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Abstract

One important solution for societies to overcome the energy crisis is to manage the production and storage of energy. In this regard, the latent heat energy storage systems have recently gained a remarkable attention. Hence, this work is devoted to enhance performance of a latent heat tube-shell storage system by using novel rectangular plate fins and circular disc plate fins with different geometrical characteristics. Different number of vanes have been employed on the fins. The different cases studied include the cases with double-fin, quadruple-fin, quintuple fin, and sextuple fins. These fins have been employed to augment heat transfer from a low temperature fluid to the PCM inside the shell container during the solidification process. To model the phase change, the enthalpy-porosity technique has been adopted. Various parameters have been used to assess the functionality of the system including the solidification process at time of 4000s, solid fraction evolution, solid fraction contours, temperature contours and etc. The results demonstrated that the case 4 (sextuple fins case) took the advantage in heat transfer augmentation and discharging process while the case with double twisted-fin showed the worst performance. The results indicated that fin length is not the only influencing factor and fin number also has a dominant role.

Keyword: Phase change material, Thermal energy storage, Latent heat storage, Heat transfer fluids, Computational fluid dynamics, and Paraffin Wax

Introduction

To move heat from one medium to another, heat exchangers are used. These substances might be gas, liquid, or the combination of the two. Both direct touch and separation by a solid wall to avoid mixing are possible. Heating and/or cooling must be supplied through heat exchangers to fulfil a process need. Direct heat input is often supplied by a furnace or steam. Consequently, the furnace or steam boiler will have to work harder to compensate for any inefficiency in heat transmission at exchangers.

The energy efficiency of a system may also be increased with the help of heat exchangers, which move heat from areas where it is not required to areas where it is. Heat exchangers are used to transfer heat between two or more process streams, or between a process stream and a utility stream (which may be hot or cold, depending on the circumstances).

Whether or not there is an available process stream to deliver that responsibility given the needed temperature approach determines whether or not a direct process-to-process heat exchanger is used instead of utilities to transfer heat. In the absence of a process stream, the necessary heating or cooling duty must be met by a utility stream.

The following are a few examples of potential uses for heat exchangers:

- Reusing the exhaust heat from a gas turbine that produces electricity. A heat exchanger may be used to either directly heat a process stream or indirectly heat it via a medium like water or hot oil. Cogeneration relies on this principle. The Combined Heat and Power Data Sheet has further details.

- Making use of process heat recovery, which, for more complicated systems, may be optimized using the pinch approach (see the Pinch Analysis Info Sheet for additional details). Creating a heat exchanger network to reuse the heat generated by a distillation train to preheat the incoming feed and preheating of crude for water/oil separation.

- Heating a process stream with a utility such as water, steam, hot oil, or molten salt.

- Cooling a process stream by use of a utility, such as air, cooling water, or refrigerant.

- Process stream inlet and outlet temperatures are the primary factors in determining the kind of hot utility to be used. The utility cost, process safety, and the specific heat capacity are other important aspects to think about.

Literature Review

[1] This work is devoted to enhance performance of a latent heat tube-shell storage system by using novel spiral fins with different geometrical characteristics. Different number of vanes have been employed on the fins with constant twisting pitch. The different cases studied include the cases with single-fin, double-fin, triple-fin and quadruple-fin. Various parameters have been used to assess the functionality of the system including the Nusselt number, total solidification time, temperature, solid fraction evolution, solid fraction contours, temperature contours and etc. The results demonstrated that the triple-fin and double-fin cases took the advantage in heat transfer augmentation and discharging process while the case with single-fin showed the worst performance. The results indicated that fin number is not the only influencing factor and fin length also has a dominant role.

[2] Recent literature on PCM-based thermal energy storage systems for buildings is reviewed in this state-of-the-art research. Passive & active systems, respectively, are used to heat and power the hybrid applications studied. In addition, a brief overview of PCMs used, their uses, thermo-physical characteristics, and techniques of inclusion, are provided. The paper stresses the need of hybridizing PCM systems and discusses the prospective efficacy of PCM in the building heating applications. This research demonstrates the continued need for both experimental studies of commercial buildings and the development and optimization of hybrid systems. Finally, recommendations are made on how active & passive heating applications might be combined to maximize energy efficiency.

[3] In the current study, a new fin arrangement and hybrid nanoparticles (MoS_2 and Fe_3O_4) were used to increase the PCM solidification rate in the "triplex-tube storage". The "natural conduction" was modeled in a computer model and checked against existing experimental evidence. Over the course of entire solidification process, the effects of varying radiation parameter, nanoparticle volume fractions, and shape factor were computed and reported on the evaluation of "liquid-solid interfaces", phase change rate, & the solidification process time. The results show that by using these techniques, PCM solidification is improving. According to the findings, the radiation parameter significantly affects the phase change rate, accounting for 74.58% of the "full solidification process time" (FST). Furthermore, the optimal parameters have been determined using Taguchi & "Response Surface Methodology" (RSM) to optimize the total solidification process time in the "triplex-tube latent heat energy storage system" (LHESS). An innovative, reasonably precise correlation for FST is established.

[4] Energy storage using the "phase change materials" (PCM) is a rapidly developing area of study. In particular, the "organic phase change materials" (OPCM) have garnered considerable interest because of their exceptional characteristics, which allow them to be integrated with thermal energy storage systems to sustainably store renewable power. Because of its poor thermal conductivity & leakage during the phase shift, however, OPCM can only be used for the thermal energy storage. The easiest way to prevent leakage and increase OPCM's storage capacity is to encase it in a protective shell using one of many encapsulation methods. The focus of this analysis is on the "thermal energy storage" and its related

thermal characteristics. Additionally, we highlight the importance of selecting materials based on a variety of characteristics and the encapsulation processes ranging from the macroscopic to nanoscale. Finally, the usage of PCMs in different applications, difficulties encountered, and potential future developments are reviewed.

[5] Phase Change Material (PCM) integration with the solar thermal applications is the subject of this study, which provides a comprehensive overview of research results produced in this area. Solar power is a promising clean energy option since it eliminates the scarcity and environmental problems of the fossil fuels, but it requires energy storage to make up for the disparity between peak demand and supply. Because of their high latent heat, PCMs are an ideal medium for "latent heat storage" (LHS). This overview focuses on current literature that addresses material issues and potential solutions for PCM coupled with the solar thermal applications. Finally, suggestions for further research and practical use are made.

[6] In order to better understand the properties of the PCM melting in the triangular cylinder containers, the numerical research has been presented. The "commercial paraffin" wax has been chosen as the PCM, and melting process is heated by a hot air stream. It has been identified and explained how the flow structure and the convective heat transfer occur around triangular cylinders. Researchers have looked at three triangular cylinders with the same capacity but varying apex angles (24 degrees, 60 degrees, and 100 degrees). Different apex angles are shown to have different effects on flow behavior and the process of the heat transfer to cylinder walls. Containers' ability to store heat is evaluated for the first time. Ansys Fluent-CFD has been used to simulate the melting process, including the flow field and the heat transport. The SIMPLE algorithm is employed with the finite volume method. Results shown that the surface temperature of the container and the effectiveness of heat storage are significantly impacted by apex angle and length of triangle's base.

Methodology

Expected Procedure to be followed during the complete study:

1. 3d Designs of computation domain have been created in CATIA.
2. Further converting file into .stp format.
3. Next, execute the simulation in ANSYS by importing the file into the ANSYS design module.
4. In this process, an imported design goes through meshing.
5. Give the domain name in the design which is use in the CFD process are specified during the naming process.
6. The PCM and fluid are all treated with the appropriate material qualities.
7. Boundary conditions are applied.
8. ANSYS workbench, with its fluid-fluent modal, is used to assess the thermal data.

Design

The current concept is a tube-shell storage system, with water flowing through the tube at a lower temperature while the PCM is loaded into the shell. Because there is no insulation between the PCM and the environment, no energy is transferred to or from the PCM via the wall. In the solidification process, the inner tube wall, which is solid, acts as a heat transfer medium between the low-temperature fluid and the PCM.

Case 1

In this case rectangular cross-sectional shape of the fins whose dimensions are 11.7 mm and 2 mm. The fins attached on tube surface as spiral path whose twisted pitch and twisted angle are 230 mm and 720° respectively. Inner diameter and thickness of the tube is 20 mm and 1.5 mm respectively. Diameter of the outer shell in which PCM filled is 70 mm. length of the geometry of the latent heat storage system is 460 mm.

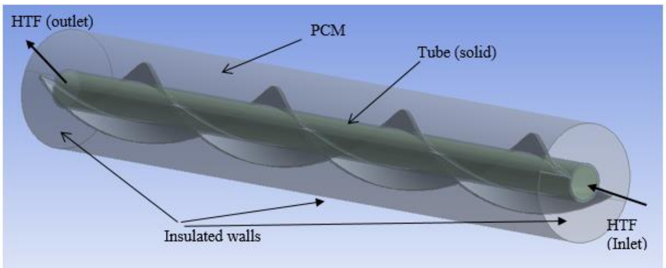

Figure 1 Design of case 1

Case 2

Inner diameter and thickness of the tube is 20 mm and 1.5 mm respectively. Diameter of the outer shell in which PCM filled is 70 mm. length of the geometry of the latent heat storage system is 460 mm. In this case four rectangular plate as fins are attached into tube surface. Fins height of 9 mm thickness of 1 mm and length of 460 mm. The angle between each fin is 90°.

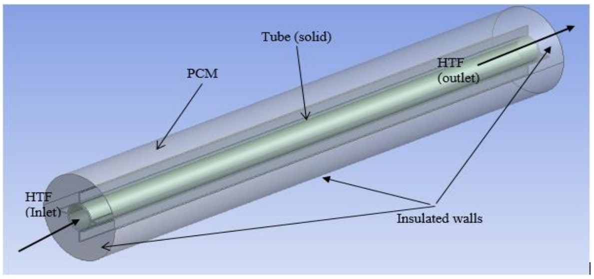

Figure 2 Design of case 2

Case 3

Inner diameter and thickness of the tube is 20 mm and 1.5 mm respectively. Diameter of the outer shell in which PCM filled is 70 mm. length of the geometry of the latent heat storage system is 460 mm. In this case five rectangular plate as fins are attached into tube surface. Fins height of 9 mm thickness of 1 mm and length of 460 mm. The angle between each fin is 72°.

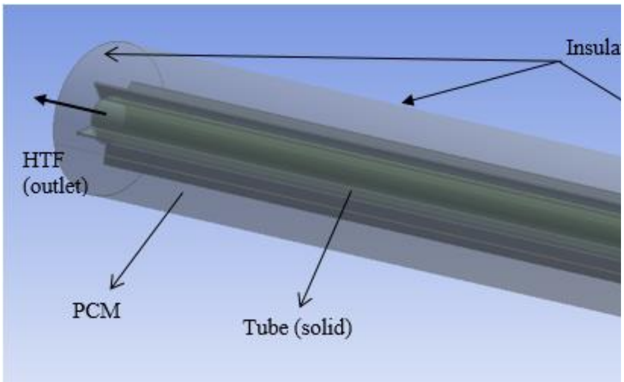

Figure 3 Design of case 3

Case 4

Inner diameter and thickness of the tube is 20 mm and 1.5 mm respectively. Diameter of the outer shell in which PCM filled is 70 mm. length of the geometry of the latent heat storage system is 460 mm. In this case six rectangular plate and 3 circular discs as fins are attached into tube surface. Rectangular fins height of 9 mm thickness of 1 mm and length of 460 mm and circular fins inner diameter and outer diameter and thickness is 23 mm, 29 mm, and 1 mm respectively. The angle between each rectangular fin is 60°. The distance between each circular fin are 92 mm from mid to mid and the distance of circular fins from start and end of the computational domain is 92 mm.

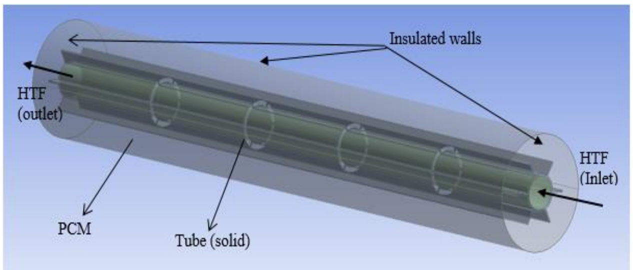

Figure 4 Design of case 4

Meshing

Figure also depicts a view of the generated mesh on all cases. The solid and PCM and water regions in the meshed model have been designated with different colors as different computational domains. Hybrid mesh (tetrahedron and hexahedron) are use in all domain of 3d geometry. Meshing element and nodes are mention in the table below.

Table 1 Meshing elements and Nodes

	Elements	**Nodes**
case 1	1012870	248262
case 2	350290	387618
case 3	357190	397089
case 4	1148363	278010

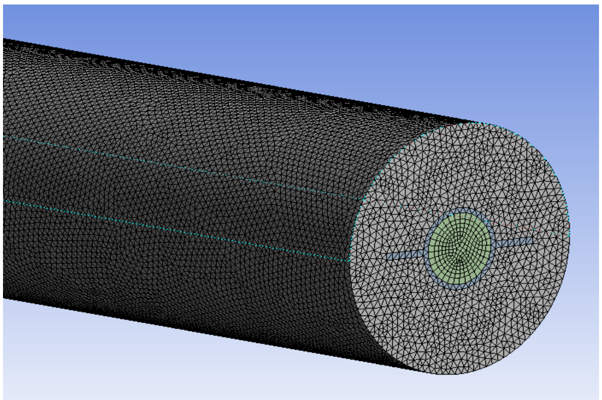

Figure 5 Meshing of computational domain

Boundary Condition

Paraffin wax, or PCM, has been poured into the PCM container. Paraffin wax, an organic PCM, is widely utilised in the literature and industry because of its abundant supply and low cost. It's an excellent option because of its great thermal storage capacity and good operating temperature. The figure provides a schematic representation of the many boundary conditions applied to the model's various borders. With the tube's entrance set to "mass flow rate," a steady stream of cold water with a flow rate of 0.0833 kg/s and a temperature of 303.15 K flows within. The PCM has no external thermal exchange since its exterior walls are insulated. Heat is transferred from the water and the PCM side via the linked walls that line the inside and enclose the fin walls. To simulate air pressure at the tube's exit border, the "pressure outlet" setting has been applied.

The k- turbulence model has been used with a Realizable model and the Enhanced Wall Treatment (EWT) as the wall function to simulate the water flow within the tube. This better captures the near wall phenomenon, such as the heat transfer and boundary layer, and produces more accurate results in the near wall regions. The pressure/velocity coupling has been implemented using the SIMPLE method, the pressure term has been discretized using the PRESTO scheme, and the momentum, energy, and turbulence terms have been discretized using the Second order upwind technique. The convergence conditions for the continuity, momentum, and energy equations are 10^{-4}, 10^{-5}, and 10^{-7}, respectively.

Therefore, paraffin wax was used as the PCM in this study. Water flows within the tube at the enclosure's center, and steel is utilized for the fins and the tube wall, as shown in research by (et al.). In Table, the thermophysical properties of the material used in this study are detailed.

Table 2 Material thermal properties

Material	Properties	unit	Value
Paraffin Wax	Density	kg/m^3	820
	Specific heat	J/kg °C	2000
	Thermal conductivity	W/m °C	0.14
	Viscosity	$Pa.s$	0.033
	Thermal expansion coefficient	1/K	$6*10^{-4}$
	Enthalpy of fusion	kJ/kg	114
	Range of melting temperature	°C	48.3 - 62
	Mushy zone constant		10^5
Water	Specific heat	J/kg °C	4190
	Density	kg/m^3	996
	Thermal conductivity	W/m °C	0.66
	Viscosity	$Pa.s$	0.001
Steel	Specific heat	J/kg °C	502
	Density	kg/m^3	8030
	Thermal conductivity	W/m °C	16.27

Validation

The data obtained by the current simulation has been compared to the published data in the literature [1] in order to evaluate the accuracy of the findings and the numerical approach chosen. The accuracy of the current numerical approach in comparison to the historical data has been assessed with the help of [1]. [1] reported contours of melt fraction at various periods throughout the melting process have been compared with the contours generated by the numerical work in Fig. The numerical simulation findings are shown to closely track the [1] results throughout the whole experimental run, with just a few spots of small discrepancy. The accuracy of current numerical approach is shown clearly proves in Fig. The findings are more qualitatively supported by Figure The melt fraction contours in the numerical studies are found to be quite consistent with those in the prior work. Therefore, the current numerical approach is trustworthy and yields correct findings, as seen in Fig.

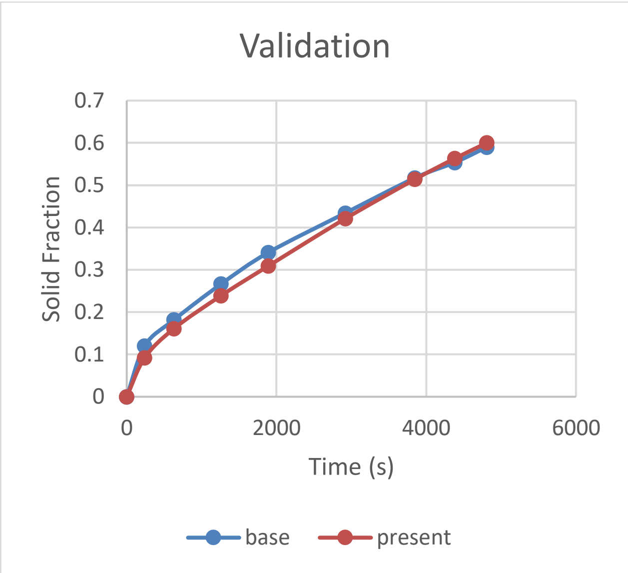

Figure 6 Validation result

Result

Solidification

The solid proportion of PCM during the solidification process is shown in Fig. for several examples with varying numbers of fins. It has been shown that the solid fraction approaches 1 when the finned case reaches a certain form and length. When comparing the performance of different finned cases, it is clear that the case with Double fin (spiral shapes) fares the poorest in terms of heat transmission. Sextuple fins provide the best performance, while the double, quadruple, and quintuple fins all outperform the double fin (spiral shape) instance. The solidification time for the sextuple-fin case is the shortest of all the examples shown in the figure below. This is followed by the quintuple-fin case, the quadruple-fin case, and the double-fin case. The solidification time for double-finned instances is the longest and for sextuple-finned cases it is the shortest. The solidification of double (spiral) and quadruple fins varies only little during the duration of the simulation.

However, in the case of a double fin, the fin is unable to completely occupy the space around the tube due to the smaller number of fins. This has a detrimental effect on heat transmission. When the number of fins is larger, however, the inverse is true, and there is less penetration within the PCM enclosure in return for a more evenly distributed set of fins around the tube's exterior. The overall simulation shows that these scenarios may simultaneously improve heat transport to the near wall areas and the tube's perimeter.

Number of fins and individual fin length are the two variables in question. Heat is distributed more uniformly across the inner tube when more fins are used. As can be seen in Fig., the uniform solidification of energy from the PCM enclosure leads to a more uniform solidification front in the cases with a larger number of fins. On the other hand, fin length is significant because it affects how far the fins can stretch within the PCM enclosure and how thoroughly they can sweep the heat away from all areas, especially the near wall regions, which are the farthest regions from the inner tube. Therefore, longer fins allow for more efficient energy transmission from faraway areas. Heat transport improves across the tube when the number of fins is increased from 2 to 4, despite the fact that the fin length decreases and the fin forms are changed. In fact, effect of fin number prevails over the effect of fin length. However, when increasing the fin number from 4 to 5, the presence of fins on five sides of the inner tube doesn't remain the influence as much as the influence of increasing the fin number from 2 to 4. Hence, increasing the heat transfer area in result solidification time is reduce from case 1 and 2. In case 4, when increasing the fins number from 5 to 6 and additionally adding the 4 discs as a fin. In this case the simulation time of the solidification is shorter than other cases. In the below figure shows that solidification at 5 different time of simulation of each case.

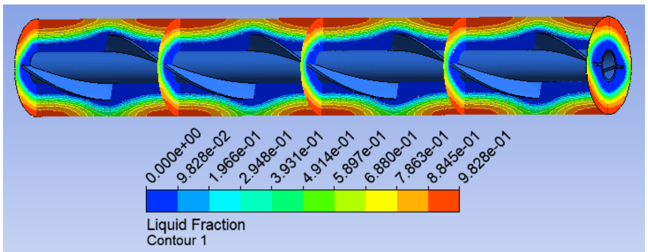

Figure 7 solid fraction of case 1

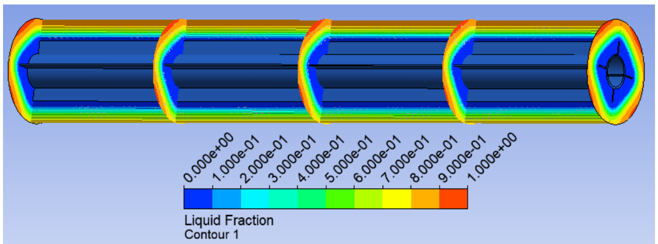

Figure 8 solid fraction of case 2

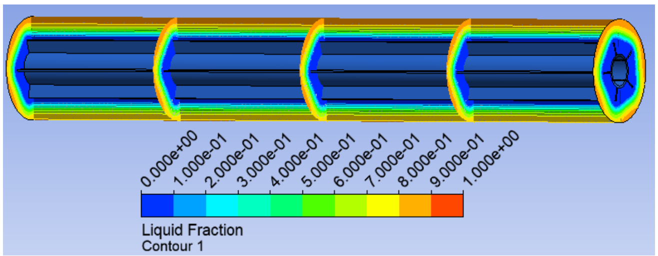

Figure 9 solid fraction of case 3

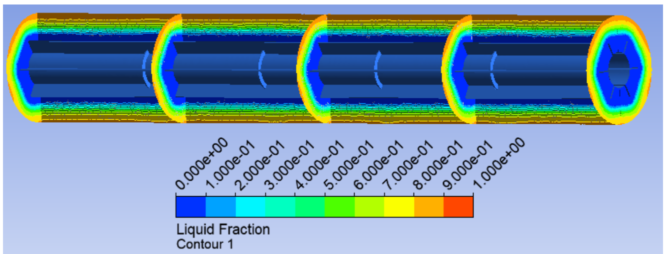

Figure 10 solid fraction of case 4

The data presented here suggests that fin length, in addition to fin number, is a critical design parameter for achieving heat transfer optimization. All cases have uniformly solidification pattern. In figure mention below shows the case 1 and case 2 having a minor difference in the solidification. In this study simulation time is 4000s. in the comparison to the weakest case, the case 2, 3 and 4 have 2%, 9.5%, and 17.8% shorter phase change period respectively.

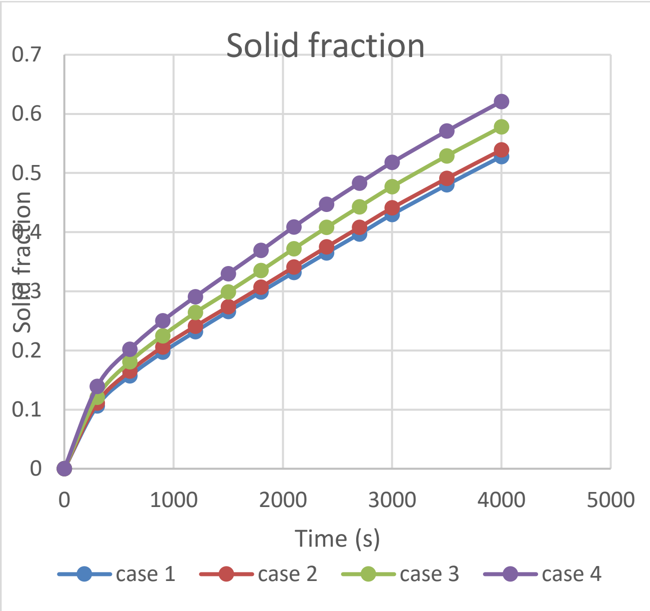

Figure 11 Comparison of the solidification of the all cases

Temperature

At various stages of the solidification process, the figure displays the temperature contours on five transverse and one axial cross section of the PCM container. While a temperature gradient is seen at the start of the heat transfer process, the domain temperature drops more evenly in situations with a greater number of fins because the thermal energy is swept from the surroundings. It's worth noting that in the sextuple-fin scenarios, the fins have a larger impact on the energy depletion. As the heat transfer increases, the temperature gradient throughout the domain increases, making it clear that the performance of each fin has a direct effect on the temperature. It is clear that the superior heat transmission properties of Case 4 cause its temperature to drop more quickly than those of the other cases. Once the PCM's temperature approaches the solidification temperature, sensible energy loss is halted and the solid front begins to grow outward towards the surroundings.

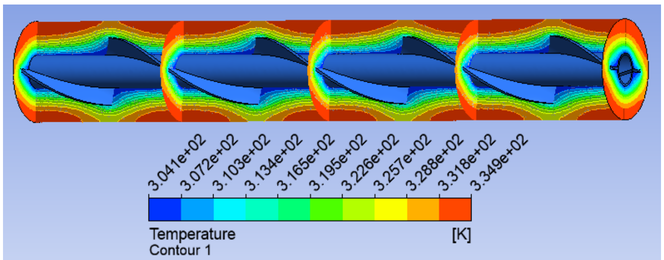

Figure 12 solid fraction of case 1

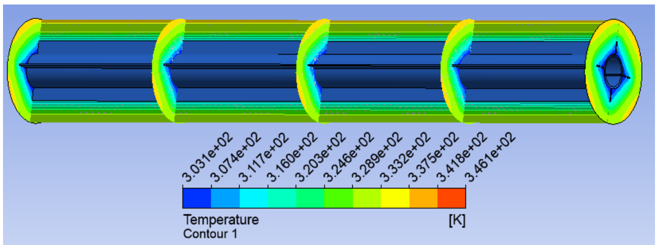

Figure 13 solid fraction of case 2

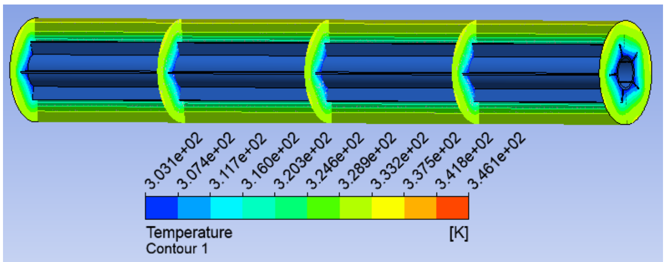

Figure 14 solid fraction of case 3

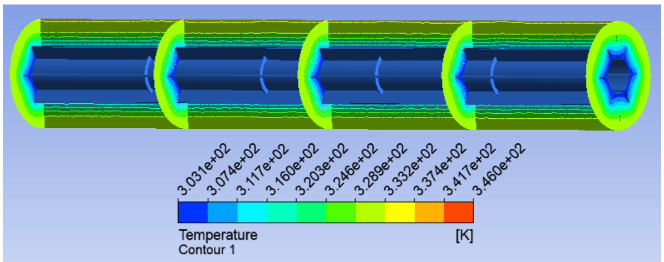

Figure 15 solid fraction of case 4

Conclusion

This research compares the solidification performance of PCM within a tube-shell LHTESS with and without twisted-fins, rectangular plate fins, and rectangular plate fins combined with disc plate fins. We have simulated and compared four alternative fin-count scenarios: double, quadruple, quintuple, and sextuple. In order to represent the phase change process and the water flow within the tube, the enthalpy-porosity method and the k-e turbulent model have been used. The approach has been shown reliable by comparing it to published experimental data. Time, solid fraction, and temperature contours within the domain have been used to analyses the data. Following are some of the most salient findings from the research:

- The presence of fins has a major impact on the phase change process. Furthermore, there is no direct link between the number of fins and phase change acceleration, and both the number and length of fins are important.

- More fins take up more room surrounding the tube, which is good for phase change acceleration.
- The sextuple fin case, also known as case 4, has the greatest performance of all of the finned cases, while the double twisted fin has the lowest.

The solidification time for Case 4 is shorter by 17.8 % compared to Case 1, which has a double twisted fin (the worst finned case).

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