Research on Optimization of Tube Structure of Phase Change Heat Storage Device

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Abstract. In view of the low heat transfer efficiency of the phase-change heat storage device and the inability to quickly respond to temperature changes, the fluid tube structure in the heat storage device was optimized, and four types of structures: circular structure, square structure, regular hexagon structure and regular triangle structure were compared and studied. Numerical simulation and optimization analysis are carried out on the pipes with the same thermal fluid circulation area but different sizes. The simulation results show that the triangular structure has the highest heat transfer efficiency in the initial stage of heat transfer due to the longest perimeter, and the heat transfer efficiency is positively correlated with the perimeter under the heat transfer mode in which heat conduction is the main body. Under the heat transfer mode dominated by convective heat transfer in the later stage of melting, the time required for the complete melting of phase change materials outside the square tube is the shortest.

Keywords: Phase change heat storage; enhanced heat transfer; structure optimization; numerical simulation

1. Introduction

As a renewable energy, solar energy contains huge energy and has broad application prospects, but it has low energy density, unstable radiation intensity, intermittent and seasonal characteristics. In order to solve the instability of solar energy, it is often combined with heat storage technology [1]. Compared with sensible heat storage and chemical reaction heat storage, phase change heat storage has the advantages of large phase change latent heat, low cost, wide phase change temperature range, simple and flexible system device and convenient use [2]. Phase change heat storage technology has attracted the attention of scholars all over the world.

Phase change materials (PCM) store and release energy in high temperature and low temperature environment respectively, which can alleviate the mismatch of time and space between energy supply and demand of the system to a certain extent, and improve the beneficial energy utilization of the system [3]. References [4,5] point out that convective heat transfer is dominant in the process of heat storage, while heat conduction is dominant in the process of heat release; The simulation results of the two models compared in reference [6,7] show that when the thickness of paraffin material is greater than 40mm, the natural convection of liquid phase has a great influence on the melting process.

At this stage, scholars at home and abroad have carried out a series of work on phase change heat storage, mainly focusing on the research on heat transfer and mechanism during material phase change. The research on structure is mainly focused on single-stage shell and tube, and the research methods include experiment and numerical simulation [8-10]. Although the experimental method is intuitive, there are difficulties in the measurement process, which is not conducive to systematic analysis. At the
same time, due to the limitations of human and material resources, the experiment cannot be comprehensive. In contrast, the numerical simulation method is more convenient and effective, and has been used in the research of energy-saving fields such as solar heat utilization, heating and air conditioning [11-13]. The numerical simulation of enhanced phase change heat storage device with two-dimensional models of circular tube, square tube, regular triangular tube and regular hexagonal tube is established by using numerical simulation software. Paraffin [14,15] has the advantages of high latent heat of phase change, no supercooling, good stability, no phase separation and corrosivity, low price and easy availability, so use paraffin as phase change material [16]. In the simulation of phase change process, considering the influence of liquid convection, Different inner tube shapes have an effect on the heat transfer intensity in the phase change zone. The optimal heat transfer rate types in different shapes of tubes are compared by numerical simulation. In this paper, the melting situation of the phase change area outside the inner tube of the phase change accumulator will be studied. Based on the method of finite element analysis, the temperature distribution, liquid phase rate and phase interface position in the process of paraffin melting will be monitored to verify the enhanced heat transfer effect of the inner tube of various structures relative to the circular tube, so as to provide a reliable basis for finding an optimal heat transfer tube type.

2. Establishment of Model

2.1. Physical Model
VYSHAK N R analyzed and compared the melting process of materials in containers with different shapes. It was concluded that the melting rate of materials encapsulated in shell and tube containers was the fastest under the same conditions [17]. As shown in figure 1, paraffin is encapsulated between the tube and the shell, the heat transfer fluid flows from left to right along the inner tube, and the fluid heat exchanges with paraffin through the inner tube wall. Paraffin was used to study this paper, and its physical parameters are shown in table 1. The shell is made of copper tube, which has good heat transfer effect, so the wall thickness can be ignored. 500mm long shell and tube phase change heat storage device is adopted. In order to ensure a certain heat flux of heat transfer fluid, four different shapes of inner tubes with the same flow area are set. The specific structure is shown in figure 2 below, and the specific dimensions of each structure are shown in table 2 below.

| Temperature/K | Density $\text{kg/m}^3$ | Specific heat $\text{J/(kg} \cdot \text{K)}$ | Thermal conductivity $\text{W/(m} \cdot \text{K)}$ | Melting potential $\text{J/kg}$ |
|---------------|-------------------|----------------|----------------|-------------------|
| Melting point: | 319               | 2500           | 0.118          | 14190             |
| Freezing point: | 315               | 1700           | 0.27           |                   |

Figure 1. Shell and tube heat storage device model.
Table 2. Pipe sizes of different structures under the same inner pipe area.

|                        | Round (diameter) | Square | Regular triangle | Regular hexagon |
|------------------------|------------------|--------|------------------|-----------------|
| Inner tube length /mm  | 10.000           | 8.862  | 13.468           | 5.498           |
| Perimeter /mm          | 31.415           | 35.448 | 40.404           | 32.988          |
| Outer tube diameter /mm| 50               |        |                  |                 |

2.2. **Mathematical Model**

The melting & solidification model in the software is used to simulate the working conditions of phase change materials. The control model includes continuity, momentum and energy equation, and the general form is expressed by formula (1) [18].

$$\frac{\partial \left( \rho \mu \phi \right)}{\partial x} + \frac{\partial \left( \rho \nu \phi \right)}{\partial y} = \frac{\partial}{\partial x} \left( I_s \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( I_s \frac{\partial \phi}{\partial y} \right) + S_s$$  \hspace{1cm} (1)

Where: \( \rho \) is the density, kg/m\(^3\); \( u \) and \( v \) is the velocity of x-axis and y-axis respectively, m/s; When \( \phi \) is \( u \) and \( v \), m/s.

2.3. **Thermodynamic Model**

From the perspective of energy, all the energy required for the melting of materials is provided by the hot fluid in the tube. The instantaneous heat release of the fluid in the pipe is shown in formula (2):

$$Q_w = \omega c_w \left( T_{out} - T_m \right)$$  \hspace{1cm} (2)

The total heat released by the hot water in the pipe within a certain period of time is shown in formula (3):

$$Q_{w,all} = \int_0^t \omega c_w \left( T_{out} - T_m \right) dt \approx \sum_{i=0}^{n-1} \omega c_w \left( T_{out,i} - T_{in,i} \right) \Delta t_i$$  \hspace{1cm} (3)

where \( \Delta t_i = t_{i+1} - t_i \)

Ideally, the whole device is insulated, and fluid heat is completely absorbed by phase change materials. Firstly, the heat of hot water is transferred to the inner tube through heat conduction. Then, the paraffin on the outside of the inner tube melts due to heat conduction on the tube side, forming a thin liquefaction layer on its surface. Finally, the remaining materials are accelerated to be melted through the combination of convective heat transfer and heat conduction until they are completely liquefied.

In terms of energy, the total energy of paraffin heat storage \( Q_t \) consists of three parts, namely, sensible heat energy of solid paraffin \( Q_{pcm,sol} \), melting latent heat of paraffin phase change \( Q_s \), and sensible heat energy of liquid paraffin \( Q_{pcm,liq} \), as shown in formula (4).

$$Q_t = Q_{pcm,sol} + Q_s + Q_{pcm,liq}$$  \hspace{1cm} (4)
Among them

\[ Q_{pcm, sol} = mc_{sol} (T_{fus} - T_{wo}) \]  \hspace{1cm} (5)

\[ Q_L = mL \]  \hspace{1cm} (6)

\[ Q_{pcm, liq} = mc_{liq} (T_{in} - T_{fus}) \]  \hspace{1cm} (7)

Where: \( c_{sol} \) is the specific heat capacity of solid paraffin, J/(kg·K); \( T_{fus} \) and \( T_{wo} \) are the melting and solid temperature of paraffin, K; \( m \) and \( mL \) are the mass of paraffin, kg; \( L \) is the latent heat of phase transformation of paraffin, kJ/Kg.

After the material outside the inner tube is liquefied, convective heat transfer will occur

\[ Q_{dl} = Sh(T_{t, j} - T_{p, j}) \]  \hspace{1cm} (8)

Where \( S \) is the surface area of pipes with different structures; \( h \) is convective heat transfer coefficient W/m²K; \( T_{t, j} \) is the temperature outside the pipe; \( T_{p, j} \) is the temperature of phase change material after paraffin liquefaction, K; \( I \) is the time; \( J \) is the axial position.

Ideally, all the heat released by water will be absorbed by the material. Therefore, according to the instantaneous energy expressions of equations (8) and (7), the expression (9) for analyzing the temperature of liquid paraffin at the next time can be obtained, which provides a certain basis for numerical simulation.

\[ T_{p, i+1, j} = T_{p, i, j} + \frac{Sh(T_{t, i, j} - T_{p, i, j})\Delta t}{m_{c_{liq}}} \quad T_{p} \in [T_{fus}, T_{liq}] \]  \hspace{1cm} (9)

3. Comparison of Numerical Models

When the heat storage device is placed horizontally, the initial temperature is 298.15K and the heating wall temperature is 373.15K, the cloud diagram of liquid phase rate change of the device with circular inner tube structure is shown in figure 3 below. Considering the effect of natural convection of liquid, the melting of paraffin area starts from the upper part of the circular tube, extends to both sides after most of the upper area melts, and then expands to the lower part of the circular tube. The melting of the lower part of the circular tube is relatively slow, and there is a melting dead zone, so it takes longer. The melting trend of the simulation is the same as that of the simulation results in document [19] and the numerical simulation results in document [20], which can verify the correctness of the simulation.

![Figure 3. Liquid phase rate nephogram of circular tube heat storage device at 50s and 100s.](image)

4. Simulation Results and Analysis

As shown in the melting cloud, the phase boundary moves continuously during the melting process of phase change area. The change of liquefaction area of tubes in different structures with time at 200s is
shown in figure 4, and the temperature change cloud diagram of tubes in different structures at 400s is shown in figure 5. It can be seen from figure 4 and figure 5 that the melting dead zone will appear in the melting process of the phase change region, and the time required for complete melting is longer, but generally speaking, the heat storage process is very fast.

Figure 4. Liquid phase rate nephogram of inner tube heat storage devices with different structures at 200s.

Figure 5. Cloud diagram of temperature distribution of tube heat storage devices with different structures at 400s.

The change of liquid phase rate with time in the phase change area outside the inner tube of the four shapes in the first six seconds is shown in figure 6. It can be seen that the heat conduction rate is closely related to the circumference of the inner tube of different shapes under the area. Before 4.3 seconds, the melting rate of the triangular inner tube with the longest circumference is the fastest, followed by the quadrilateral, followed by the triangle, and the slowest is the circular structure. After 4.3 seconds, the quadrilateral tube gradually replaces the triangular tube to achieve the fastest. It can be considered that the later convective heat transfer gradually occupies the dominant heat transfer role under the action of gravity and buoyancy.

Figure 6. Variation curve of liquid phase rate of tubes with different shapes with time in the first six seconds.

The variation curves of liquid phase rate in the phase change area outside the four different shapes of heat exchange tubes in the first 1500 seconds are obtained by simulation calculation, as shown in figure 7. Among the four kinds of heat storage devices with inner tube, the melting rate in the phase change area of square structure is the fastest to complete the melting state, followed by the device with
hexagonal structure, and the time to complete the melting is longer, and the heat storage time of inner
tube with triangular structure is the longest.

It can be seen from figure 7 that the heat storage efficiency of the inner tube with triangular structure
is the worst because the convective heat transfer generally starts at the opposite direction of gravity, that
is, directly above the heat pipe. The circumference of the inner tube with triangular structure is the
largest among the four structures with the same area, and the heat conduction efficiency is the highest.
However, since the upper heat transfer starts from one point, the convective heat transfer effect is the
worst, So it takes the longest.

![Figure 7](image)

**Figure 7.** variation curve of liquid phase rate with time for four different structure tubes.

5. Conclusion
(1) For the four kinds of heat storage devices with inner tubes with different structures, when the
cross-sectional area of the inner tube is the same, the heat exchange effect of the square inner tube is
the best, and the time required for the complete melting of phase change materials is about 40% higher
than that of the circular tube, but the change of the inner tube structure will increase the complexity of
the process and bring a certain increase in cost.

(2) For four kinds of heat storage devices with inner tubes with different structures, when the
cross-sectional area of the inner tube is the same, the initial melting rate of the material is related to the
circumference of the inner tube. The longer the circumference is, the stronger the heat conduction
effect is, and the faster the melting rate is.

(3) With the melting of phase change materials, convective heat transfer gradually becomes the
dominant heat transfer, and starts at the end of the inner tube away from the gravity direction. The
melting starts at the end away from the gravity direction. The top and area of the tube in the equilateral
triangle structure are the smallest, and the convective heat transfer is the worst, so the time required
for complete melting is the longest.

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