Study on enhancing heat transfer performance of spiral groove tube in phase change heat storage for solar energy

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Abstract Based on the energy storage problem for solar energy utilization and the advantages of spiral groove tube heat exchanger, spiral groove tubes were used in the solar energy phase change heat storage. The thermal storage process of heat reservoir was simulated numerically. Firstly, the simulation method and the reliability of the used model are verified experimentally with smooth tube. Using spiral groove tube as water flow pipe and phase change material as heat storage medium, The three-dimensional model of heat storage was built by Gambit software and the grids were divided by ICEM. The heat storage process in the spiral groove tube and smooth tube heat storage were numerically simulated and the heat transfer enhancing effect was investigated. The influence of structural parameters such as groove pitch and groove depth on the heat storage process is simulated numerically and the influence rules are analyzed. The results show that the convective heat transfer intensity and heat transfer capability are enhanced when the smooth tubes are substituted by spiral groove tubes in the phase change heat storage and the heat storage time becomes shorter. In the range of this paper, the optimal structural parameters of spiral groove tube is groove pitch $p=7\text{mm}$ and groove depth $e=0.4\text{mm}$.

1. Introduction
In recent years, Li et al [1] conducted an experimental study on the phase change heat storage of paraffin wax outside the tube, and obtained the phase change heat storage law of the concentric casing heat accumulator. Cui et al. [2] proposed an improvement scheme based on the heat accumulator structure of Li et al.: It can effectively increase the convection intensity of phase change material in the phase change process and improve the efficiency of heat transfer to reasonably increase the number of inner tubes of the casing accumulator.

Spirally grooved tubes, also known as threaded tubes, are used to enhance the heat transfer of gases or liquids in tubes and to enhance the boiling of liquids in tubes or the condensation of steam outside tubes [3-4]. Spirally grooved tubes have a good heat transfer performance. Many scholars have studied the heat transfer and flow resistance of spirally grooved tubes [5-8]. Figure 1 is a schematic diagram of spirally grooved tubes, where $d$ is the pipe diameter, $2t$ is the groove width, $p$ is the pitch, $e$ is the groove depth, and $\beta$ is the helix angle[9-10]. The effects of different structural parameters on heat transfer enhancement performance of phase change heat storage were studied.

2. Model establishment

2.1. Physical model
Figure 2 is the schematic structural diagram of a phase change heat storage device designed. \( H=313\text{mm}, D=126\text{mm}, L=31\text{mm} \). Enhance overall heat transfer performance when fluid passes through spirally grooved tubes [11].

In this paper, the structural parameters of the spiral grooved tube with structural parameters of \( p=6\text{mm}, e=0.5\text{mm} \) and \( d=13\text{mm} \) are selected as the benchmark. Other parameters are shown in Table 1 and Table 2. The heat transfer fluid in the inner tube is water, and the phase change material is encapsulated between the inner tube and the shell. In order to prevent the heat loss of the whole shell, the outer wall of the shell needs to be wrapped with insulation material. In order to enhance the energy storage capacity of phase change materials, many scholars have done a lot of theoretical and experimental research [12]. Therefore, the phase change material used in the device is paraffin with 10% expanded graphite, and its physical parameters are shown in Table 3 [13]. Grid independent verification is done. The grid size is 3 and the time is not long 1s.

Table 1. Structural parameters of spiral groove tube at different groove depth.

| Structure | Diameter | Groove depth | Slot distance | Section number |
|-----------|----------|--------------|---------------|---------------|
| 1         | 13       | 0.4          | 6             | 48            |
| 2         | 13       | 0.6          | 6             | 48            |

Table 2. Structural parameters of spiral groove tube at different groove pitch.

| Structure | Diameter | Groove depth | Slot distance | Section number |
|-----------|----------|--------------|---------------|---------------|
| 1         | 13       | 0.5          | 5             | 57            |
| 2         | 13       | 0.5          | 7             | 41            |

Table 3. Physical property parameter of phase change material with 10% expanded graphite.

| Status     | Melting point(K) | Dissolution heat(kJ/kg) | Density (kg/m3) | Specific heat (kJ/(kg/K)) | Thermal Conductivity (W/(m·K)) |
|------------|------------------|-------------------------|-----------------|--------------------------|-------------------------------|
|Solid phase | 328              | 235                     | 890             | 1.9                      | 1.5                           |

2.2. Establishment of Mathematical Model
The Fluent software is used to numerically simulate the heat storage process of the heat storage device. The assumptions used in the numerical calculation are [14-15]:

- paraffin wax is pure and homosexual;
- The accumulator model ignores the wall thickness of the inner tube, not considering heat conduction of the tube;
- ignore the wall thickness of the outer cylinder and the heat loss of the outer wall surface;
- phase change material, the fluid in the liquid phase region is an incompressible Newtonian fluid
- Consider the influence of natural convection in the pipe, natural convection is laminar
Solidification/thaw model used in the Fluent software takes enthalpy as the variable to be determined, and the energy equation phase in the change region is [16].

3. Fluent parameter setting

The Solidification&Melting model is used in the phase change material area, and the turbulence model is opened in the inner pipe fluid area. The unsteady state, hidden test and separation solver are used to solve the problem. In order to get the convergent solution more quickly, SIMPLEC algorithm is adopted and relaxation factor is reduced appropriately. The flow rate of hot fluid is 0.4m/s and the initial temperature is 343K. Pressure-outlet is the standard atmospheric pressure. The boundary condition of the outer wall of the accumulator is adiabatic. The interface between the phase change material zone and the inner tube wall is coupled. The initial temperature of the accumulator is the ambient temperature (300k).

4. Results and discusses

4.1. Analysis of simulation results of spiral grooved tube and light tube phase change heat accumulator

When the melting time is 1000s, the temperature distribution of the accumulator at the outlet section of the hot water in the tube is shown in the nephogram of Figure 3(a) and Figure 4(a). It can be seen that the minimum temperature of phase change area in spirally grooved tube accumulator is 320 K at 1000s, and that in smooth tube accumulator is 323 K. The temperature of phase change area in smooth tube accumulator is higher than that in spirally grooved tube accumulator. The heat transfer of phase change material in spirally grooved tube accumulator is small at the initial stage of melting. Figure 3(b) and Figure 4(b) are temperature distribution nephograms of accumulators at 2000s. In the smooth tube accumulator the temperature of the outer layer of the tube is 326K, and the inner layer is still similar to that of 1000s. In the threaded grooved tube accumulator, the temperature of the phase change material region is higher than 336 K, and the melting and temperature rise area in the phase change material region of the spiral grooved tube accumulator is obviously larger than that of the smooth tube phase change accumulator. With the increase of time, the phase change material near the tube wall melts gradually. Figure 3(c) and Figure 4(c) are temperature distribution nephograms of accumulators at 3000s. In the spirally grooved tube phase change accumulator model, the temperature in the phase change region of the accumulator is above 340 K, and the phase change materials have all melted. It shows that the heat transfer capacity of the threaded grooved tube phase change accumulator is stronger than that of the smooth tube accumulator.

Figure 5 can be seen from the Figure that the overall change trend of the liquid rate curve of the smooth tube and spirally grooved tube phase change heat accumulator is uniform. However, the melting rates and rules of the phase change materials in the two phase change accumulators are obviously different. Before 1500s, at the same melting time, the liquid phase ratio of smooth tube accumulator was higher than that of spiral grooved tube accumulator. After 1500s, the increase rate of liquid phase ratio of smooth tube accumulator decreases sharply, while that of spirally grooved tube accumulator increases rapidly. When it reaches 2000 s, the liquid phase ratio of spirally grooved tube accumulator is higher than that of smooth tube accumulator. About 2400s, the liquid phase ratio of spirally grooved tube accumulator reaches 100%, while that of smooth tube is only about 70%.

The fluid resistance of the spirally grooved tube is much greater than that of the smooth tube at the initial time, and the fluid flow is unstable, so the heat transfer coefficient is low. With the prolongation of time, the unique groove design inside the spirally grooved tube makes the boundary layer outside the spirally grooved tube unstable, which increases the thermal disturbance inside and outside the tube, and generates eddies to thin the boundary layer. At the same time, the heat transfer mode of hot water and phase change material in the tube is mainly convective heat transfer. The convective heat transfer intensity of spirally grooved tube accumulator is higher than that of smooth tube accumulator.
Therefore, the growth rate of liquid phase ratio of spirally grooved tube accumulator is larger than that of smooth tube accumulator.

![Figure 3. Distribution of Temperature in the spiral groove tube phase change heat storage at different time](image)

![Figure 4. Distribution of Temperature in the smooth tube phase change heat storage at different times](image)

![Figure 5. Liquid phase fractions curve at different times in the spiral groove tube and smooth tube heat storage](image)

4.2. Analysis of Simulation Results of Spiral Grooved Tubes with Different Structures

It can be seen from the Figure 6 that the change trend of liquid phase ratio in the heat storage process of three spiral grooved tube heat accumulators with different pitches is same, and the liquid phase ratio gradually increases with the increase of time. The changes of liquid phase ratio of the three structures with time before 100s are same approximately. After 100s, with the increase of time, the liquid fraction of spirally grooved tube accumulator with pitch of 7 mm is higher than that with pitch of 5 mm and 6 mm. When it reaches about 1500s, the liquid phase ratio of accumulator with pitch of 7mm increases slowly, while that of spiral grooved tube accumulator with pitch of 5mm and 6mm increases rapidly. The total melting time of the phase change material of the heat accumulator with a pitch of 7mm is about 2000s, while the total melting time of the phase change material with pitches of 5mm and 6mm is 2200s. During the whole heat storage process.
The numerical simulation process is unsteady. Before 100s, the hot water had not reached a steady flow state. The heat transfer mode of hot water and phase change materials is mainly heat conduction, and the heat transfer is little affected by different structures. Therefore, in the initial stage of heat transfer, the heat transfer efficiency of spiral grooved tube heat accumulator with large pitch is higher than that of heat accumulator with small pitch, thus the liquid phase ratio is higher. At about 1500s, the flow of hot water in the tube is stable gradually, the heat exchange between hot water and phase change material is more and more obviously affected by the structure of the heat exchange tube. The smaller the pitch, the greater the disturbance received by the flow of fluid on the hot water side, the thinner the boundary layer, and the better the heat transfer. The optimum spacing parameter is 7mm.

Figure 6. Liquid phase fractions curve of different groove pitch at different times in the spiral groove tube heat storage

Figure 7. Liquid phase fractions curve of different groove depth at different times in the spiral groove tube heat storage

Figure 7 is the change curve of liquid phase ratio with time in the heat storage process of the spiral grooved tube accumulator when the groove depth of the spiral grooved tube is 0.4mm, 0.5mm and 0.6mm respectively. Before 1300s, the liquid phase ratio of the spiral grooved tube accumulator with a groove depth of 0.4mm and 0.6mm coincides and is higher than that of the accumulator with a groove depth of 0.5 mm. Between 1400s and 1600s, the liquid phase ratio of accumulator with groove depth of 0.6mm increases slowly, while that of spiral grooved tube accumulator with groove depth of 0.4mm and 0.5mm increases rapidly. The liquid phase ratio increases rapidly after 1600s. The time required for complete melting is 1500s, 2200s and 2100s, respectively.

Although the water flow in the tube has not reached a stable flow state at the initial time, the deeper the groove depth, the greater the resistance, and the smaller the heat transfer quantity between hot water and phase change material. Therefore, before 1300s, the liquid phase ratio of spiral grooved tube accumulator with groove depth of 0.5mm is lower than that of accumulator with groove depth of 0.4 mm. At the same time, the deeper the groove depth is, the larger the heat exchange area is. At the initial stage of heat storage, the phase change material area is solid, and the heat transfer mode around the spiral groove tube is mainly heat conduction. Its heat transfer is more affected by the heat exchange area, resulting in the liquid phase ratio of the spiral groove tube accumulator with a groove depth of 0.6mm before 1300s is higher than that of the accumulator with a groove depth of 0.5 mm. After 1400s, the fluid in the pipe gradually reaches a steady flow state and the phase change material region is gradually melting near the spirally grooved tube wall, changing from solid state to liquid state. The heat transfer mode between phase change material and the outer wall of spiral grooved tube was mainly convective heat transfer. The convective heat transfer of the fluid on both sides was gradually enhanced under the influence of the structural parameters of spiral grooved tube. Therefore, after 1600s, the liquid phase ratio curves of spiral grooved tube accumulator increase rapidly with three different groove depths. The time for the phase change materials of three spiral grooved tube heat accumulators with different groove depths to completely melt is 1800s, 2200s and 2000s respectively. In the simulation range of this paper, the groove depth of spiral groove tube is 0.4 mm.
5. Conclusion
The influence of spiral groove pitch $P$ and groove depth $e$ on heat transfer enhancement process in the heat accumulation is investigated and the calculation results are analyzed. The spirally grooved tube is chosen as the flow passage of heat transfer medium, and the smooth tube is compared. Under the same conditions, the absolute melting time is shorter than that of smooth tube. The pitch and depth of spirally grooved tube have different effects on different stages of heat storage process. In the initial stage of melting, pitch and groove depth have little influence on the heat storage process, and the liquid phase ratio is not much different from the melting process of the optical tube heat storage device. After 1500s, the pitch and groove depth have more influence on the heat transfer capacity of the spiral tube heat storage process. In the simulation range of this paper, the optimum structural parameters of spirally grooved tubes are: the pitch $P=7$ mm and groove depth $e=0.4$ mm, respectively. The simulation results in this paper provide some data for the design of phase change heat accumulator in the process of solar energy utilization.

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