used three aluminum tubes, each with a diameter of 25 mm, at an angle of 60° (internal angle) from one another, and an acrylic shell having internal diameter of 134 mm with wall thickness is of 10 mm. The impact of a thermal energy storage system operating with a variable temperature source was investigated. Both the impact of altering phase angle and amplitude on the PCM melting rate were analyzed. Computational fluid dynamics (CFD) has been used to perform the simulations by varying the amplitude and phase of the user defined function (UDF). It is discovered that the low phase will require a significant amount of time—roughly 56 hours—but that the time required for PCM melting can be slashed to just 108 minutes once the amplitude is raised to 12t (t in seconds). This is good even with temperature variations and having no fins.

Keywords- PCM, Energy Storage, Latent Heat, Waste Heat Fluctuations, Damping

I. INTRODUCTION

Global warming, ozone depletion, and environmental pollution have all grown recently. The depletion of natural resources and fossil fuels has resulted in an increase in the cost of energy. The utilization of renewable energy sources and the recovery or storage of waste heat create a demand that benefits the environment in addition to facilitating more efficient use of energy sources. Utilizing waste heat energy has been the subject of numerous study reports. To guarantee stability and uninterrupted operation, the thermal energy storage unit becomes an essential component of the waste heat energy system. According to statistics, the energy consumption of 69 nations—including Brazil, Thailand, China, India, South Africa and Pakistan has dramatically increased. The need for heating, ventilation, and air conditioning (HVAC) has grown along with the desire for a better working environment, which includes optimal humidity, temperature, and air quality. This has resulted in a rise in energy usage. One effective way to improve a system's thermal efficiency is through heat recovery and storage. This lowers carbon dioxide emissions and energy consumption, which in turn lessens pollution to the environment and global warming. One of the primary sources of waste heat is industrial waste heat, which is the heat generated during an industrial operation that is discarded or thrown into the environment without being used. Heat loss from most of the industrial machinery and processes. Heat transfer during transportation, radiation and heat from combustion are some of the causes of waste heat. There are three different temperature categories for heat loss: high, moderate, and low. To maximize the efficiency of the waste heat recovery system, the Waste Heat Recovery

(WHR) system has been implemented for all waste heat ranges. Waste heat radiation (WHR) occurs in three temperature ranges: high (above 400°C), medium (between 100 and 400°C), and low (below 100°C). Most of the waste heat is typically produced by direct combustion, which occurs at high temperatures; combustion in combustion units occurs at medium temperatures; and combustion in processes, equipment, and parts occurs at low temperatures. Most researchers focus on PCM's behavior and chemical characteristics, or how they behave under constant melting and solidification. To imitate the real-world problem on computers, some academics are working on functions that are closer to the variations. Some are trying to reduce the size of this system without sacrificing its storage capacity so that it can be used in various applications and by industries at a reasonable cost. The concept of storing energy in a PCM-based system to be used when needed will soon become a reality because energy supplies are running out and waste heat is causing environmental pollution in the form of global warming.

A shell and tube heat exchanger with a length of one meter, diameter of 25 mm, and one tube diameter of 12.5 mm was utilized by Ruicheng Jiang et al. [1]. Hot fluid was flowing through the tube while the PCM was kept in the shell. They investigated the effects of phase and amplitude changes using a heat source that fluctuated. They discovered that while amplitude has no significant impact on the PCM's melting rate, phase increases reduce both the melting time and storage capacity. A shell and tube heat exchanger with a copper tube that is positioned in the center of the 121mm diameter shell and has a diameter of 32.1mm and a thickness of 3mm was utilized by Lehar Asip Khan et al. [2]. Fins with an effective length of 36 mm apiece were built on tubes spaced 120° apart. This paper demonstrates that conduction is small at the beginning of melting but becomes considerable as melting proceeds. They concluded that the PCM's melting time will be shortened by long fin. In the steel billet exhaust, Fabio Dal Margo et al. [3] replaced the antiquated heat storage system with a contemporary PCM-based thermal energy storage system, claiming a 38–52% increase in thermal storage and a 15.5–17% increase in efficiency over the previous system. An energy storage system for solar energy was invented by Mario Escobar Ochoa et al. [4]. Because solar energy strength varies during the day and is influenced by the weather. He created a PCM-based energy storage system to harness the material's latent heat. Since much of the energy stored in solar heat storage systems comes from external sources like the sun and radiation, he investigated the impact of wind direction and speed on external heat transfer. For I.C. engines, Dhananjay Thombare et.al. [5] suggested a thermal energy store mechanism. I.C. engines only produce 30 to 40% of their heat efficiently, and the remaining heat is lost, polluting the environment. They demonstrated how a significant quantity of waste energy may be saved and put to good use, such as heating the intake of air or water, or producing electricity. Prior to Mareul Jimenez Areida et al. work [6], the majority of thermal energy storage research was focused on maintaining a steady temperature. For the first time, they investigated how the system's efficiency was affected by temperature fluctuations. Additionally, they contrasted the latent heat storage system and steam control, two contemporary energy storage technologies. They concluded that while a latent heat storage system can smooth out waste heat oscillations, steam control can only lessen the intensity of the fluctuations. The temperature behavior of a hollow block in the Sahelian zone, with or without phase change material (PCM), was studied by Zoma et al. [7]. The PCMs utilized in this investigation were hydrated salt and RT27 paraffin, which had respective melting points of 27°C and 29.9°C and latent heats of fusion of 179 kJ/kg and 184 kJ/kg. The internal wall temperatures with and without PCM have been examined. It is discovered that the hollow block's inner wall has a lower temperature than a hollow block without PCM. This is a result of the PCM absorbing heat to melt. Sreenath V.R. et.al. study the effect of ambient conditions and choice of (PCM) on the thermal performance of a metal foam (MF)-PCM composite heat sink. They used paraffin wax as a PCM. The study shows that at higher ambient conditions the PCM melting rate is higher i.e. 30-35°C. [8]. R. Deepak Selvakumar et.al. do the numerical analysis for melting of an organic phase change material (PCM) in a square thermal energy storage (TES) capsule with an array of high voltage wire electrodes has been performed. The aim of the study is to investigate the effect of direction of electric field on the melting process under different configurations of grounded walls. Different cases were analyzed and studied the effect of electric field on PCM melting process [9].

II. Problem Statement

The transfer of energy from a hot reservoir to a cold reservoir is responsible for most of the processes that go on around us. Regretfully, there is some waste heat generated during the process of heat transfer. This waste heat should be minimized and recovered as it has the capability to be used for useful purposes. Storing thermal energy in a storage system is one way to increase the thermal efficiency of thermal systems. The problem is that waste heat fluctuates in temperature can harm the device and hence, most of the waste heat is wasted. The variation of heat during a process like from cement kiln, waste from automobiles, from different waste heat chimneys is not constant and has thermal fluctuations. But this waste heat has the potential to be used for some other useful purposes if its fluctuations are removed or minimized. To achieve a constant temperature, a thermal energy storage damping system based on some suitable PCM has been designed, simulated and experimental setup is made to verify the results. This system saves fluctuating waste heat and can be used as and when needed. Depending on the material used, waste heat is stored as latent heat in PCM. Since the energy is kept at a consistent temperature, it can be used as needed.

III. Proposed Solution Specifications

A shell and tube heat exchanger are the thermal energy storage devices used in this investigation. The 134 mm in diameter and 10 mm in thickness acrylic material that makes up the shell. Within the shell, three aluminum tubes, each with a diameter of 25 mm, are positioned 60 degrees apart. Since stearic acid melts at 69.4 °C, the PCM present in the shell is stearic acid in this instance. This falls comfortably within the 80–90 °C hot fluid temperature range that was used for this project. The PCM is melting because of hot fluid passing through the tubes. This PCM is melted, and energy stored in the PCM. The recovery of this stored energy is demonstrated by passing cold fluid through the same tubes that collect PCM's latent heat. In the process, PCM solidifies, and water is heated. The latent heat and temperature are now constant despite the heating source's fluctuations in waste heat.

Most tasks in the modern world are completed by machines, which emit heat as a byproduct of their operation. Every piece of equipment, from internal combustion engines to washing machines and lawnmowers, produces waste heat that is released into the atmosphere and contributes to global warming. With the help of this study, a way to maximize the use of that waste heat is suggested, which can be applied as needed. In addition to making the world more pleasant and environmentally friendly, this will assist business in conserving fuel, which will raise thermal efficiency and ultimately boost the economy. As a result, the energy resources that were previously available were used more effectively, particularly the longer-lasting fossil fuels. At the steel billet exhaust, Italian engineers installed a state-of-the-art PCM-based thermal energy storage system in lieu of the traditional one. They reported a 38–52% increase in thermal storage and a 15.5–17% increase in thermal efficiency over the old systems.

The applicability of this research spans a wide range of sectors, from small to large sectors producing waste heat. Waste heat exists in every industry and can be stored properly to be put to good use. Waste heat recovery has applications for the waste heat emitted from the many sources listed below.

- As shown in this study, it can be utilized to recover exhaust heat from I.C. engines by storing it in a PCM-based storage device. Organic Rankine Cycle thermal energy recovery (ORC).
- In thermal power plants that run on furnace oil, natural gas, coal, LNG, or any other fuel to recover waste heat.
- To recover steel billet furnace waste heat, which can be utilized for reheating. It can be used to store waste heat from clinkers in the cement industry.

A heat exchanger to be used for the intended function must be chosen as part of the design procedure for this study. To reduce the PCM melting time, a shell and tube heat exchanger with various tube configurations was simulated. Following preliminary simulations, a shell and tube heat exchange with three tubes that are 25 mm in diameter and arranged at an angle of 60°(internally) from one another was conducted. To investigate the impact of these variations on the melting rate and PCM storage capacity, the design was first simulated at a constant input temperature and then with the input temperature fluctuating in a sinusoidal manner with varying amplitude and phase. This is used to study the effect on PCM melting rate and its storage capacity.

IV. Project design and Implementations

First, a shell and tube heat exchanger were selected with a single tube inside the shell. But for the storage capacity the melting time was very high, which is not feasible. Next effort is made to design a shell and tube heat exchanger with multiple tubes and their orientation within the shell. The three tubes are placed parallel of each other in one direction and these tubes are equidistance with each other. This arrangement again did not serve the purpose i.e. time taken to melt the PCM is large. After this the three tubes are placed in an equilateral triangle orientation. This orientation was also suggested by previous researchers. The simulation is done with equilateral triangle orientation first with 12.5mm tubes and then with 25mm tubes simulated. The melting time and storage capacity were optimal with three tubes placed in an equilateral triangle and tubes diameter is of 25mm. This design was finalized for further analysis.

A. Mathematical Modeling & Governing Equations

After getting the simulation results and getting the optimal geometry the next step was the implementation of these results. The simulations were carried out on a 2-D shell and tube heat exchanger with shell is made of acrylic material and the tubes were made of aluminum and shaped according to the selected design. The shell has an outer diameter of 134mm and inner diameter of 114mm.

- Each tube had a diameter of 25mm that are placed 120° from each other.
- Thermocouples are placed in the shell by making holes. These holes are insulated with rubber bushes to prevent heat loss.

To perform a simulation of the problem statement ANSYS® 2019 was used.

In ANSYS® its CFX module for computational fluid dynamics (CFD) was used to study the melting of PCM. A 2-D model simulation was selected due to a lack of computational resources. CFD model is based on the basic fluid mechanics equations that is continuity, momentum, and energy equations for problem solving in a discretized manner. The continuity equation is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{1}$$

The 2-D momentum equation is given below:

Momentum in x-direction:

$$\rho \frac{\mathrm{D}u}{\mathrm{D}t} = \rho g_x - \frac{\partial \rho}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

Momentum in y-direction:

$$\rho \frac{\mathrm{D}v}{\mathrm{D}t} = \rho g_y - \frac{\partial \rho}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

Here ρ is the density of the fluid, μ is the kinematic viscosity and p is pressure of the working fluid. The momentum source term Fi deals with the effect of momentum variation of liquid PCM due to buoyancy. Momentum source term can be considered as the damping term according to Darcy's law.

$$Fi = A_{mushy} \frac{(1-\alpha^2)}{\alpha^3 + \varepsilon} \mu_i \tag{4}$$

The velocity of the mushy zone is determined by the value of A_{mushy}. Larger the value of A_{mushy} larger will be the fluctuations in the solution. In this study suitable value was given and a small term was added in denominator, so it never goes to infinity.

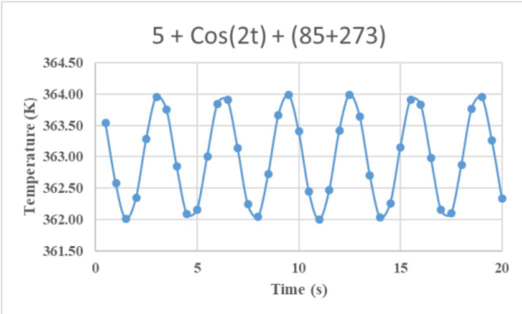
B. Assumptions

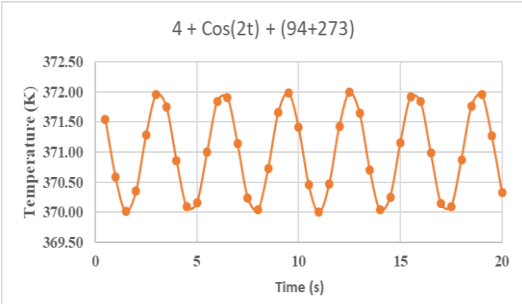
During this study the radiation effect is neglected as compared to the natural convection. The outer surface of the shell is considered adiabatic, and the inner walls of tubes are isothermal. The density of PCM is considered as Boussinesq density i.e. mean constant density is used to solve the governing equations. Change of volume during the phase change is neglected so 2_D constant enthalpy and porosity methodology is used. The solid liquid (mushy zone) is treated as the porous medium and porosity is equal to the melting fraction of PCM.

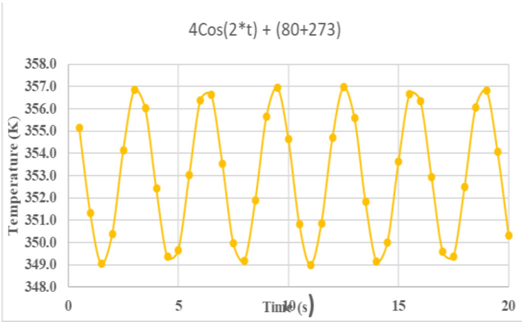
C. Simulation Details

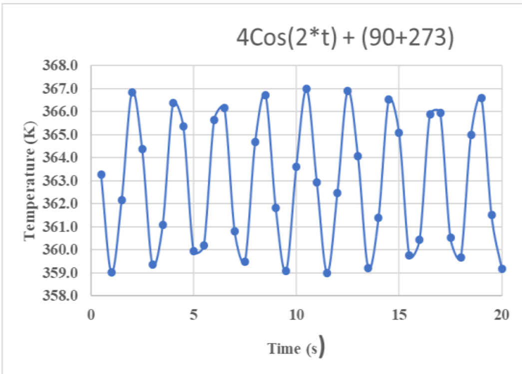
Flow type transient was selected. Melting and solidification module was used for simulation purposes. Energy equation was turned on. The viscous laminar model was used to solve the problem as here viscosity has a significant role. The tubes temperature at its inlet is a user defined function. As temperature is fluctuating, for simulation purpose fluctuating temperatures were given through user defined function (udf). The time step used is 0.0125s and number of iterations were hundred thousand (100000). The real time graphs of user define functions are given below. The simulation was stopped when the residuals had the difference of $1\text{x}10^{-6}$.

One of the temperature fluctuation functions is defined in (4). The first term shows the mean axis, the second term is for the fluctuation and the third term is the average temperature. Following are the cases, and their graph studied numerically.









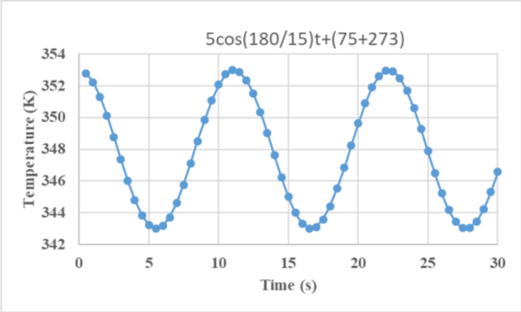


Figure 1. Real time graph for different udf used

Figure 1 Shows temperature fluctuations following the cosine curve with some shift in each defined udf. The constant temperature is 358 K. The maximum amplitude variation in these udf is max 372K and lowest is 343 K.

V. Experimental Setup and Working

The experimental setup contains three reservoirs i.e., two hot and one cold reservoir. Two hot reservoirs are used to introduce fluctuations in the prototype. To start, the control valves coming from the hot reservoirs are opened and closed using the code. Water in the hot reservoir is heated using an electric heater, installed in the reservoir. As the desired temperature is reached i.e. (80°C and 90°C) for each reservoir the heater is turned off. Thirty thermocouples are fixed around the radial length of the shell to collect temperature of PCM at each point. The hot reservoir keeps flowing water until all the PCM is melted and latent heat is stored in the PCM. Then the cold reservoir valve opened and flowed through the tubes. In this process, cold water absorbs heat from the PCM. The thermocouples will give temperatures both for melting and solidification of PCM. The temperature of the cold water will be constant and hence the objective is achieved i.e. the fluctuation in temperature (due to fluctuation in waste heat) has been removed. The thermocouples are also attached at the inlet and outlet of water, to ensure there is minimal or negligible heat transfer along the length of the shell as in this study 2D design and analysis is done, so the length is ignored in the simulations. The schematic diagram is given in Figure-2.

For solving the CFD problem it is observed that the pressure term involved in momentum, continuity and energy equation but there is no relationship between pressure and velocity. Before this algorithm, researchers used to guess the pressure value and determine the velocity that may or may not satisfy the continuity equation. All the algorithms Semi-Implicit Method for Pressure Linked Equations (SIMPLE), Pressure Implicit with Splitting operators (PISO), and Pressure Implicit Method for Pressure linked Equation (PIMPLE) and work on developing the pressure equation and finding a corrected value of pressure. This pressure is used to find the velocity that satisfies the continuity equation. All these algorithms are based on iterative solution process, but PISO and PIMPLE are both used for transient cases whereas SIMPLE is used for steady-state cases. The only things that differentiate these techniques are the corrector equation and several correctors used in an algorithm.

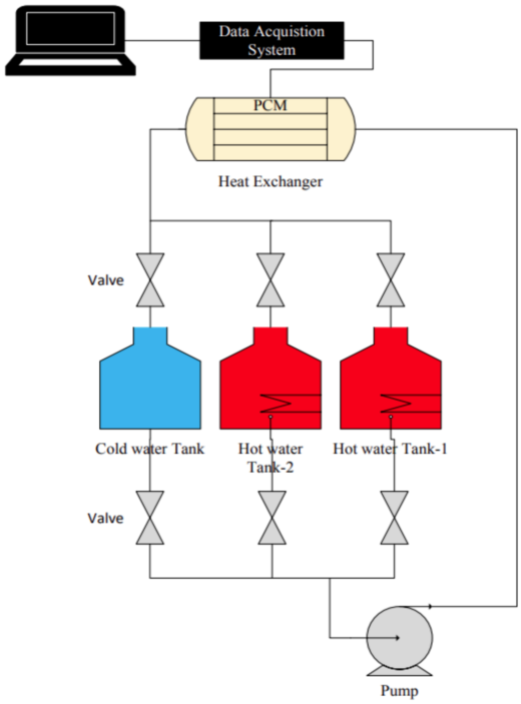


Figure 2. Schematic Diagram of Prototype

As in this case the transient one hence we use the PISO algorithm. To start with the problem PISO solves the momentum equation and then the corrected pressure equation. After this, the calculated pressure is used to find the velocity that will satisfy the continuity equation. Once corrected values of velocity and pressure are obtained then all the equations are solved at each node until the difference between each value is equal to the set convergence criteria. The PISO algorithm is fast, easy to use and accurate as compared to the SIMPLE algorithm for transient flow and use double check correction criteria for better results.

The flow chart shown in Figure-3 depicts the PISO algorithm i.e. how it works.

Hardware Details

Hardware includes three water reservoirs i.e., two hot reservoirs and one cold reservoir. A shell and tube heat exchanger is used as the thermal energy storage system. The shell and tube heat exchanger consists of a shell of diameter 134mm and thickness of 10mm encapsulating three aluminum tubes of diameter 25mm that are placed at 1200 from each other. Tubes contain water and shell is filled with PCM i.e. stearic acid in this case. The schematic view of a shell and tube heat exchanger is shown in

Figure 4. Three tubes are placed parallel and at equidistance from each other.

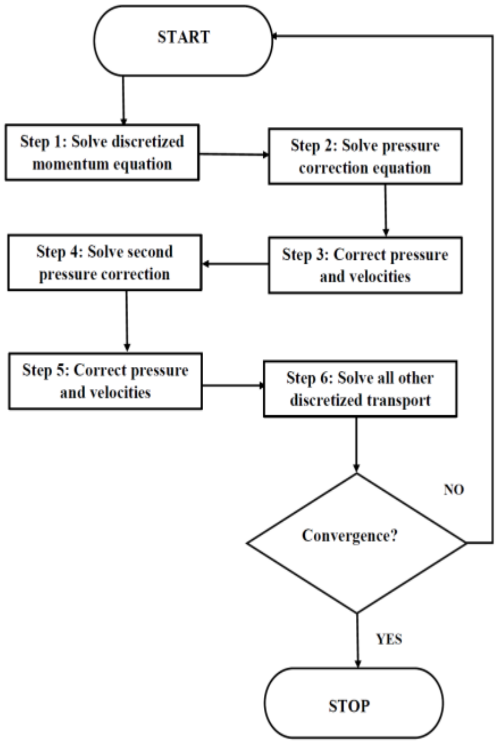


Figure 3. PISO Algorithm Flowchart

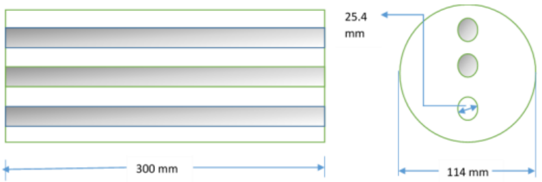


Figure 4.Shell and tube heat exchanger model used for simulation

The other configuration used is to place tubes in an equilateral triangle configuration with a center-to-center tube distance is 57 mm in the case of a 25.4 mm diameter tube. This configuration is shown in Figure-5.

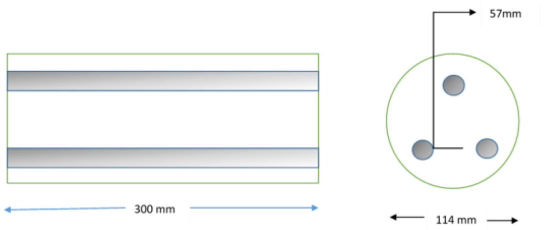


Figure 5 Selected tube orientation for Shell and tube Heat Exchanger

3D model is created in Creo® Parametric Software. Dimensions and shown in Figure-6 and dimensions are mentioned in Table-1.

Table 1. Shell and Tube Dimensions

Equipment	Dimensions (mm)
Aluminum Tubes Inner Diameter	25.4
Aluminum Tubes Outer Diameter	28.6
Shell Inner Diameter	114
Shell Outer Diameter	134
Shell Length	300


Figure 6. 3D model of Heat Exchanger

After knowing all dimensions, the final design was made. It consists of three water reservoirs i.e. two hot and one cold. UPVC pipes were used to flow water through the tubes and the PCM was stored in the shell. Experimental setup is shown in Figure-7.

Figure 7. Experimental Setup

VI. Numerical Solutions & Analysis

A. Grid Independence Curve

To have a reliable solution and it does not depend on mesh size, grid independence has been done. During this study of different numbers of computational cells, we used (Grid A =10000, Grid B = 15000 Grid C = 20000 and Grid D=25000) for case 1. The change in melting fraction was considered as errors but the change is negligible. So, grid D was selected for further cases.

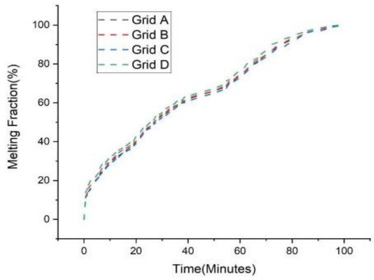


Figure 8. Grid Independence Curve

B. Domain Configuration

For numerical analysis, the two-dimensional domain cross section of heat exchanger is used as shown in Figure-9. The outer diameter of heat exchanger is (D_o) 134mm and the inner diameter (D_i) is 114mm. Each tube has a diameter of 25.4mm and thickness of 3.2mm. The total length of each tube is 300mm. The green area is showing the phase change material.

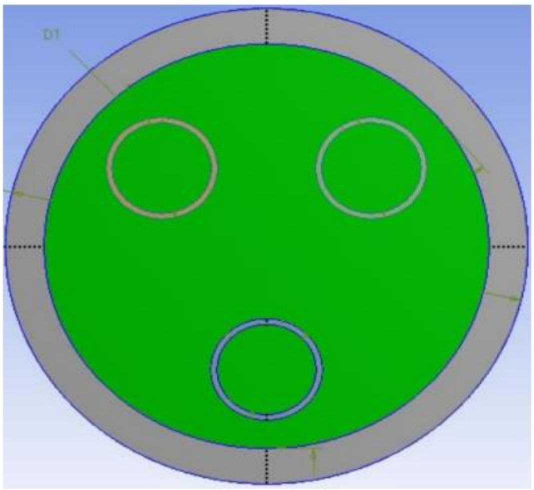


Figure 9. Cross-sectional view of Heat Exchanger with tubes and shell, filled with PCM

Stearic acid is used as PCM which has the advantage of losing its latent heat slowly. So, this makes the best material for latent thermal energy storage (LTES) applications. Stearic acid Thermophysical properties are shown in Table 2.

Table 2. Thermophysical Properties of Stearic Acid

Properties	Stearic Acid
Thermal Conductivity, $k(Wm^{-1}K^{-1})$	0.29
Dynamic Viscosity, , μ $(kgm^{-1}s^{-1})$	0.0078
Thermal Expansion Coefficient, , β (K^{-1})	0.00081
Solidus Temperature of PCM, T_s (K)	327
Liquidus Temperature of PCM, T_l (K)	337
Density of PCM, Solid , $\rho_s(kg\ m^{-3})$	1150
Density of PCM, Liquid, $\rho_l(kg\ m^{-3})$	1008
Specific heat of PCM, Solid, Cp_s $(J\ kg^{-1}K^{-1})$	2830
Specific heat of PCM, liquid, Cp_l $(J\ kg^{-1}K^{-1})$	2380
Latent heat of fusion, $L_f(kJ\ kg^{-1})$	186.5

Assumptions:

To make problems easy to solve some reasonable assumptions are made. First, the outer part of shell of heat exchanger is supposed to be insulated and no heat transfer occurs which makes it adiabatic. Boussinesq approximation is used to model the effect of density variation which reduces non-linearity of the problem. The variation in volume due to density also be neglected. The simulation is run on a 2-D planar heat exchanger. The comparison of inlet and outlet temperature of water was studied at 70◦C as shown in Figure-10 to justify this assumption. During the beginning, the heat transfer is more, and the temperature drop across the shell is maximum but then it decreases with time due to less available temperature gradient.

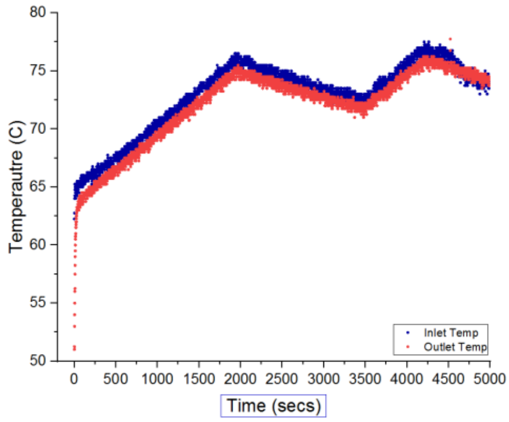


Figure 10. Comparison of Inlet and Outlet Temperature

VII. Results and Discussion

Shell and tube heat exchanger with three tubes at equilateral triangular configuration was used for simulation purpose and the same is used for experimental verification with PCM (stearic acid) and results are discussed. The effects on melting time and stored energy were investigated from time to time. The melting process of PCM under the heat source is affected by the fluctuating properties of the heat sources. Therefore, the effects of heat source duration and amplitude are thoroughly investigated over the period. To observe the effect on melting time and energy. Two UDF functions have been defined for this purpose and used.

A. Validation of Numerical Methodology:

For validation of numerical methodology, the results are first compared with the published results and then with the experimental results. For this purpose, a latent thermal energy unit (LiNO3-NaNO3-KCl) is used as PCM is analyzed. The liquid melting fraction of the present study is compared with the study of (Z.Li, X.Yu, L. Wang et al., 2020) as shown in Figure-11 below. In this study, PCM is kept inside a heat exchanger at 298K. The fluctuating temperature is given to aluminum tube. For case 2 in (Z.Li, X.Yu, L. Wang et al., 2020) with period of one minute. Melting fraction profile of PCM of present study with comparison of (Z.Li, X.Yu, L. Wang et al., 2020) shows that there is slight change in melting fraction of present study as compared to the study of (Z.Li, X.Yu, L. Wang et al., 2020) which tells that this numerical methodology is correct for existing study.[2] The increment of temperature is related to conduction dominant heat transfer mechanism.

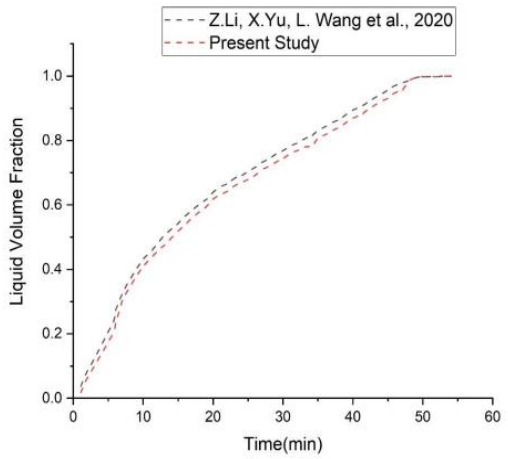
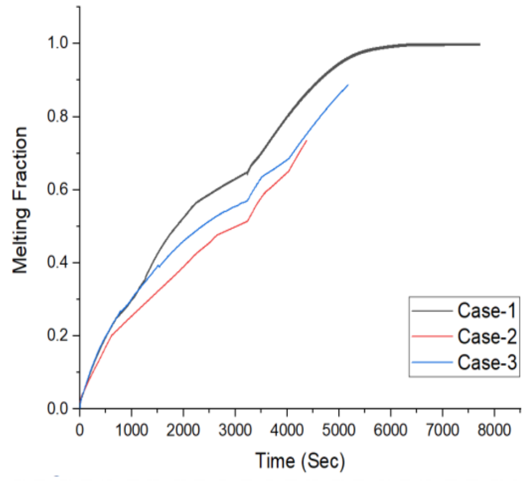


Figure 11. Numerical simulation validation

B. Cases

By altering the temperature's phase and amplitude, six distinct scenarios were examined. Table 1 includes a mention of these six UDFs. Their impact on PCM's enthalpy change and melting time is examined. The system's energy storage is measured by enthalpy change. A fraction of PCM melts is shown in Figure 12.



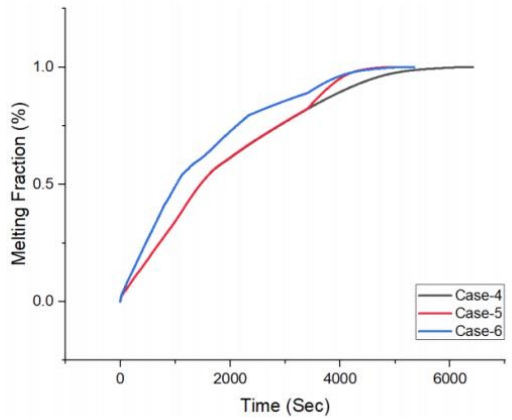


Figure 12. Time Vs PCM Melting Fraction

It can be observed that 90% of PCM melts faster but the some PCM left un-melted at the bottom that take almost 20% of the total time for PCM to melt. This is because as PCM melted its thermal conductivity is less as compared to in solid state. Therefore, when most (90%) PCM melted the thermal conductivity reduces and hence the melting process slows down. Figure-13 shows the same phenomenon.

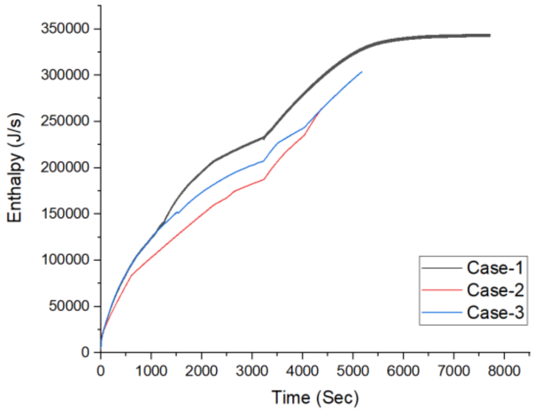


Figure 13. Comparison of Cases for Melting Time Vs Enthalpy Stored

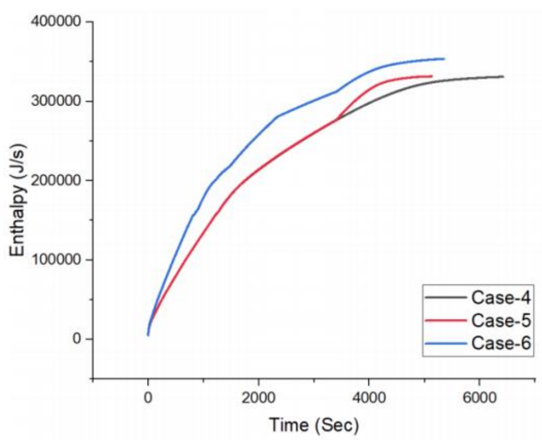
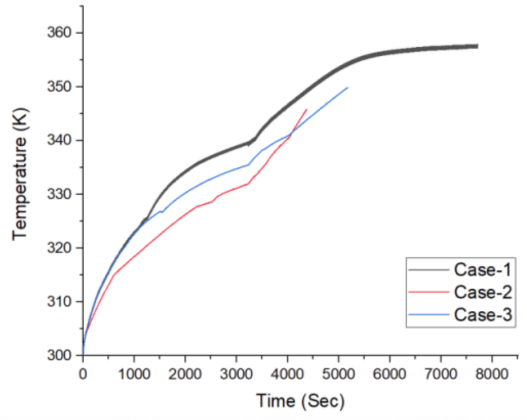


Figure 14 Comparison of Cases for Melting Time vs Enthalpy Stored

Figure-14 shows the amount of energy stored in the PCM during the time of melting. Maximum of 300 kJ/kg of energy is stored during the process of melting.



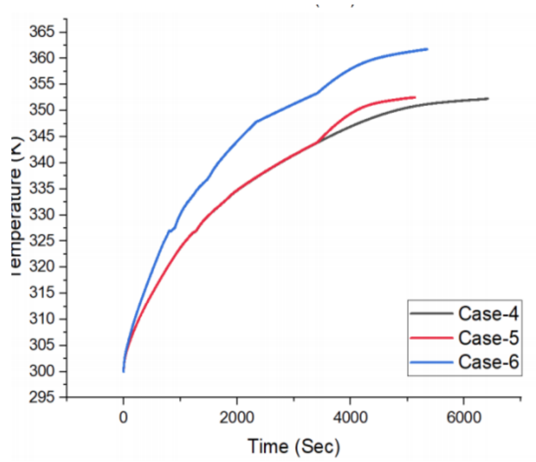


Figure 15. Comparison of Cases for Temperature Vs Time

Figure-15 shows the trend of how the temperature of the PCM increases rapidly at the start. This occur because for first 1000s heat transfer occur dominantly through conduction as the melting occur convection gets dominant. During the last 1000s temperature change is slow because of sea of PCM left at the bottom.

C. Comparison of Numerical and Experimental Results

To justify this study, it is important to compare experimental results with the simulation results, If these are close it means our assumption taking this study 2D is justified. The figure- below shows the temperature variation of inlet and outlet temperatures for the first 1000s is almost constant. The maximum difference between inlet and outlet temperatures was 7-8K which is negligible. The difference between inlet and outlet temperature is higher in the beginning because of more temperature gradient available.

Case-4 (constant temperature 85°C) data is used for simulation as well as for experimental purposes. The Iso-surfaces tool in ANSYS® 2019 is used after finding the position of thermocouples dipped in a thermal storage unit. The simulation results and experimental results show a very good comparison with the maximum error of 4%. To ensure constant temperature throughout three thermocouples were dipped in the reservoir. Constant temperature experimental and theoretical (simulation) results of Case-4 are compared and there very close with an error or only 4%. Figure-15 depicts the same.

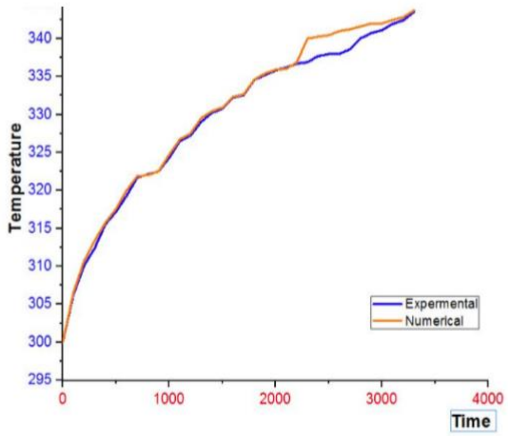


Figure 16. Comparison of Results (Case 4)

To validate this study on melting of the PCM under the fluctuating heat source a cosine wave must produce temperature fluctuation experimentally as well as given in udf, only then results can be compared. For this purpose, d valves are used to control the flowrate of the two hot reservoirs. To ensure a cosine wave we noted the inlet temperatures using thermocouples. At present it is done my manual valves, but better and more accurate results will be obtained by having computer-controlled solenoid valves, which are not used due to financial constraints.

D. Temperature and flow rate calculation

$$m\,C_p T_{avg} = m_1\,C_p T_1 + m_2\,C_p T_2 \tag{5}$$

As fluid in both hot reservoirs is same so C_p has same value.

$$m\,T_{avg} = m_1\,T_1 + m_2\,T_2 \tag{6}$$

Hence, from equation (vi), T_{avg} can be found as:

$$T_{avg} = \frac{m_1}{m}T_1 + \frac{m_2}{m}T_2 \tag{7}$$

Using relation given in Eq. (7) valves are used to achieve the required temperature at a particular point. Cosine wave was produced by taking various points on the MATLAB® and the valves were varied with the same slope to achieve the cosine wave. Comparison between the numerical fluctuations and the actual fluctuation is given in the Figure-16

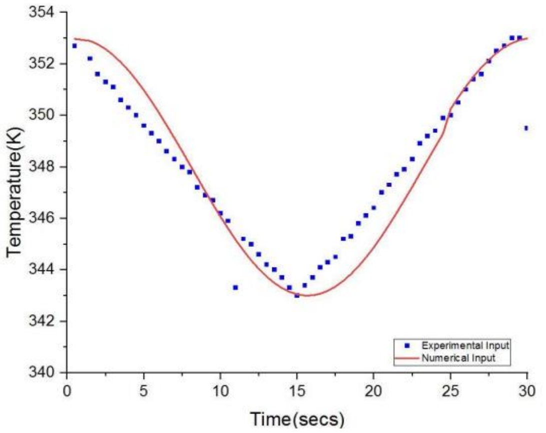


Figure 17. Comparison of Actual and Theoretical Wave

The results of both waves were compared i.e. using the data obtained for the average melting temperature of PCM from the numerical simulation and the data obtained from the physical model. Figure-18 shows comparison of average melting temperature of experimental and theoretical results. There is some difference in both the results as the experimental udf is being controlled manually which is mentioned earlier. If it is done by using solenoid valves having computer control, then the error is very low.

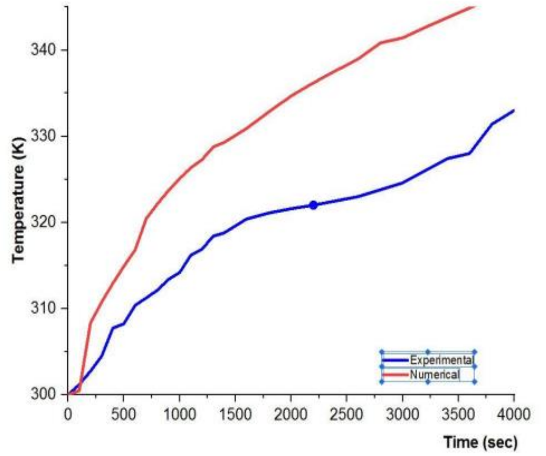


Figure18. Melting Temperature Comparison of Numerical and Experimental Results

E. Melting and Temperature Contours

In contours shown in Figure-18, the melting fraction of case-6 is dominant and takes less time to melt because of high temperature. The convection heat transfer rate becomes dominant after 1000 seconds. The heat transfer is seen right from the start. PCM temperature quickly rises from the upper section due to convection, which enhances the melting of PCM. The temperature contours of PCM are shown in Figure-19. In temperature contours in Case-6 90% of the fraction is at the melting temperature which is the same trend as in fraction of PCM melted.

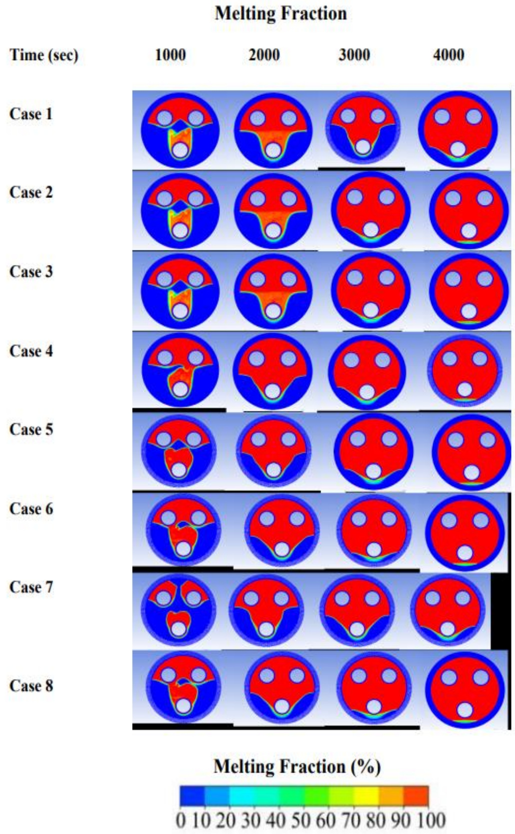


Figure 14 PCM Melting Fraction Contours

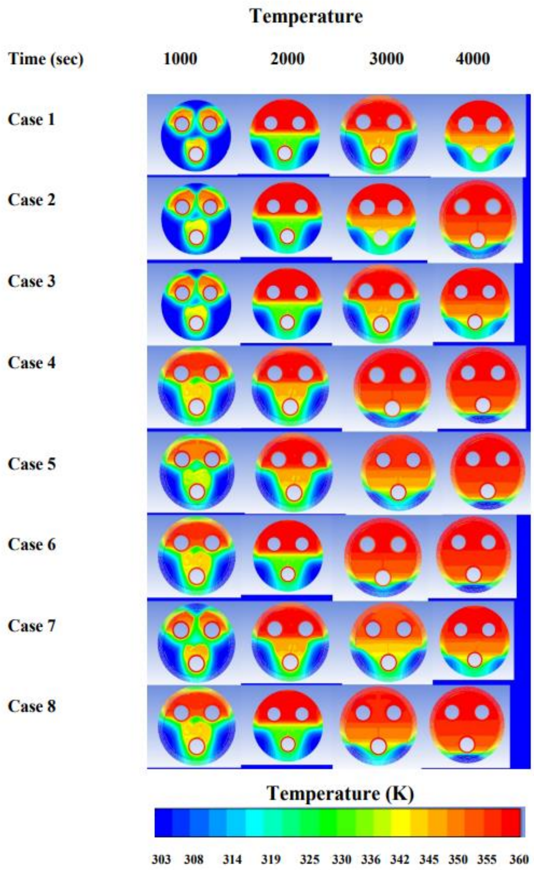


Figure 19 Temperature of Melting Fractions

VIII. CONCLUSION

Numerical analysis has been done to design a latent heat storage unit to damp the thermal fluctuations and analyze the effect of fluctuating temperature on melting of phase change material. Simulation results are compared with experimental results and these results are well close to each other even 2D assumption has been taken. It shows that making simulation easy and simple 2D model gives quite reasonable results. For experimental setup shell and tube hear exchanger with three tubes made of aluminum place in equilateral triangle fashion. The simulations results tell us that by convection, the melting starts from the walls of the tube and then due to natural convection it exceeds. In the beginning conductive heat transfer is dominant, afterward natural convection takes this role as melting of PCM starts. A study of both constant and fluctuating temperatures is done and observed that at constant temperature PCM takes less time to melt as compared to fluctuating temperature which is because at constant temperature amplitude is constant and temperature gradient gradually changes but in fluctuation temperature, the amplitude is varying with time and hence the temperature gradient is also changing abruptly, therefore more time to melt PCM. But the aim of the study is achieved the thermal fluctuation has been done and PCM is at the constant temperature and that energy can be restored by freezing it. Therefore, using PCM to store waste fluctuation heat, which is mostly the case from automobiles, industry, etc.

It is recommended that study should be done with the same configuration of tubes but with fins. Also, it should be studied for different materials for tubes and fins.

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