Research on Temperature Distribution of Single Tank Using Molten Salt for Thermal Storage

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Abstract. The temperature distribution of the storage tank with molten salt as the heat storage medium during the discharge process is introduced in the article. In order to analyze the temperature distribution of molten salt in a storage tank and improve the heat exchange effect, the exothermic process of a single thermal storage tank equipped with an immersion heat exchanger was studied. Fluent software was used in the analysis to study the influence of different heat transfer areas, structures and layouts on temperature distribution by means of numerical simulation. The results show that if the heat exchange area is increased, the temperature uniformity and heat transfer speed in the tank will strengthen. By reducing the tube diameter of heat exchanger, the temperature difference in the axial direction can be reduced. When the heat exchanger is arranged above, the temperature stratification in the tank will be improved, and the heat exchange will be more sufficient.

1. Introduction
In view of the current energy development trend, vigorously developing renewable energy is essential to the energy transition, and it is also conducive to solving the problem of climate change [1]. Studies have shown that the energy structure of China is characterized by "high carbon". Coal as the main energy consumption structure has further led to the destruction of ecological environment [2]. The research of Fernández-García et al. [3] and Gong et al. [4] provides proof that solar energy has become an important subject for research in various countries in the world due to its advantages such as clean and pollution-free. Solar power technology has gradually developed into a renewable energy technology with great potential. Thermal storage technology is an important technology with high energy efficiency that can make the existing resources rationally used and the use of renewable energy optimized [5]. Widely used in the field of solar power generation, the technology of molten salt energy storage has been recognized [6]. At present, in the medium and high temperature molten salt heat storage technology, double-tank heat storage method and Thermocline heat storage are widely used [7]. The two-tank heat storage system includes a cold tank and a hot tank, both of which are required to be able to store the molten salt. The utilization of single-tank heat storage has been widely studied by scholars, which can effectively reduce costs and save space. Among the various forms of single-tank systems, the thermocline heat storage as a hot issue is the focus of research. Compared with traditional dual-tank heat storage systems, it can reduce investment costs by 20% -37% [8]. However, how to effectively control the separation of hot and cold fluids during operation, which is regarded as the main difficulty in the practical application of the thermal storage of the inclined stratosphere, is an urgent nodus.
In order to reduce the investment and operating costs caused by heat storage, a single thermal storage tank equipped with an immersion heat exchanger was designed. With the decrease of molten salt temperature, the method of increasing the heat exchange area is adopted make up for the problem of insufficient heat exchange. The effects of different factors on the temperature distribution during the exothermic process of molten salt were studied using numerical simulation.

2. Research methods

2.1. Principle of single thermal storage tank
In this paper, a single thermal storage tank using molten salt is designed. The heat storage and release process of molten salt is carried out in the tank. The heat storage tank in this paper is a cylindrical tank with a u-shaped multistage heat exchanger to ensure the generation of steam with constant temperature. The heat storage medium adopts a ternary molten salt composed of 53% KNO3-7% NaNO3-40% NaNO2. During the heat release process, as the heat release time increases, the temperature of the molten salt decreases. In this paper, a four-stage heat exchanger is proposed, through which the controller adjusts the heat transfer area according to different molten salt temperatures to meet the user's requirements. The heat exchanger is a salt-water heat exchanger, in which the forced flow occurs when the cold fluid flows in the tube driven by the power of the pump, while the molten salt uses the density difference caused by its own temperature change to form natural convection. The heat storage device mainly uses off-peak electricity to store heat at night and release heat during the day. In the heat storage stage, the molten salt is heated for 6 hours from the initial temperature of 200°C to the final state of 400°C. Since the exothermic process is the main working process and research content of the molten salt system, the temperature distribution in the exothermic process of molten salt in the heat storage device is simulated, and the influence of different factors on the temperature distribution is analyzed.

2.2. Research methods

2.2.1. Establishment of simulation model. The single tank heat storage device is a cylindrical tank with a volume of 3m, a tank radius of 1.24m and a height of 2.48m. Figure 1 shows its profile. To simplify the calculation, the heat transfer problem is simplified into a model, which is a two-dimensional, unsteady and variable laminar convection heat transfer model.

![Figure 1. Sectional view of a single tank with immersed heat exchanger](image)

Only the two-dimensional flow and heat transfer in the axial and radial directions of the tank are considered. The molten salt is considered as laminar flow, and there is no flow and heat transfer along the circumference. The outer wall of the tank body is considered as an adiabatic wall. Other physical property parameters are fixed values, except for density and viscosity. The fluid in the multi-stage heat exchanger is an incompressible Newtonian fluid. The fluid absorbs heat without dissipation. The fluid flow direction only considers the axial flow and the radial velocity component is ignored. The dimensions of the multi-stage heat exchanger are shown in Table 1. In terms of condition setting, the heat exchange tube surface is simplified as a variable negative internal heat source, in which the heat flux density is embedded in the shared library using UDF and connected to the Fluent solver. During the heat exchange process, the conservation equations of mass, momentum, and energy are satisfied.
The initial state in the tank is set to the state when the molten salt heat storage is completed, and the internal temperature tends to be the same as 673.15K.

| Name                             | Tube inner diameter (m) | Tube outer diameter (m) | Total length (m) | Height (m) |
|----------------------------------|-------------------------|-------------------------|------------------|------------|
| First stage heat exchanger       | 0.023                   | 0.025                   | 11.20            | 0.79       |
| Second stage heat exchanger      | 0.023                   | 0.025                   | 13.65            | 0.96       |
| Third stage heat exchanger       | 0.023                   | 0.025                   | 17.80            | 1.30       |
| Fourth stage heat exchanger      | 0.023                   | 0.025                   | 25.75            | 1.89       |

2.2.2. Simulation. Based on the establishment of the device model and the analysis of heat transfer, the creation of a two-dimensional mathematical model of the heat storage tank was completed. The simplified structure model of the storage tank was established using GAMBIT software. In the analysis, the tank body was divided into two regions, namely the molten salt region and U-shaped heat exchanger region. The main flow area adopts quadrilateral structured grid, while the U heat exchanger area adopts triangular unstructured grid. The SIMPLE algorithm is adopted for the solution of pressure and velocity coupling, and the Boussineq hypothesis is adopted for the buoyancy caused by the temperature difference in the axial direction of the molten salt. As the heat release time increases, the density of the molten salt changes, resulting in a density difference, which causes a flow under the action of gravity. A situation is generated, which is reflected in a certain discrepancy in temperature distribution along the vertical direction. Therefore, studying the temperature distribution law in the tank has a great effect on improving heat storage performance. FLUENT15.0 software was used to simulate and analyze the temperature distribution inside the storage tank during the exothermic process, so as to analyze the movement characteristics of the natural convection of molten salt. In addition, the influence of different heat transfer areas, heat exchanger structures and different layouts on temperature distribution were analyzed.

3. Results and analysis

3.1. Effect of different heat exchange areas on temperature distribution

The temperature distribution rules of the first stage and fourth stage heat exchangers were explored to analyze the effect of different heat exchange areas on the temperature distribution in the tank. The nephograms showing temperature distribution in the thermal storage tank with heat release duration of 30 minutes, 60 minutes and 90 minutes were analyzed. The changes of the axial temperature in the tank with time for the first-stage and four-stage heat exchangers are shown in Figure 2 and Figure 3, respectively.
The conclusion that the radial temperature variation of the first-stage heat exchanger is not obvious can be drawn from Figure 2, but the temperature change along the vertical direction is large. The temperature above the tank is high and evenly distributed, while the temperature below is low and there is obvious stratification. As the heat release time increases, the stratification of the temperature below becomes more and more obvious. The reason for this phenomenon is the heat transfer between the molten salt and the cold fluid near the u-shaped tube, which dissipates heat rapidly, with a lower average temperature and a larger density. Therefore, the molten salt flows downward under the action of gravity, while the surrounding high-temperature molten salt moves upward under the action of buoyancy and lift. The mixing of fluids forms natural convection, which intensifies the heat exchange to the point of forming more intense temperature stratification. The molten salt in the upper area is far away from the U-tube heat exchanger, which is less affected by natural convection, and the upper molten salt temperature is higher and the distribution is more uniform. As can be seen from Figure 3, the average temperatures of the fourth stage heat exchanger are 506K, 489K and 472K when the heat is released for 30 minutes, 60 minutes and 90 minutes, respectively. Comparing the temperature field distribution of the first-stage heat exchanger, the uniform temperature distribution in the upper part is broken, the obvious temperature stratification in the middle part disappears, and the temperature stratification in the tank is improved. The increase in the heat exchange area of the fourth-stage heat exchanger plays a role, which makes the heat transfer area between the upper and lower fluids increase, the disturbance is strengthened, and the heat exchange in the axial direction is strengthened, so the internal temperature distribution is more uniform.

3.2. Effect of different structures on temperature distribution

The structure of the U-shaped heat exchanger includes tube length, tube diameter, the radius of curvature and so on. To study the effect of different tube inner diameters on the heat transfer performance, the heat exchange conditions of the first-stage heat exchangers with inner diameters of 21mm, 23mm, and 25mm were simulated under the premise of keeping the heat exchange area unchanged, and the internal temperature of the tank was studied.
Figure 4 shows the axial variation of temperature under different inner diameters during heat release. The conclusion that the temperature of molten salt varies greatly along the axis can be clearly obtained. When the results with inner diameters of 0.025m, 0.023m, and 0.021m are analyzed, the maximum temperature difference values in the axial direction of the molten salt correspond to 87K, 86K, 84K, and the corresponding average temperatures are 634K, 631K, 626K, respectively. It can be seen that when the inner diameter is 0.021m, the average temperature is the lowest, the maximum temperature difference in the axial direction is relatively lowest, and the temperature distribution is relatively uniform. Therefore, reducing the inner diameter of the heat exchanger achieves the result of lowering the average temperature and weakening the temperature difference in the axial direction. This is because the structure of the U-shaped tube will affect the temperature distribution and velocity distribution of the molten salt. Reducing the inner diameter of the U-shaped tube heat exchanger can increase the number of winding turns and increase the height of the heat exchanger, so as to accelerate the heat transfer between molten salt and cold fluid and make the heat transfer more complete. This inducement reduces the average temperature of molten salt and minifies the axial difference.

3.3. Effect of different layouts on temperature distribution

To study the influence of different heat exchanger layouts on the rule of heat transfer and the temperature distribution, two situations in the tank with heat exchangers arranged above and below was analyzed. Figure 5 and Figure 6 respectively reflect the temperature distribution of the heat dissipation for 10 minutes, 20 minutes and 30 minutes under the two arrangements.

The simulation of the heat exchanger placed underneath is shown Figure 5. When the heat was released for 10 min, 20min, 30min, the temperature existed in the range of 669K~646K, 667K~643K, 666K~632K, and the corresponding average temperature is 663K, 657K, 651K, respectively. At this time, obvious temperature stratification existed in the upper and lower layers. Two zones are formed in the tank. The zone above the u-tube heat exchanger has a higher molten salt temperature, and the zone below the u-tube heat exchanger forms an obvious temperature stratification, with a large temperature change, but the temperature along the radial direction in the tank is inconspicuous. The working conditions of the U-shaped tube heat exchanger arranged above are shown in Figure 6. When the
exoergic time was 10min, 20min, 30min, the temperature exist in the range of 670K~660K, 658K~650K, 650K~640K, and the corresponding average temperature is 663K, 655K, 646K, respectively. It is found that there are obvious stratification phenomena in both the radial and axial directions of the molten salt temperature, which is caused by the cold fluid entering and leaving the tank from above to heat exchange with the molten salt. The molten salt for heat exchange with the cold fluid is mainly located in the upper region, where the molten salt temperature decreases rapidly and the corresponding density increases. The molten salt above moves downward, while the molten salt with higher temperature moves upward under the action of buoyancy and lift, resulting in stable natural convection in the tank. By comparison, it can be found that by placing the heat exchanger on the upper side, the average velocity of the molten salt increases, and the heat transfer is more adequate. By adopting this arrangement, the temperature stratification phenomenon is well suppressed as well as the temperature distribution gradually tends to be consistent. Therefore, the temperature stratification in the tank is well improved when the heat exchanger is placed above.

4. Conclusions
Analyzing the research of this article, the following conclusions can be summarized.

1) Compared with the first-stage heat exchanger, the contact area between the four-stage heat exchanger and the molten salt is larger, which intensifies the disturbance between the upper and lower part of the fluid, strengthens the heat exchange in the axial direction, and effectively improves the temperature distribution.

2) Reducing the inner diameter of the heat exchanger can reduce the average temperature of molten salt in the tank, reduce the axial temperature difference and make the temperature distribution more uniform.

3) Compared with arranging the heat exchanger in the lower part, the arrangement of the upper part can make the temperature distribution more uniform and improve the temperature stratification phenomenon.

4) The research results provide a reference for understanding the thermal performance of the thermal process and further optimizing the structure.

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