Turkish Online Journal of Qualitative Inquiry (TOJQI)
Volume 12, Issue 10, October 2021: 4528-4539

Design Optimization of Thermal Energy Storage System

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Abstract

Thermal energy storage system is necessary to improve the efficiency of solar thermal applications (STEA) and to eliminate the imbalance between energy supply and energy demand. Among the thermal energy storage devices, the latent heat storage device (LHTES) has received a lot of attention due to its high energy density per unit of mass / volume at almost constant temperatures. Although extensive research has been carried out in recent years, an integrated study of the design of the PCM heat exchanger is rare. This article presents a numerical and simulation study of the phase change process dominated by heat conduction in thermal storage units. Water as a heat transfer fluid (HTF) flows through the tube for the charging and discharging cycles and paraffin wax as phase change material (PCM) is filled in the shell. With the previous assumptions, we have designed and performed the simulation of the thermal energy storage system using the ANSYS software. An in-depth constant study is additionally administrated for various radii. After the simulation and analysis, we concluded that if the tube radius is exaggerated the heat transfer space also increased with reduces the time to charge and discharge the energy stored in the PCM.

Keywords: Thermal energy storage (TES), Phase change material (PCM)

1. Introduction

Renewable energy is playing a vital role in the generation of clean energy and avoiding negative effects of pollutions in our environment. Out of all the renewable sources of energy solar energy has the potential to reach all the demands of industrial and domestic applications. Hence, incorporating efficient energy storage systems along with renewable energy sources is essential. Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium, so that the stored energy can be used later, either for heating and cooling applications or for power generation. Generally, Phase change material (PCM) is used as the storage medium in the Thermal energy storage system, because of its good storage density. Phase change materials (PCMs) are able to absorb, store and release large amounts of latent heat over a defined temperature range when the material changes phase or state. PCM’s play a key role in improving the energy efficiency in the thermal energy storage system. PCM thermal storage system indicates high performance and has the advantages of high storage capacity and nearly constant thermal energy. Most Solar Thermal Energy Applications required a constant or near-constant temperature for high-efficiency strategies. The performance of the thermal energy storage system depends on the thermo physical properties of the PCM and the design of the storage system. The heat energy stored in the storage system is transferred to the appliance by means of a Heat Transfer Fluid (HTF).The difference between the phase change temperature of the PCM and inlet temperature of HTF is the driving force of heat transfer between PCM and HTF.

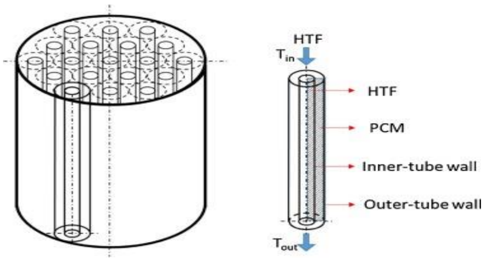
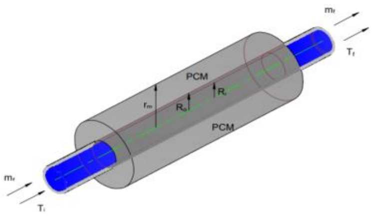


Figure.1 Shell and tube thermal energy storage system

1.1.Shell and tube thermal energy storage system:

There are various geometries that can be used for thermal energy storage systems such as spherical capsule geometry, square and rectangular geometry, and cylindrical capsule geometry. Out of these Cylindrical geometries are considered most promising for devices for commercial heat exchangers, such as the double pipe heat exchanger and shell and the tube heat exchanger, because of their high-efficiency in a minimum volume. Most researchers use this geometry for LHTES, filling the PCM in the tube side or in the annulus (shell). Commercial products of PCMs are delivered in these geometries.



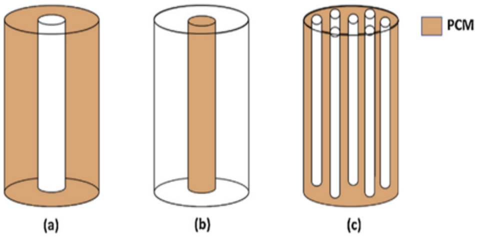


Figure.2 Shell and tube thermal storage system
exchanger: a) with the Inlet and Outlet flow
model c) Multi-tube model

Figure.3 Types of Shell and Tube heat
Cylinder model b) Pipe

There are several factors which affects the total melting time, solidification time and stored energy of Thermal Energy Storage System. So, it always recommended to select the optimum design to enhance the performance of TES. There are three different types of Shell and tube heat exchanger as shown in the figure below. Among these we have chosen the cylinder model for our project mainly for one reason**:**

- **Shell to tube diameter ratio:**

The shell to tube diameter ratio “R” is the most significant parameter which affects the performance. As this ratio increases, the amount of PCM increases and hence stored energy can be increased. However, this leads to an increase in melting time and solidification time.

R = Diameter of the shell /Diameter of the tube

Hence, we chose cylindrical model which has the better shell and tube diameter ratio of 3.5 approximately, can store more amount of PCM and provides better storage capacity. It also helps in reducing the fluctuations of HTF outlet temperature.

2. Numerical Simulation:

A numerical and experimental investigation of phase change process dominated by heat conduction in a thermal storage unit is presented in this paper. The thermal energy storage involves a shell and tube arrangement where paraffin wax as phase change material (PCM) is filled in the shell. Water as heat transfer fluid (HTF) is passed inside the tube for both charging and discharging cycles. According to the conservation of energy, a simple numerical method called alternative iteration between thermal resistance and temperature has been developed for the analysis of heat transfer between the PCM and HTF during charging and discharging cycles. Experimental arrangement has been designed and built to examine the physical validity of the numerical results. Comparison between the numerical predictions and the experimental data shows a good agreement.

2.1. Assumptions:

While developing the mathematical model for heat transfer the following assumption were made:

- The thermo physical properties for both HTF and PCM were constant with respect to temperature.
- The thermal conduction in the axial direction is neglected for both PCM and HTF.
- Natural convection inside the PCM was not considered i.e. buoyancy force for volume change due to phase change was ignored.
- The initial temperature of the storage was uniform and it was in melting temperature.
- Adiabatic wall was assumed.
- The HTF entering inside was laminar and simultaneously developing

2.2. Software Used:

Software used for executing the design and run the simulation with the boundary conditions.

- ANSYS 2021 WORKBENCH for designing
- ANSYS 2021WORKBENCH for simulation

2.3. Formulas Used:

Heat required $Q = P_h \times t$

Mass of PCM $m_{pcm} = Q_T / h_m$

Energy stored by PCM $Q_{pcm} = m_{pcm} \times ((a_m \times h_m) + C_{sp} \times (T_m - T_i) + C_{lp} \times (T_f - T_m))$

Mass Flow rate $m^* = \rho_{HTF} \times q^*$

For Melting Process

$$r_l(x,t)=\sqrt{1+(\int_0^t \frac{hfD_i}{H\rho_l} \times \frac{R_f}{(R_f+R_w+R_l(x,t)} \times \left[T_f(x,t)-T_m\right]dt}$$

$$T_f(x,t)=T_m+[T_{in}(t)-T_m] \times \exp[-\frac{\pi D_i h_f}{Cp_f m_f(t)} \times \frac{R_f}{R_f R_w R_l(x,t)} \times x]$$

For Solidification process

$$r_s(x,t)=\sqrt{1+(\int_0^t \frac{hfD_i}{H\rho_s} \times \frac{R_f}{(R_f+R_w+R_s(x,t)} \times \left[T_f-T_m(x,t)\right]dt}$$

$$T_f(x,t)=T_m+[T_m-T_{in}(t)] \times \exp[-\frac{\pi D_i h_f}{Cp_f m_f(t)} \times \frac{R_f}{R_f R_w R_s(x,t)} \times x]$$

2.4. PCM Properties:

Properties	Units	Values
Melting temperature	°C	61
Density in liquid state	kg/m3	790
Density in solid state	kg/m3	910
Specific heat of solid	J/kg K	2000
Specific heat of liquid	J/kg K	2150
Latent heat	J/kg	190000
Thermal conductivity in solid	W/m·K	0.24
Thermal conductivity in liquid	W/m·K	0.22
Kinematic viscosity	m2 /s	0.0000052
Dynamic viscosity solid	N s/m2	0.004732
Dynamic viscosity liquid	N s/m2	0.004108

Table.1 Thermo physical properties of paraffin wax.

2.5. HTF Properties:

Properties	Units	Values
Water at =25°C		
Density	kg/m^3	997
Specific heat	J/kg K	4179
Thermal conductivity	W/m·K	0.613

Dynamic viscosity	N s/m^2	0.000855
Water at = 88 °C		
Density	kg/m^3	967.1
Specific heat	kg/m^3	4203
Thermal conductivity	W/m·K	0.674
Dynamic viscosity	N s/m^2	0.000324

Table.2 Thermo physical properties of water.

2.6. Calculations:

Heat required for cooking for 1 hour.

$Q = P_h$ x t

$P_h = 220$ W/m^2

$P_h = 440$ W

$P_h = 26.4$ KJ/MIN

Q = 440 W X 60 MIN

Q = 1584 KJ

Considering 80 % efficiency = 1.584 x 1.2

$Q_T = 1900$ KJ

Amount of PCM (paraffin wax) required:

PCM required = amount of heat required/heat of fusion of PCM

PCM required = 1900/190

PCM required = 10KG

Energy stored by PCM:

The mathematical expression of energy storage of PCM is given by

$$Q_{pcm} = m_{pcm} \times ((a_m \times h_m) + C_{sp} \times (T_m - T_i) + C_{lp} \times (T_f - T_m))$$

m_{pcm} = Mass of PCM

$C_{pcm}(s)$ = Specific heat of PCM at solid state

$C_{pcm}(l)$ = Specific heat of PCM at liquid state

Tm = Melting temperature of PCM

Ta = Initial temperature of PCM

T_{max} = Maximum temperature of PCM

L = Latent heat of fusion of PCM = am x hm

After substituting all the values in the equation:

$$Q_{pcm} = 10[2.0(61-25) + 190 + 2.15(88-61)]$$

$$Q_{pcm} = 3200.5 \text{ KJ}$$

3. Modelling and Simulation:

The shell and tube thermal energy storage system is generated in the ANSYS with the given standard dimensions. Then the model is meshed with edge sizing in the simulator. The outer pipe of the PCM and HTF is selected and meshed by edge sizing. After the meshing the model is divided into 160512 Elements and 165765 Nodes. Then the model is assigned with all the materials. Outer shell of PCM and HTF is considered as steel, paraffin wax is taken as PCM and water is taken as HTF. Thermal energy storage system is given with all the boundary conditions given below and then the simulation is done for 1200sec (20 mins). Then the solidification temperature and other parameters have been observed for different times.

3.1.Boundary Conditions:

- Inlet temperature – 361k with mass flow rate of 0.005kg/s.
- Inner pipe outwall is considered as shell conduction with thickness 0.001m.
- Outlet type is considered as outflow and temperature as 298k.
- Pcm face inlet – thermal condition as system coupling.
- Pcm face outlet – thermal condition as system coupling.
- Wall fluid domain inner pipe is considered as shell conduction with thickness 0.001m and thermal condition as system coupled.
- Wall inner pipe – thermal condition as system coupling.
- Wall outer pipe solid - thermal condition as system coupling.
- Wall outer pipe solid pcm - is considered as shell conduction with thickness 0.001m and thermal condition as coupled.

3.2. Dimensions used for designing the Thermal Storage System with the Standard Diameter:

- Outer diameter of the outer pipe = 112 mm
- Inner diameter of the outer pipe = 104 mm

- Outer diameter of the inner pipe = 35mm
- Inner diameter of the inner pipe = 32mm
- Total length = 1000 mm

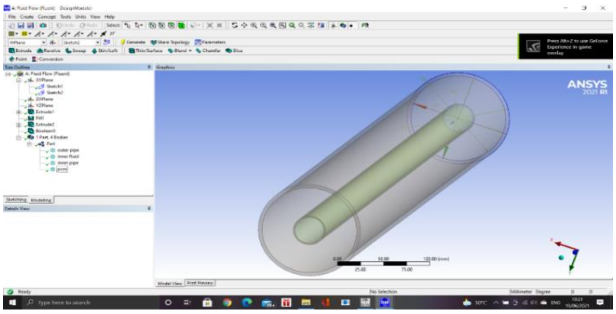


Figure.4 3D Model of the Thermal energy storage energy system

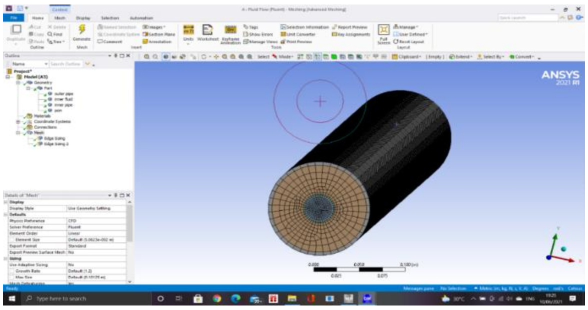


Figure.5 Meshed model of the Thermal storage system

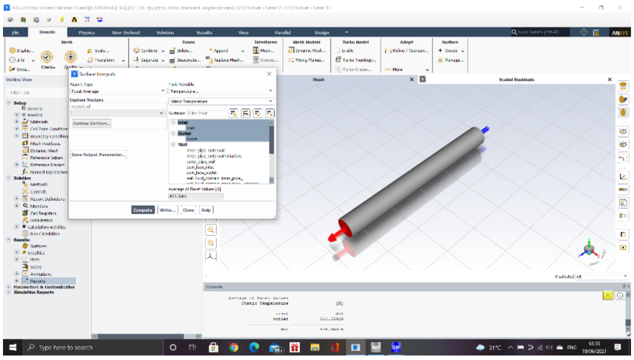


Figure.6 Model with the Inlet and Outlet flow

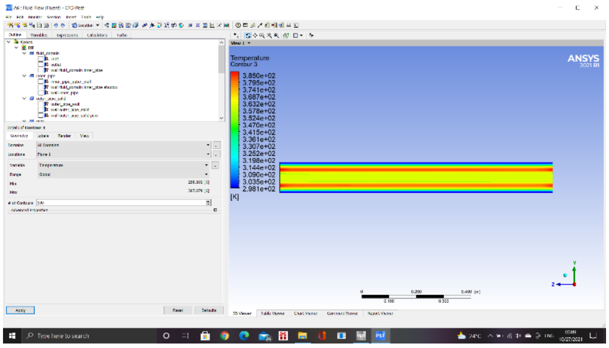


Figure.7 Tempurature Contour of thermal energy thermal energy storage system with standard diameter . standard diameter.

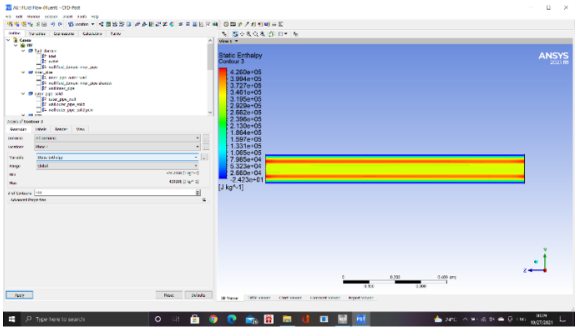


Figure.8 Static Enthalpy Contour of storage system with

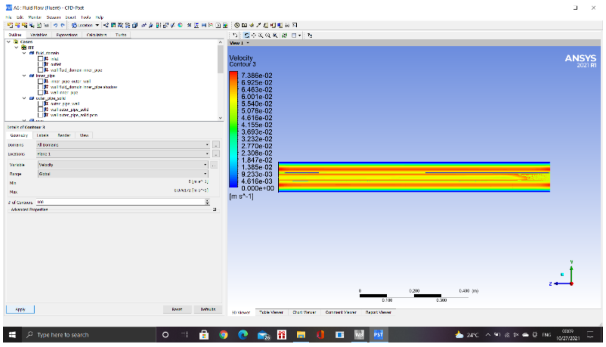


Figure.9 Velocity Contour of thermal energy storage system with standard diameter.

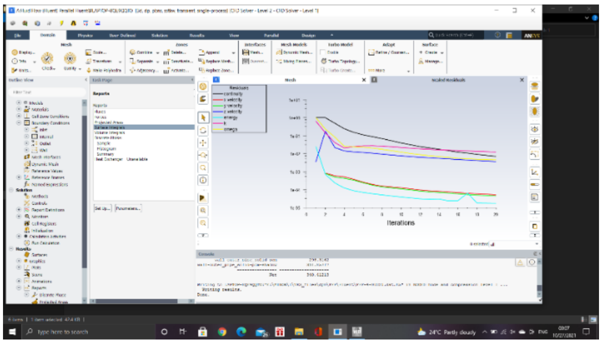


Figure. 10 Energy and Velocity vs Time graph of thermal energy storage system with standard diameter.

3.3. Dimensions used for designing the Thermal Storage System with the Increased Diameter:

- Outer diameter of the outer pipe = 115 mm
- Inner diameter of the outer pipe = 107 mm
- Outer diameter of the inner pipe = 38 mm
- Inner diameter of the inner pipe = 35 mm
- Total length = 1000 mm

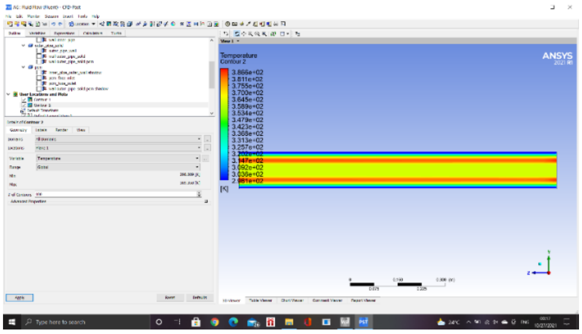


Figure.11 Tempurature Contour of thermal energy storage system with increased diameter.

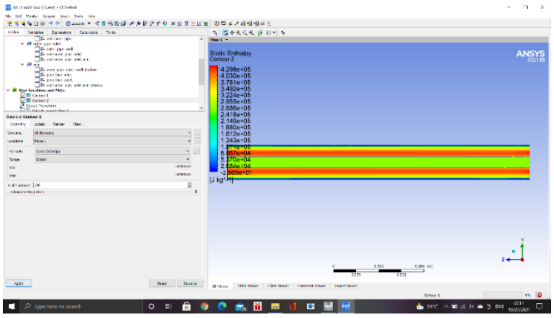


Figure.12 Static Enthalpy Contour of thermal energy storage system with increased diameter.

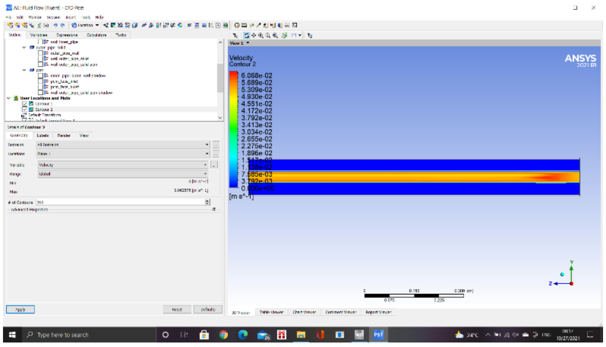


Figure.13 Velocity Contour of thermal energy storage system with increased diameter.

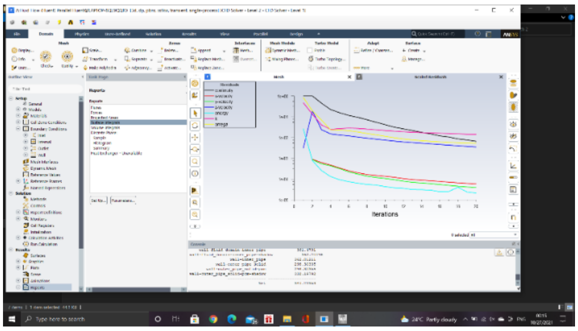
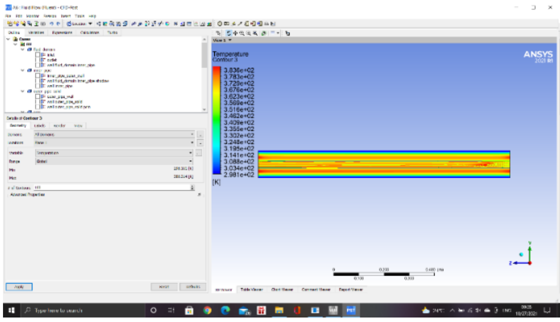


Figure.14 Energy and Velocity vs Time graph of thermal energy storage system with increased diameter.

3.4. Dimensions used for designing the Thermal Storage System with the Decreased Diameter:

- Outer diameter of the outer pipe = 109 mm
- Inner diameter of the outer pipe = 101 mm
- Outer diameter of the inner pipe = 32 mm
- Inner diameter of the inner pipe = 29 mm
- Total length = 1000 mm



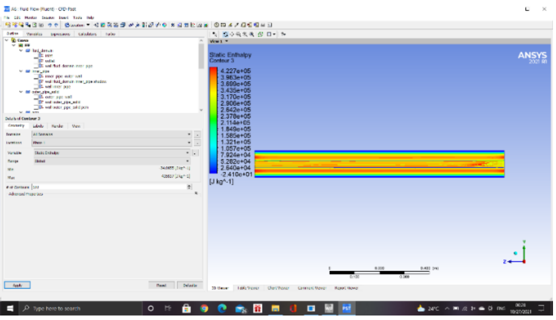
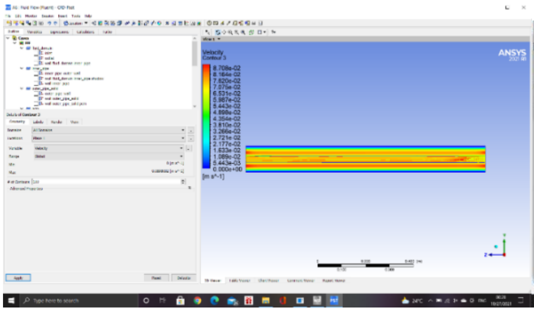


Figure.15 Tempurature Contour of thermal energy **Figure.16** Static Enthalpy Contour of thermal energy storage system with decreased diameter. storage system with decreased diameter.



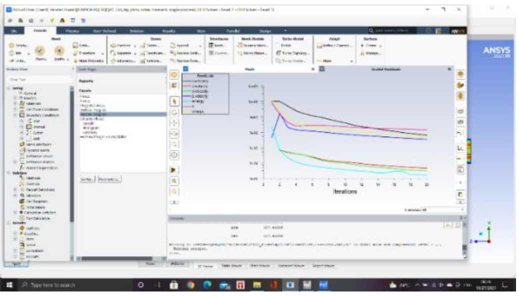
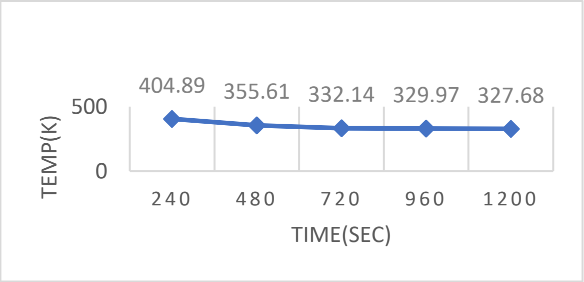


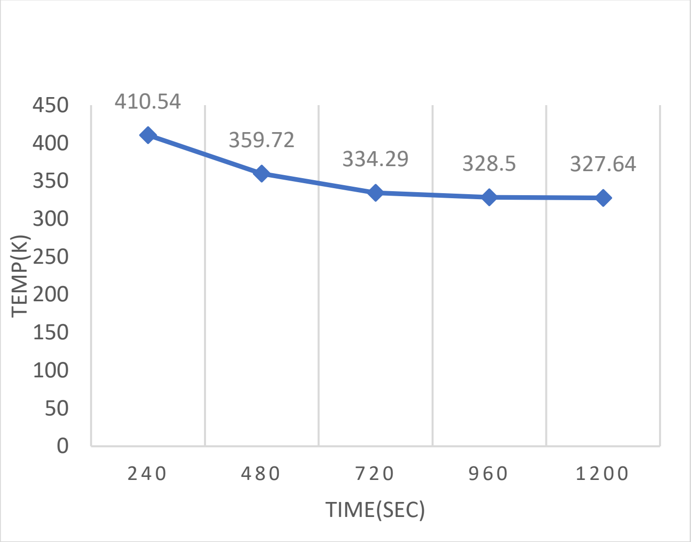
Figure.17 Velocity Contour of thermal energy storage **Figure.18** Energy and Velocity vs Time graph of system with decreased diameter. thermal energy storage system with decreased diameter.

4.Result:



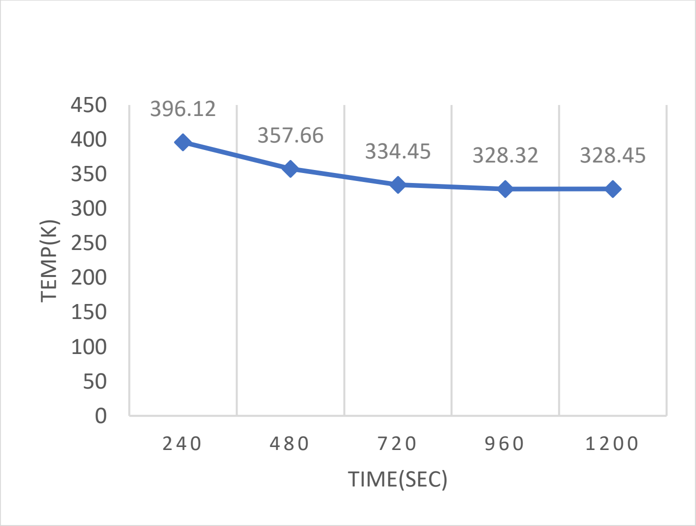
Graph-1: TEMPERATURE vs TIME graph of the thermal storage system with the standard diameter.

The minimum and maximum temperature obtained by the analysis are 327.68 K and 404.89 k in a time duration of 1200 sec.The maximum velocity of the streamline in the flow of the Heat transfer fluid is 7.386e-02 m/s.The maximum static enthalpy obtained by the analysis is 4.260e+05 J/KG.



Graph-2: TEMPERATURE vs TIME graph of the thermal storage system with the increased diameter.

The minimum and maximum temperature obtained by the analysis are 327.64 K and 410.54 k in a time duration of 1200 sec.The maximum velocity of the streamline in the flow of the Heat transfer fluid is 6.068e-02 m/s.The maximum static enthalpy obtained by the analysis is 4.260e+05 J/KG.



Graph-3: TEMPERATURE vs TIME graph of the thermal storage system with the decreased diameter.

The minimum and maximum temperature obtained by the analysis are 328.45 K and 396.12 k in a time duration of 1200 sec.The maximum velocity of the streamline in the flow of the Heat transfer fluid is 8.708e-02 m/s.The maximum static enthalpy obtained by the analysis is 4.227e+05 J/KG.

4.1. Future Scopes:

As future work we can analyse the performance of LTES by using multiple phase change material of different melting points in a single storage system. There is a variety of other suggestions in the current research on how to improve charging and discharging performance of LTES, of many mentioned in the literature study. One on the most promising and common is a multi-tube heat exchanger. Such an exchanger in a vertical orientation should be examined. It is not only the orientation and tube setup that should be considered, but as mentioned before, also which PCM is used, and research on new PCM's.For the enhancement of heat transfer longitudinal fins can be introduced. For the enhancement of heat transfer by multiple PCMs, PCMs can be chosen such that their melting points are in geometric progression. Moreover, Different heat transfer fluid which has the better heat transfer rate can be used.

5.Conclusion

After conduction numerical and software simulation of different radii we came to the conculsion that the increased tube radius with a constant thickness allows the PCM to solidify or melt quicker and the outlet temperature shift near to the inlet temperature of the HTF for higher tube radius. If the tube radius is increased the heat transfer area also increased. More heat will be conducted from HTF to PCM. Another possible way to explain the reduced operating time of the system is that an increased tube radius allows less PCM inside the shell. So less time is required to solidify or melt the PCM inside the shell. Due to the increased tube radius we can observe that the maximum temperature of the PCM is also increased**.**

References (APA)

[1]. Design and Development of Thermal Energy Storage System by using PCM-(IJSTE - International Journal of Science Technology & Engineering | Volume 5 | Issue 7 | January 2019)

[2]. Design and Fabrication of Solar Thermal Energy Storage System Using Potash Alum as a PCM-Muhammad Suleman Malik,Naveed Iftikhar, Abdul Wadood , Muhammad Omer Khan,Muhammad Usman Asghar, Shahbaz Khan, Tahir Khurshaid 5, Ki-Chai Kim,Zabdur Rehman and S. Tauqeer ul Islam Rizvi

[3]. Influence of operational and design parameters on the performance of a PCM based heat exchanger for thermal energy storage – A review Lokesh Kalapala, Jaya Krishna Devanuri

[4]. Design and optimization of solid thermal energy storage modules for solar thermal power plant applications-Yongfang Jian,Quentin Falcoz, Pierre Neveu,Fengwu Bai,Yan Wanga,Zhifeng Wanga-SCIENCE DIRECT-Applied Energy Volume 139, 1 February 2015, Pages 30-42

[5]. Review of solar cooling methods and thermal storage options-L.A. Chidambarama,A.S. Ramanab,G. Kamaraja,R. Velrajc-SCIENCE DIRECT-Renewable and Sustainable Energy Reviews Volume 15, Issue 6, August 2011, Pages 3220-3228

[6]. Performance analysis of thermal energy storage systems using phase change material-Adele Caron,Soupart,Jean-Francois Fourmigue, Philippe Marty,Raphael Couturier-SCIENCE DIRECT-Applied Thermal Engineering Volume 98, 5 April 2016, Pages 1286-1296

[7]. A review of solar collectors and thermal energy storage in solar thermal applications-Y. Tian a, C.Y. Zhao-SCIENCE DIRECT-Applied Energy Volume 104, April 2013, Pages 538-553

[8]. Review of mathematical modeling on latent heat thermal energy storage systems using phase change material-Prashant Vermaa, Varuna, S.K. Singalb SCIENCE DIRECT-Renewable and Sustainable Energy Reviews 12 (2008)

[9]. Numerical modeling for solid–liquid phase change phenomena in porous media: Shell-and-tube type latent heat thermal energy storage-Zhenyu Liu, Yuanpeng Yao, Huiying Wu-SCIENCE DIRECT-Applied Energy Volume 112, December 2013, Pages 1222-1232

[10]. CFD applications for latent heat thermal energy storage- AbduljalilA.Alabidin, SohifBinMat,K.Sopian,M.Y.Sulaiman,AbdulrahmanTh.Mohammed-SCIENCE DIRECT-Renewable and Sustainable Energy Reviews Volume 20, April 2013, Pages 353-363Abraham, S, Brooke R. Noriega, Ju Young Shin (2018). College students eating habits and knowledge of nutritional requirements. Journal of Nutrition and Human Health, 2(1), 13-17.

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