Simulation and experimental research on the phase change heat storage tank of Solar thermal power generation system

Jinghui Song¹, Hui Yuan², Jianhua Deng¹

¹Guangdong Electric Power Research Institute Energy technologies Ltd. Guangzhou 510080, China; ²North China Electric Power University, Baoding 071000, China

Abstract. A mathematical model was set up to simulate the heat transfer process and performance of the molten salt phase change heat storage tank of the solar power and cooling system driven by Solar thermal power generation system. Meanwhile, an experiment is also built to validate the model. For this thermal storage tank, mature industrial intermediate-temperature ternary salt is selected. ANSYS software is utilized to simulate the performance of heat transfer process of phase change based on the enthalpy method. Heat transfer characteristics and factors are analyzed according to the results of the simulation and experiment. The results shows that the data coming form the simulation and the test fit each other well and the simulation is acceptable.

1. Introduction

With the continuous development of solar thermal utilization, as well as the inherent instability and low-density of solar energy, storing excess solar energy timely will make the maximum use of it. Meanwhile, for solar thermal power generation, it is vital to maintain the generator running smoothly [1].

Phase change thermal storage, with its safe and stable performance, high thermal storage density, economic features, accesses to a wide range of research and application. Anica Trp et al [2] established a phase change heat exchange model of paraffin and water in the application of FORTRAN programming language, verify the accuracy of the model in comparison of the experimental test; Hamid Ait Adine, Hamid El Qarnia [3] gave the method to simulate the phase change energy storage by using shell and tube heat exchanger structure, analyzed the key factors affecting the thermal storage; X. Li et al [4] simulated the characteristics of the phase change material in the structure of the packed bed by using ANASYS software and the experiment data.

In this paper, the performance of the heat storage tank equipped with solar collector system performance simulation and experimental study. The numerical calculation method was used to carry out the simulation calculation. Based on the simulation results, the heat transfer process and mechanism of the heat storage tank were analyzed. The simulation was verified through experiments. In this paper, simulation and experiment on the solar collector system with a thermal storage tank are carried out to analyze the heat transfer process of the storage tank.
Table 1. Design parameters of the thermal storage tank

| Relevant parameter                             | Values |
|-----------------------------------------------|--------|
| Fluid’s inlet temperature(℃)                 | 180    |
| Fluid’s outlet temperature(℃)                | 160    |
| Refrigerator’s rated power (kW)              | 50     |
| Refrigerator’s COP                           | 0.6    |
| Refrigerator’s COP                           | 0.6    |
| Phase change temperature (℃)                 | 142    |
| Sensible temperature difference (℃)          | 40     |
| Latent heat (kJ/kg)                          | 75.3   |
| Density (kg/m³)                              | 1978   |
| Specific heat capacity (kJ/kg·K)             | 1.424  |

The heat storage tank is mainly used to provide heat for the absorption chiller’s running, the heat storage efficiency is 85%, while 0.6 is the COP of the single-effect cycle of the chiller. The energy amount for the exothermic process is obtained from the formula 1,

\[ Q_{out} = \frac{50 \times 2 \times 3600}{0.6 \times 0.85} = 0.705 \text{MJ} \]  

(1)

The mass of the molten and the volume of the storage tank is given by the physical properties of the molten salt,

\[ m = \frac{Q_{out}}{C_p T + H} = 5250 \text{kg} \]  

(2)

Where, \( T \)— temperature difference of sensible heat transfer, K; \( H \)—latent heat, kJ/kg; \( C_p \)—specific heat capacity, kJ / kg·K.

The density of the salt is about 1978 kg/m³, the volume is 2.64 m³. The volume of the thermal storage tank volume is about 2.9 m³ considering a 10% margin.

2. Theoretical Analysis

The heat exchange process of the molten salt phase change has the following characteristics. First, the phase change temperature is not a constant temperature point, but a phase transition range, in this temperature range where the ternary salt are molten at the same time and does not exist a clear solid-liquid phase change interface; second, the phase change interface has been in constant progress, leading to the unsolvable equation which are descriptions of the problem. Meanwhile, due to the complex of the natural convection in the heat transfer and the influence the fluid and the heat resistance of the wall bring about, a more reliable thermal storage system model must be put forward by numerical simulation method. The following assumptions were made about this heat storage tank model:

1) the fluid in the tube is incompressible and the flow is laminar;
2) molten salt material is uniform and isotropic;
3) heat storage tank surface insulation;
4) take 142~145 ℃ as molten salt phase transition zone;
5) The enhancement of heat transfer due to natural convection of molten salt during phase transformation is equivalent to the increase of thermal conductivity of molten salt in molten state. The mathematical model of the heat transfer model is described, divided into hot fluid and molten salt material. For a hot charge fluid, which flows through the heat exchanger tube, the flow equation includes the mass conservation equation, the momentum conservation equation, the energy conservation equation, as follows.

Mass conservation equation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

Momentum conservation equation:

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} - \rho g
\]

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho v^2)}{\partial x} + \frac{\partial (\rho vv)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} - \rho g
\]

\[
\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho ww)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}
\]

Energy conservation equation:

\[
\frac{\partial (\rho T)}{\partial t} + \frac{\partial (\rho u T)}{\partial x} + \frac{\partial (\rho v T)}{\partial y} + \frac{\partial (\rho w T)}{\partial z} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right)
\]

Where, \( \rho \) is the fluid density, \( T \) is the temperature, \( u, v, w \) respectively expressed as the three directions of the flow velocity component, \( p \) is the pressure, \( g \) is the acceleration of gravity, \( k \) is the thermal conductivity, \( \tau \) is the stress tensor between the fluid micelles.

As for the molten material, select enthalpy method \(^{[6]}\) to characterize the heat transfer process of phase change heat storage material. The liquid fraction \( \gamma \) is 1 when the molten salt is liquid, 0 when solid. Fraction between 0 and 1 means that the enthalpy of the material is \( \gamma \) times the solid phase enthalpy.

The boundary conditions are set as follows:

Initial conditions: at \( t = 0 \), the temperatures of fluid and the salt are given according to the design parameters for the tank.

Boundary conditions:

at \( t > 0 \),

inlet: \( T_f = T_{in}, u = v_{in}, v = 0, w = 0 \)

outlet: \( \frac{\partial T_f}{\partial x} |_{out} = 0, \frac{\partial w}{\partial z} |_{out} = 0 \)

Tank’s wall: \( \frac{\partial T_f}{\partial x} |_{shell} = 0, \frac{\partial T_f}{\partial y} |_{shell} = 0, \frac{\partial T_f}{\partial z} |_{shell} = 0 \)

3. Experimental Research

3.1 Model building

Numerical experimental model of heat storage tank is established by using ANSYS software. Fig. 1 shows the mesh model completed in ICEM-CFD.

Here we simulate a typical hot filling process in order to describe the thermal process. In this case, water inlet temperature is set to 180 °C, the initial temperature of the tank is 100 °C. The molten salt are all solid, while the wall’s insulated. At \( t = 0s \), hot water begins to flow into the tank.

According to the numerical model proposed above, establish an experimental model for the verification of simulation and the physical body is shown in Fig. 2.
3.2 Simulation and experimental results

Through the simulation, the temperature of the heat storage tank is shown in Fig. 3. Seen from the figure, the temperature of the tank’s center rises rapidly in the first few minutes and appears evident phase change characteristics later when the temperature maintains in a relative stable value. Meanwhile, the temperature on the edge of the tank rises slowly. During the early period of the heat charging process, the main manner for heat transfer is conduction. But in the later period, nature convection plays an obvious role and the temperature difference between the salt on the edge and salt on the center is increasing, both of which improve the heat transfer from hotter salt to colder salt. The phase transient temperature range is about 138-143°C. And at last the temperature of the whole salt trends to be steady where the temperature difference between the center and edge remains 25°C.

Compared with the results from simulation, the temperature obtained from experiment fit well with the simulation curve except that the rising speed of the experiment curve is slower than that in simulation in all the process. The reasons causing the error are as follows. One is that the boundary condition is impossible to be insulated completely which is easy to meet in the simulation. So there is some inescapable heat loss on the tank’s wall leading to the low temperature increase. Another is that the equivalence using the improvement of thermal conductivity to instead the effect of the molten salt’s nature convection in the simulation will speed up the salt’s temperature rising.

Finally, further study on the impact that water of different inlet temperature brings to the heat charging process is done. Fig.4 shows the temperature curve of the heat storage tank which indicates the higher the temperature of the fluid is, the greater the slope of the initial range of the curve is. When the inlet temperature is high, the temperature rise rate increases, time where the salt begins to melt can be relatively reduced, which means the entire charging time decreases evidently.
In addition, when the flow rate of the fluid is 0.05m/s, 0.15m/s, 0.25m/s, corresponding numerical calculations are carried out. The total heat transfer coefficient is obtained. The values are 58.9W/m²-K, 59.6W/m²-K and 60.6W/m²-K, whose difference is not significant.

4. Conclusion

In this paper, the heat transfer process of the ternary salt that occurs in a heat storage tank was simulated, the results are verified by experiment. The heat charging process can be divided into three stages according to the phases state of the salt. The first stage is the heat transfer in solid state, where heat conduction is dominant. The second stage is phase change period when part of the solid salt changes into liquid molten salt, the rest remains solid. The third stage is a period where most of the salt is molten to liquid and conduction and convection coexist; In addition, when the inlet flow rate is constant, the higher the inlet temperature is, the stronger the heat transfer is. When the inlet flow’s temperature is steady, increasing the flow rate of the fluid merely contributes to enhancement of the heat transfer for the thermal resistance mainly exists on side of the salt. Therefore, on the one hand, this method can be used to guide the design of similar heat storage tank thermal storage structure; on the other hand, the design of the collector system is of great significance, such as determining the system heat collection capacity, heat collection temperature, storage time and other key parameter.

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