Study of Heat Transfer Performance of Insulating Layer of Molten Salt Storage Tank

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Abstract. Molten salt storage tank is one of the core equipment of solar thermal power station. The design of thermal insulation layer of molten salt storage tank plays an important role in its safety and economy. It is of great commercial value and academic significance to study the heat transfer performance of the insulating layer of molten salt storage tank. In this paper, the heat transfer models of molten salt storage tank, external insulation layer and tank foundation are established. The temperature distribution and heat loss of the tank are studied. The influence of the insulation nails on the heat transfer performance of the insulation layer is analyzed. The results show that the maximum heat loss lies in insulation layer of the tank wall. Besides, the thickness of the insulating layer greatly influences the temperature drop of molten salt and the time required for steady-state heat transfer. Reasonable setting the length of insulation nail can effectively reduce the surface temperature and heat loss of the insulating layer of molten salt storage tank.

1. Introduction

At present, CSP(Concentrating Solar Power) has become strategic emerging industries supported by many countries. CSP has been expected to solve the problem of energy storage in the field of new energy. Compared with photovoltaic power generation, the energy storage technology of photothermal power generation can avoid the problem of no power generation at night and rainy days, and can achieve continuous power generation and peak load regulation.

Thermal storage of molten salt storage tanks is the key to continuous and stable power generation for CSP. The molten salt storage tank is the core equipment of the heat storage system, and its safety and economy are of vital importance to the CSP. Currently, both trough and tower CSP use molten salt heat storage technology. Because molten salt has a higher freezing point \[1-3\], the poor thermal insulation performance of molten salt storage tanks not only affects the economics of CSP stations, but also causes irreversible damage to molten salt storage tanks. Therefore, improving thermal insulation performance of the molten salt storage tank is meaningful and important.

Many scholars have made relevant basic research on the heat dissipation performance of molten salt storage tanks, which provide a reference for the thermal insulation of molten salt storage tanks. Fischedick et al\[4\] carried out a finite element analysis of the heat storage system of the ANDASOL power station. The results showed that there was a high energy loss at the lower edge of the molten
salt storage tank. Therefore, the detailed design of the lower edge has a great impact on the overall heat loss of the molten salt storage tank and localized solidification of the molten salt. Chen et al.[5] calculated the heat transfer performance of the bottom insulation layer of the storage tank, the influence of storage tank design temperature and ambient temperature on the heat transfer performance of tank bottom insulation layer was studied. The results showed that the heat transfer capacity of the insulation layer and the wind speed of the pipeline increased, when the design temperature increases. Zaversky [6] et al studied two-tank heat storage system. In their work, a transient molten salt storage tank model was established, and the heat dissipation performance of the storage tank was studied. Li and Du [7-8] carried out the design, modeling and analysis of a small double-tank heat storage system. The results showed that the temperature of the molten salt tank does not change significantly over time. Besides, the temperature drop of the edge and the bottom is great, and the contribution of the side-wall insulation layer to the insulation performance is greater than that of the top insulation layer. The heat loss increases with the increase of the storage temperature, and the height diameter ratio has little effect on the heat loss. The above studies mostly use simplified models to calculate the heat loss. The simulated results are different from the actual situation. Therefore, a heat transfer model of molten salt storage tanks, external thermal insulation layers, and storage tank foundations is established in this paper, and the factors that affect the heat loss of storage tanks are comprehensively considered. Besides, the influence of the thermal insulation structure (thermal insulation nails) on the heat loss is considered.

In this paper, the heat transfer performance of a molten salt storage tank is studied using CFD(Computational fluid dynamics) methods. The weak points of the heat loss of the molten salt storage tank are analyzed, and investigated and discussed the performance of the thermal insulation layer. The influence of thermal insulation nails on the heat transfer performance of thermal insulation layer is studied. The results provide theoretical basis for the design of thermal insulation layer and the estimation of natural temperature drop of molten salt storage tank.

2. Model description

2.1 Geometric model

The high temperature molten salt storage tank in the double tank molten salt heat storage system of the tower CSP is modeled. The main parameters of the molten salt storage tank are shown in Table1. The geometric model of molten salt storage tank is shown in Figure 1. The storage tank adopts a self-supporting vault structure. The top of the tank and the outer surface of the tank wall are covered with aluminum silicate fiber felt as a thermal insulation layer. The thermal insulation layer at the bottom of the tank is composed of sand cushion layer, heat-resistant concrete layer, shale ceramsite layer and ordinary concrete layer.

| Item                  | High temperature molten salt storage tank |
|-----------------------|-------------------------------------------|
| Average diameter / mm | 25030                                     |
| Shell height / mm     | 12500                                     |
| Tank top factor       | 1.2                                       |
| Design temperature / °C | 580                                      |
| Operating temperature / °C | 565                        |
| Wall thickness / mm   | 30/25/19/14/12/12                       |
| Tank material         | SA240 TP347H                              |
| Design insulation thickness / mm | 800          |
2.2 Heat transfer model

2.2.1 Thermal conductivity of insulation. The heat insulation layer on the outside of the molten salt storage tank transfers heat by means of heat conduction. Although the tank roof is a vaulted structure, the tank roof coefficient is relatively small and can be approximated by flat plate heat conduction. The bottom insulation layer of the tank is composed of a multi-layer structure, which can also be considered as one-dimensional multi-layer flat plate heat conduction. The expression of heat transfer is shown as follow.

\[ Q_1 = A \cdot \frac{t_1 - t_{n+1}}{\sum_{i=1}^{n} \frac{1}{\lambda_i} \delta_i} \tag{1} \]

The wall of the molten salt storage tank can be considered as one-dimensional multilayer cylinder wall heat conduction. The expression of heat transfer is shown as follow.

\[ Q_2 = \frac{2\pi A \Delta t}{\sum_{i=1}^{n} \frac{1}{\lambda_i} \delta_i \rho_i} \tag{2} \]

Where A is the heat transfer area; \( \delta \) is the thickness of the heat transfer medium; \( \lambda \) is the thermal conductivity; \( r \) is the radius of the cylinder.

2.2.2 Convection heat transfer inside molten salt storage tanks. The convective heat transfer between molten salt and the inner surface of the storage tank, can be expressed by the dimensionless Nusselt number (Nu). Nusselt number (Nu) is usually a function of the Prandtl number (Pr) and the Grashof number (Gr), that is:

\[ N_u = c \cdot (Gr \cdot Pr)^n \tag{3} \]

\[ Gr \cdot Pr = \frac{g \beta \theta_w L^3}{\nu^2} \tag{4} \]

\[ P_r = \frac{\nu}{\alpha} \tag{5} \]

Where L is the characteristic dimension; g is the acceleration of gravity; \( \theta_w \) is the characteristic temperature; \( \beta \) is 1 / T; \( \nu \) is the kinematic viscosity of air; \( \alpha \) is the heat diffusivity.

The natural convection between molten salt and tank wall can be calculated in Equations(6,7).

\[ N_u = \frac{hL}{k} = 0.68 \cdot P_r^{0.3} \cdot \frac{Gr^{0.4}}{(0.952 + P_r)^{1.4}} \quad 10 < Gr \cdot P_r < 10^8 \tag{6} \]

\[ N_u = \frac{hL}{k} = 0.13 \cdot \left( P_r \cdot Gr \right)^{0.5} \quad Gr \cdot P_r > 10^8 \tag{7} \]

Convection heat transfer exists between the molten salt in the tank and the upper gas phase space. Convection heat transfer can be expressed in Equations(8,9).

\[ N_u = 0.54 \cdot \left( P_r \cdot Gr \right)^{0.5} 10^5 < Gr \cdot P_r < 10^7 \tag{8} \]

\[ N_u = 0.15 \cdot \left( P_r \cdot Gr \right)^{0.5} 10^7 < Gr \cdot P_r < 10^{10} \tag{9} \]

The natural convection between the molten salt and the bottom of the tank can be expressed in Equation(10).

\[ N_u = 0.27 \cdot \left( P_r \cdot Gr \right)^{0.5} 10^5 < Gr \cdot P_r < 10^{10} \tag{10} \]
2.2.3 Radiation heat transfer inside molten salt tank. There are three surfaces of the radiant heat transfer in the molten salt tank, namely, the molten salt surface, the tank top inner surface and the tank wall non-wet inner surface. The tank top inner surface and the tank wall non-wet inner surface are stainless steel. Their emissivity is set to 0.35. The molten salt surface can absorb almost all incident radiation, which can be approximated as a black body. Its emissivity is set to 0.95. The surface of the molten salt and the inner surface of the tank can be approximated as two parallel disks, and the angle coefficient can be expressed in Equation (11).

\[
F_{1-2} = \frac{1}{2a^2} \cdot \left( d^2 + a^2 + b^2 - \sqrt{(d^2 + a^2 + b^2)^2 - 4a^2 b^2} \right)
\]  

(11)

In this article, the molten salt liquid surface and the tank top stainless steel surface can be regarded as concentric circles with the same radius, so:

\[
a = b = r_i
\]  

(12)

3. Numerical method and verification

3.1 Meshing model

In order to the high calculation accuracy and save calculation time, a combination of structured grid and unstructured grid is chosen in this paper. Besides, a dense structured grid was used in key areas such as the tank wall, its nearby insulation layer and tank bottom insulation layer. At the same time, considering the material characteristics, the thermal insulation layer of the foundation is divided layer by layer based on different materials. The total number of grids in the calculation domain is about 1 million, shown in Figure 2.

![Fig. 2 Meshing model of molten salt storage tanks](image)

3.2 Boundary conditions

The heat dissipation loss of the tank is studied by CFD-Fluent. The ambient temperature is set to 4.3℃ according to the local average temperature. There is lots of radiation heat transfer among the tank wall, the top of the tank and the bottom of the tank. The radiation model adopts the S-S model. The temperature of molten salt in the given molten salt storage tank is 565℃. As the compressive strength of concrete foundation significantly decreases at high temperature, forced ventilation pipe is used to take away heat in the project and keep the temperature of concrete foundation not more than 90℃. Therefore, the constant wall temperature boundary condition is set at the bottom of the tank to calculate the transient heat dissipation process of the high temperature molten salt tank.

3.3 Simulation verification

Based on the theory of heat transfer, the insulation layer lies in the outside of the tank wall, and its structure is similar to the thin-wall cylinder. The theoretical value of temperature in the insulation layer is calculated as shown in Figure 3. The results show that the maximum error between the theoretical value and the calculated value is 3.37%, verifying the accuracy of the numerical results.
4. Results and discussion

4.1 Effect of thermal insulation thickness on heat loss of molten salt storage tank

The thickness of the insulation layer is set to 800mm, the initial molten salt temperature is 565℃, and the height of the molten salt liquid level is fixed to 6m. The temperature distribution of molten salt after natural cooling at ambient temperature for 12 hours is shown in Fig. 4 (a) and Fig. 4 (b). It can be seen that the temperature distribution of molten salt in the tank is uniform, and the maximum temperature is about 554 ℃. The temperature in the insulation layer of tank top and tank wall is uniformly reduced to the ambient temperature, which shows that the insulation layer effectively reduces the heat loss of molten salt tank.

Figure 4 (c) shows the temperature distribution of molten salt in the tank. The temperature distribution of molten salt is in the range of 531.9-554.9℃. Due to the large temperature gradient at the joint of tank bottom and tank wall, the temperature there is relatively low, with a difference of 23℃ from the maximum temperature. The reason for this phenomenon is that the edge plate directly contacts the bottom concrete after protruding a certain distance from the tank wall. As shown in Figure 4(d), the temperature at the outer edge of the edge plate is still as high as 427 ℃, which causes the heat loss increased significantly. Therefore, when setting a thermal insulation layer for a molten salt storage tank, the attention can be paid to strengthening the insulation at the joint between the bottom of the tank and the wall, for reducing the possibility of local freezing of the molten salt.
Figure 4 Temperature distribution of molten salt storage tank

The height of molten salt has a certain effect on the heat loss of the storage tank. The heat loss at the tank wall increases as liquid level height increases, and the heat loss at the tank top and the bottom basically remains unchanged with the increase in liquid level[7]. The average design level of the storage tank as the calculation condition is taken. Table 2 shows get the heat loss of the bottom, wall and top of the tank after the natural cooling from the initial state to 12 hours.

It can be known from Table 2 that the heat loss of the tank wall is the largest, accounting for about 47.1% -53.9% of the total loss. Thus, the thickness of the thermal insulation layer of the tank wall greatly influences on the overall thermal insulation effect of the storage tank. With the increase of the insulation thickness, the heat loss power of the tank wall and the tank top significantly reduces. But the heat loss at the bottom of the tank has little effect. Increasing the thermal insulation thickness can improve the thermal insulation effect of the molten salt storage tank. The thicker the thermal insulation layer is, the smaller the influence of heat loss becomes, and the proportion of heat dissipation loss at the bottom of the tank increases. Therefore, to improve the thermal insulation effect, we should not only study the thickness of the thermal insulation layer, but also consider measures to reduce heat dissipation at the bottom of the tank.

Table 2 Heat loss of molten salt storage tanks

| Heat loss /kW | Insulation thickness /mm |
|--------------|--------------------------|
|              | 400         | 600    | 800   | 1000  |
| Tank top     | 110.92      | 102.19 | 92.65 | 89.49 |
| Tank wall    | 209.08      | 183.46 | 158.14| 139.67|
| Tank bottom  | 68.15       | 67.27  | 67.27 | 67.69 |
| Total heat loss | 388.15 | 352.92 | 318.06| 296.85|

4.2 Change of temperature of molten salt with time

Figure 5 is a curve of the average temperature of molten salt with time. Due to the large temperature difference among the molten salt, the thermal insulation layer and the concrete foundation in the initial state, the molten salt began to heat the thermal insulation layer and the concrete layer, and the temperature sharply dropped. As the heating process continues, the molten salt storage tank system achieves stable heat transfer, and the temperature drop of the molten salt tends to be linear. When the insulation thickness is 800mm, the time to reach stable heat transfer is about 6 hours, and the temperature drop of the molten salt is maintained at 0.12°C per hour. Thus, when the insulation thickness decreases, the shorter the time to reach steady state heat transfer will decrease and the temperature drop of molten salt in the steady state will go up.
Figure 5 Temperature curve of molten salt

Figure 6 Temperature curve of gas phase space of molten salt liquid level

Figure 6 shows the temperature distribution curve of molten salt liquid level and upper gas phase space with time. It can be seen that as time goes on, the temperature of gas-phase space is more and more close to the molten salt temperature, but there is always a certain temperature difference between gas-phase and molten salt temperature. After 26h, the temperature difference between gas-phase and liquid-phase is only 2.7 ℃, and then basically remains unchanged. It can be seen that the insulation layer on the top of the tank can effectively reduce the heat dissipation on the top of the tank, making the temperature of the top space close to the molten salt temperature.

4.3 Effect of thermal insulation nail on heat loss of tank wall

The insulation nails are welded on the outside of the tank wall at a certain distance to support the weight of the insulation layer. This will increase the heat loss of the tank wall and affect the insulation effect of the tank wall. For the high temperature molten salt storage tank with 800mm wall insulation layer thickness, four different insulation nails (0mm, 750mm, 780mm, 800mm) are set to calculate the heat loss, and the influence of insulation nails on the heat loss of the tank wall is studied.

Figure 7 Temperature distribution of the outer surface of the thermal insulation layer under different thermal insulation nail lengths
Table 3 Effect of thermal insulation nail on heat loss of tank wall

| Insulation nail length/mm | Outer surface temperature of insulation layer /℃ | Surface heat loss of insulation layer/(w/m²) | Heat loss promotion rate |
|---------------------------|--------------------------------------------------|---------------------------------------------|--------------------------|
| 0                         | 7.38                                             | 61.52                                       | 0                        |
| 750                       | 7.44-10.44                                       | 68.08                                       | 10.67%                   |
| 780                       | 7.39-16.89                                       | 68.76                                       | 11.76%                   |
| 800                       | 7.41-37.58                                       | 70.56                                       | 14.69%                   |

Figure 7 shows the temperature distribution on the outer surface of the insulation layer under different nail lengths. When the insulation nail passes through the insulation layer, the maximum temperature of the outer surface can reach 37.5 ℃. When the length of the nail is 780mm, 750mm and there is no nail, the maximum temperature of the outer surface is 16.89 ℃, 10.44 ℃ and 7.38 ℃, respectively. This shows that the surface temperature can be effectively reduced by reducing the length of insulation nails. The heat loss of tank wall increased by 10.67% - 14.69% compared with that without heat preservation nails. It can be seen that the heat loss of the tank wall is greatly influenced by the insulation nails. Therefore, the influence of insulation nails on the insulation performance should be fully considered in the design. If the structure allows, shorter insulation nails should be used as far as possible to improve the insulation effect of molten salt storage tank.

5. Conclusion

The geometric model and heat transfer model of the high-temperature molten salt storage tank insulation layer are established in this paper. The temperature distribution of the high-temperature molten salt storage tank under natural cooling is analyzed. The influence of the thermal insulation thickness on the heat loss of the molten salt storage tank is studied. The change law of molten salt temperature with time in high temperature molten salt tanks is explored. The influence of thermal insulation nail length on the heat loss of tank walls is compared, and the following conclusions have been drawn:

1) The heat loss at the junction between the tank wall and the tank bottom is the largest, causing the molten salt temperature at that location to differ by more than 23℃ from the average temperature. Properly setting the insulation layer can optimize the insulation at the connection.

2) With the increase of insulation thickness, the heat loss power of the tank wall and tank top is obviously reduced, but it has no effect on the heat loss of the tank bottom. The influence of the heat loss become weak with the increase of thickness of insulation layer. The optimization design of the thermal insulation layer and the reduction of the heat dissipation at the bottom of the tank can enhance the thermal insulation effect of the heat storage tank.

3) The time required for steady-state heat transfer decreases with the decrease of the thickness of the insulating layer. The temperature drop of molten salt increases with the decrease of the thickness of the insulating layer. The temperature difference between the upper gas phase space of molten salt and molten salt decreases with the increase of time, and finally it is stable at 2.7 ℃. The insulation layer on the top of the tank can effectively reduce the heat dissipation on the top of the tank, so that the temperature of the top space is close to the molten salt temperature.

4) Compared with the working condition without insulation nails, the heat loss of the tank wall increases by 10.67% - 14.69%. Decreasing the length of insulation nails can enhance the insulation effect of the molten salt tank.

Acknowledgments

This work was supported by science and technology project of Power Construction Corporation of China Ltd (Project No.: DJ-ZDZX-2018-02).

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