Study on heat transfer enhancement of solar finned tube phase change regenerator

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Abstract. Based on the problems of heat storage in the process of solar energy utilization and the advantages of finned tube heat exchanger, the finned tube is applied into the solar phase change heat accumulator and the heat storage process of the phase change material is simulated numerically. The results show that the use of finned tube instead of smooth tube in solar phase change heat accumulator can effectively improve the heat transfer intensity of the outside of the tube during phase change heat storage, thus enhancing the heat transfer capacity of the whole heat accumulator and shortening the heat storage time. In the simulation range of this paper, the optimum structure parameter of finned tube is: finned outer diameter of \( D_2 = 28 \) mm, fins thickness of \( t = 1 \) mm, fins number of \( c = 13 \), spacing between fins of \( h = 25 \) mm.

1. Introduction

As a new energy, solar energy has attracted more and more attention due to its abundant resources, no need of transportation and no pollution to the environment. However, its low energy density, unstable radiation intensity, intermittent and seasonal, the energy supply and demand sides do not match in time and intensity, which limits its application and needs to be combined with certain energy storage methods. Phase change heat storage device is becoming the preferred choice of energy storage system due to its high heat storage density, high thermal efficiency, stable heat absorption and release temperature and easy control operation. Heat transfer process in phase change heat storage is a very complex boundary movement problem. The phase transition interface moves, and the subsequent latent heat is absorbed or released, which makes the situation more complicated[1].

Nagano[2] designed a simple vertical shell and tube heat exchange unit to store the energy in the low temperature range of 60-90 ℃. The results show that the heat storage capacity of latent heat of phase change can reach 2-2.5 times of the sensible heat storage capacity. Cui Haiting[3] increased the number of tubes on the basis of concentric casings. The comparative analysis shows that the heat storage capacity of the multi tube arrangement model is stronger than that of the concentric tube model. Jiang Jingzhi [4] introduced spirally grooved tubes into solar phase change regenerators, and the heat storage process of spirally grooved tubes and smooth tubes is simulated numerically. The results show that the spiral groove tube can effectively improve the convective heat transfer intensity and the heat transfer capacity in the process of phase change heat storage, and shorten the heat storage time. Peng Lan[5] studied the heat storage unit of casing shell and tube with sodium acetate as phase change material by experiment. The results show that the phase change time of the unit is greatly shortened before and after adding inner longitudinal fins. Ismail[6] discusses the influence of rib length,
thickness and quantity on phase transition process, and concluded that the length and quantity of ribs have a greater influence on phase transition process, while the thickness has a little influence.

2. Model establishment

2.1. Physical model

As shown in figure 1, the regenerator consists of a cylinder and four finned tubes. Hot water flows in the finned tube, and phase change thermal storage material is encapsulated between the outer wall of the tube and the cylinder. Figure 2 is the schematic diagram of regenerator structure. The circular cylinder with external height H =313mm and diameter D=126mm. Four inner pipes with diameter d =13mm are symmetrically distributed along the center. The vertical and horizontal spacing of the center of the four inner pipes L=42.4mm. In this paper, the fin tubes with multiple parameters are compared, the outer diameter of fins is D2=28~36mm, the distance between fins is h=25~78mm, the number of fins is c=3~13, and the thickness of fins is t=1~3mm.

2.2. Selection of phase change thermal storage materials

Paraffin has good heat storage performance, but the thermal conductivity of pure paraffin is small, and the heat storage process is very slow. The paraffin with 10% expanded graphite has strong thermal storage capacity, and its thermal conductivity is much higher than that of pure paraffin. Therefore, paraffin with 10% expanded graphite is used as phase change thermal storage material in this numerical simulation[7].

2.3. Establishment of mathematical model

Fluent software is used to simulate the heat storage process of the heat storage device. The following basic assumptions are used in the numerical calculation[8]:

a) The heat conduction resistance of the inner tube is ignored;
b) Outer cylinder wall insulation;
c) In phase change materials, the fluid in the liquid phase region is incompressible Newtonian fluid;
d) Ignoring the influence of natural convection.

The solidification/melting model used in the Fluent software takes enthalpy as the variable to be determined, and the energy equation phase in the change regionis.

3. Fluent solver settings

3.1. Solution model

In the phase change material region, and the unsteady state, implicit algorithm and separation solver are used to solve the problem. In order to get the convergent solution faster, the SIMPLEC algorithm
is used, the correction coefficient is 0, and the relaxation factor is adjusted appropriately.

3.2. Setting of initial and boundary conditions

The outer wall of the finned tube is set at a constant temperature of 343K.

The boundary condition of phase change thermal storage device is adiabatic.

The initial temperature of the phase change thermal storage material of the regenerator is the ambient temperature (300K).

In addition, in order to get the parameters of temperature and liquid phase ratio in the process of heat storage and release. The monitor must be set before iteration. In this paper, the average temperature and average liquid phase ratio monitor in the phase change area is set to monitor the whole process of heat storage and melting.

4. Results and discuss

4.1. Simulation results analysis of fin tube and smooth tube phase change regenerator

![Figure 3. liquid phase distribution of smooth tube at different time](image)

![Figure 4. liquid phase distribution of finned tube at different time](image)
Figure 3 is the liquid phase distribution of smooth tube at different time and figure 4 shows the liquid phase distribution of finned tube at different time. Finned tube with $t = 1\text{mm}$, $h = 40\text{mm}$, $c = 7$, $D_2 = 28\text{mm}$ and smooth pipe $d=14\text{mm}$. It can be seen from the cloud diagram of liquid phase ratio at different times, with the change of time, the phase change material in the regenerator gradually heats up and melts. The initial heat transfer process mainly occurs around the heat transfer tube, mainly heat conduction. Heat transfer from the heat transfer tube to the phase change material. When the liquid paraffin completely envelops the heat exchange tube. The heat is transferred from the high temperature liquid phase region to the low temperature solid phase region, and the main heat transfer process occurs at the solid-liquid interface. It can be seen from the cloud diagram of liquid phase ratio of finned tube regenerator, because of the existence of fins, the boundary of solid-liquid phase becomes more tortuous, which makes more solid-phase phase change heat storage materials can contact with high-temperature liquid-phase materials, thus enhancing the heat transfer. As can be seen from Figure 5, the liquid phase ratio of smooth tube regenerator reaches 1 at about 10800s and the heat storage process is completed. The heat storage process of finned tube regenerator is completed at about 6800s, and the heat storage time is 37\% shorter than that of smooth tube.

4.2. Analysis of simulation results of finned tube phase change regenerators with different structures

Figure 6 shows the change curve of liquid phase ratio at different time in the process of heat storage of finned tube regenerator with the same fin thickness and fin spacing and different fin outer diameter. It can be seen that with the increase of fin outer diameter, the melting time is shortened. The melting time is about 6900s when the fin outer diameter is 28mm, 6000s when the fin outer diameter is 32mm, and 5800s when the fin outer diameter is 36mm. The above data show that the heat transfer efficiency can be effectively improved by properly increasing the external diameter of fins. This is because the larger fin radius provides a larger heat transfer area, which makes the heat transfer from the high temperature wall to the phase change material more quickly. At the same time, the increase of fin radius also makes the solid-liquid interface more wavy, and the heat of high-temperature liquid phase material can be transferred to the low-temperature solid-phase region more quickly. When the outer diameter of the fin increases to 32mm, the heat transfer efficiency does not increase significantly with the increase of the outer diameter.
Figure 7 shows the change curve of liquid phase ratio at different time in finned tube regenerator with \( t = 1 \), \( D_2 = 28 \), and different fin number of \( c \). When the number of fins is \( c = 3 \), the melting time is about 7800s, and when \( c = 5 \), the melting time is about 7600s. The regenerators with \( c = 7 \) and \( c = 9 \) completed the melting and heat storage process in 6800s and 6500s respectively. When \( c = 13 \), \( h = 25 \), the heat transfer area is the largest, and the melting time was the shortest, about 5800s. Which was the fastest group of experimental parameters. The heat transfer area can be increased by increasing the number of fins as well as by increasing the external diameter of fins. The effect of increasing the number of fins on the solid-liquid interface is different from that of increasing the external diameter of fins, which will increase the wave crest and trough of the wavy interface. This also enhances the heat transfer intensity in the liquid and solid regions. Therefore, increasing the number of fins can improve the heat transfer performance.

5. Conclusion

The fin tube is introduced into the phase change regenerator, and its simulation analysis is carried out to investigate the enhanced heat transfer effect of the fin tube relative to the smooth tube. The effects of fin spacing \( h \), fin diameter \( D_2 \) and fin number \( c \) on the structural parameters of finned tube are discussed. It can be concluded from the analysis of the data that the fin tube has an obvious effect on the heat transfer enhancement of the regenerator, and an appropriate increasing of the number of fins is the best means of heat transfer enhancement. In the simulation range of this paper, the optimal structural parameters of the fin tube are \( D_2 = 28\text{mm} \), \( t = 1\text{mm} \), \( c = 13 \), and \( h = 25\text{mm} \). The zigzag paste area greatly accelerates the moving speed of the solid-liquid phase boundary. Replacing the smooth tube with the finned tube is an effective way to improve the heat storage and release speed of the phase change accumulator. The simulation results of this paper provide a certain data basis for the design of the phase change regenerator in the process of solar energy utilization.

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