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Analysis and Research on Anti-Condensation Performance of Molten Salt Control Valve

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ABSTRACT

During the molten salt flow process in the molten salt control valve, localized temperatures may fall below the solidification point of the molten salt, leading to partial solidification within the valve body and consequently affecting the flow performance of the valve. This study conducts temperature and flow field simulations under various operating conditions to investigate the potential occurrence of solidification during the molten salt flow process. Specifically, it analyzes whether the molten salt temperature drops below its solidification point under three extreme scenarios: fully open valve position, sudden valve closure with residual molten salt remaining in the valve body, and abrupt flow interruption due to pipeline equipment failure. The research findings demonstrate that molten salt solidification does not occur in any of these three scenarios, providing valuable reference data for subsequent optimization design of molten salt control valves.

KEYWORDS

Molten Salt Solidification; Molten Salt Control Valve; Solidification Temperature; Optimized Design.

1. INTRODUCTION

The molten salt regulating valve is a key equipment in the molten salt pipeline of a photothermal power station. During the operation of the photothermal power generation system, if the flow of molten salt in the flow channel of the molten salt regulating valve drops below the molten salt's freezing point, the molten salt will solidify, causing the flow channel of the molten salt regulating valve to be clogged with molten salt crystals. Therefore, the analysis and research on the anti-freezing performance of the molten salt regulating valve have become a hot topic in recent years. In recent years, scholars at home and abroad have conducted research on the structural optimization of molten salt valves and the heating system. Mu Shihui et al.[1]analyzed the energy-saving optimization problem of the anti-freezing electric heater for the molten salt valve, and optimized the temperature of the electric heater of the molten salt valve through software. Shen Xiaolei et al. [2] studied the parabolic photothermal power station and conducted an analysis, proposing relevant suggestions for the electric heating system. Hu Yonghai et al. [3]studied the molten salt stop valve of a 50MW photothermal power station, providing temperature field data for thermal deformation analysis and static strength analysis, and offering a reference direction for related design. Wu Wangsong et al. [4] established a two-dimensional model for the electric heater molten salt pipeline with direct contact heating and simulated the thawing and melting process of the binary molten salt in the pipe to analyze the melting efficiency of the molten salt under different conditions. Shi Yufeng et al. [5]studied the linear Fresnel photothermal power generation and further designed and researched the electric heating control system. Shen Hengyun et al. [6] conducted numerical simulation of the flow capacity of the molten salt swing check valve, and used the dynamic grid technology to conduct dynamic simulation of the flow field analysis. Liu Wenxiang et al.[7]simulated the molten salt regulating valve with a general plunger core and a new pressure reducing valve core, and verified the accuracy of the simulation results through experiments. LISHUXUN et al. [8]conducted simulation analysis under different opening degrees of the molten salt valve, analyzing the vibration problem of the pipeline inside the valve under low-temperature conditions.

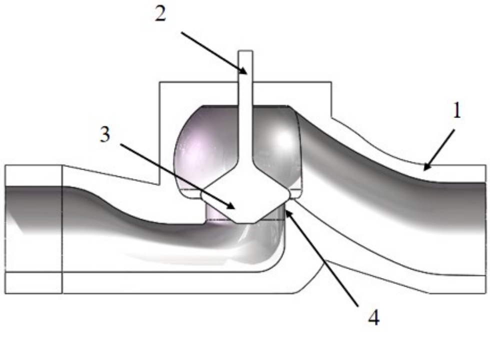
The above scholars mainly conducted research on the analysis of the internal flow field of the molten salt valve, the improvement of the valve core structure, and the storage heat system, and achieved remarkable research results. However, there are relatively few research papers on the prevention of molten salt solidification related to the molten salt regulating valve. This study mainly uses simulation analysis software to investigate whether the molten salt temperature field distribution of the molten salt regulating valve in the 50MW tower photothermal power station in Delehan City, Qinghai Province is lower than the molten salt's freezing point under extreme environmental conditions, providing a reference direction for further optimization design of the molten salt regulating valve's anti-freezing.

2. FINITE ELEMENT NUMERICAL SIMULATION

2.1. Overview

The subject of this study is the molten salt regulating valve used in the 50MW tower-type solar thermal power station located in Delinha City, Qinghai Province. Its main function is to adjust the flow of molten salt passing through the flow channel inside the valve body by the movement of the valve stem along the axis of the valve seat, thereby preventing damage to the molten salt pump, transportation pipelines and related equipment, ensuring the safe and reliable operation of the entire solar thermal power generation system. The regulating valve in this study is a DN65 molten salt regulating valve with a design temperature of 600℃. At the same time, this study analyzes the temperature field distribution of the molten salt regulating valve into three situations: under extreme environmental conditions, situation 1 is the full opening of the molten salt regulating valve, situation 2 is the sudden closure of the valve while the molten salt inside the valve body has not been completely discharged, and situation 3 is the sudden interruption of molten salt flow due to pipeline and equipment failure. The study examines whether the molten salt temperature is lower than the molten salt freezing temperature in these three scenarios.

2.2. Geometric Model



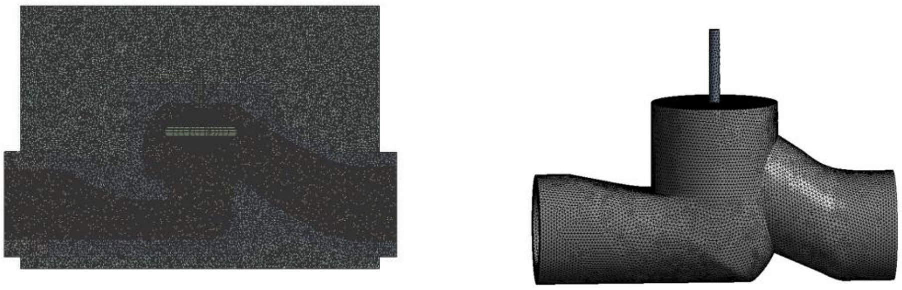
1. Valve body 2. Valve stem 3. Valve core 4. Valve seat

Fig 1. Three-dimensional model of molten salt regulating valve

The subjects of this study are the molten salt regulating valves used in the 50MW tower-type solar thermal power station located in Delingha City, Qinghai Province. The three-dimensional model of the valve body and flow channels of the molten salt regulating valve was established using Solidworks, as shown in Figure 1. The molten salt regulating valve consists of a valve core, valve body, and valve stem, and the flow rate and pressure at the outlet of the valve body are regulated by the movement of the valve core.

1) Grid division

The internal flow channel extraction was carried out using the Designmodel module in Ansys software, and the mesh module was used to divide the grid with tetrahedral grids. At the same time, to eliminate the influence of the number of grids on the numerical simulation results, the independence verification of the model was conducted. The computational fluid domain of the numerical model in this study includes the air domain and the molten salt domain. The grid model of the regulating valve was divided into eight types of grids, with the grid numbers m being 880,000, 1,290,000, 1,760,000, 1,970,000, 2,160,000, 2,580,000, and 2,790,000. The average temperature of the molten salt outlet under the large opening of the molten salt regulating valve was taken as the basis for the independence verification. The simulation analysis of the valve flow channel models with 8 different grid numbers was carried out, and it was found that when the grid number increased to 2,160,000 to 2,790,000, the average temperature of the molten salt outlet of the regulating valve observed remained stable at around 300.22°C with almost no change. Therefore, the model grid number was determined to be 2,160,000, and the grid model is shown in Figure 2(a-c).



(a)Calculate the grid model (b)Valve grid model

(c)Molten salt domain grid model

Fig 2. Grid model of molten salt control valve

2) Boundary condition setting

Using a binary molten salt at 300°C in a cold loop, its physical properties are shown in Table 1. The gravitational acceleration is set to -9.81 m/s². The boundary conditions include the inlet velocity and the outlet pressure. The air in the air domain is set as an ideal gas. Meanwhile, the historical extreme minimum temperature in Deleh City, Qinghai Province, is -30°C. Therefore, the temperature of the four walls of the air domain is set to -30°C. For situation 1, the valve is fully open, the boundary condition inlet velocity is 5 m/s, and the outlet pressure is 0 Pa. For situation 2, the valve is closed, the boundary condition inlet velocity is 5 m/s, and the outlet pressure is 0 Pa. For situation 3, the valve is fully open, the boundary condition inlet velocity is 0.01 m/s, and the outlet pressure is 0 Pa. The standard k-ε model is used as the turbulence model. The steady-state temperature field results are calculated using the Ansys software Fluent module and the steady-state heat module. The iterative algorithm is the pseudo-transient algorithm. To accelerate the convergence process, the time step of the fluid domain is set as the aggressive algorithm. The SIMPLE algorithm with pressure and velocity coupling is used for calculation. The discretization format of the pressure phase is selected as PRESTO, and the number of calculation steps is 2000. The stability of the temperature field of the molten salt regulating valve is ensured.

Table 1. Physical properties of molten salt

Medium name	Molten salt
T/(°C)	300
ρ/(kg/m^3)	1899
μ/(Pa·s)	0.00326
W/(m·°C)	0.499
KJ/(kg·°C)	1.495

3. ANALYSIS OF SIMULATION RESULT

3.1. Valve Simulation for Working Condition 1

In condition 1, the software was used to simulate the full opening of the molten salt regulating valve, and it was operated normally simultaneously in the photothermal power generation pipeline system. At the same time, there was no insulation layer. The analysis was conducted to determine whether there would be a phenomenon of molten salt solidification in the internal molten salt domain temperature field. The simulation was carried out by establishing a model, dividing the grid, and setting boundary conditions to obtain the temperature field of the regulating valve. As shown in Figure 3, the temperature distribution of the symmetrical plane section of the molten salt regulating valve is uniform. Since the molten salt domain is the heat source with the highest overall temperature, the temperature of the solid domain changes due to the heat transfer from the molten salt domain, and there is a significant temperature stratification. The air domain is also affected by the temperature of the molten salt domain, and the temperature of the air near the outer wall of the valve changes. Some of the air temperatures are higher than 3°C, while the temperature of the molten salt domain is basically between 267.08°C and 300.09°C. At 300°C, the melting point of the molten salt is 220°C - 238°C. In condition 1, the lowest temperature of the molten salt domain is higher than the melting point of the molten salt, and Figure 4 shows that the temperature distribution of the valve outer wall is reasonable. The molten salt in the middle cavity flows less, resulting in little influence on the wall temperature. Some outer wall temperatures are lower than 9.57°C. From the velocity distribution in Figure 5, the molten salt enters from the upper right and exits from the lower left. Due to the valve structure, its maximum velocity is at the valve opening position. There is also a part of low velocity area, which is prone to vortex formation and may have an impact on the solidification of the molten salt. In conclusion, condition 1 will not result in the solidification of the molten salt.

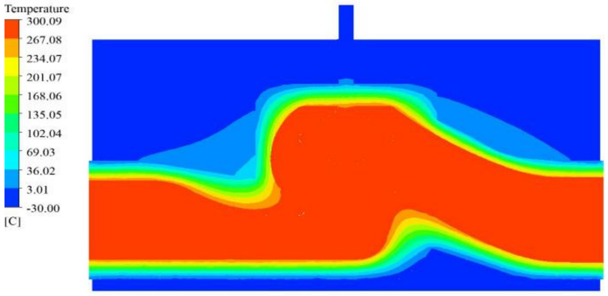


Fig 3. Temperature distribution on the symmetry plane

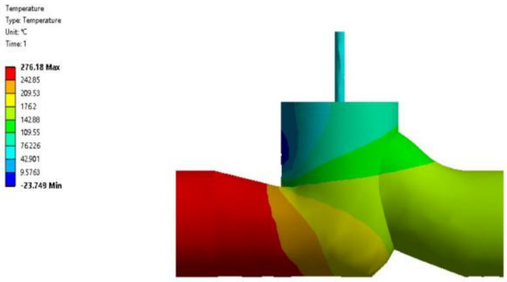


Fig 4. Temperature distribution in the solid domain

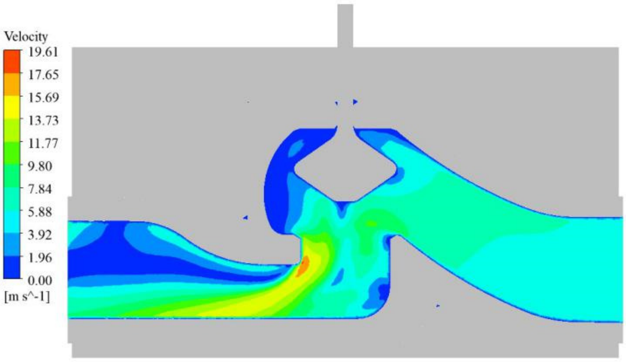


Fig 5. Velocity distribution symmetry plane

3.2. Valve Simulation for Working Condition 2

In condition 2, the Fluent software was used to simulate the downward movement of the valve stem of the molten salt regulating valve, which caused the molten salt regulating valve to suddenly close, and at the same time, the molten salt filled the entire valve cavity without being completely discharged. Moreover, there was no insulation layer. The analysis was conducted to determine whether the lowest temperature of the molten salt under this condition was lower than the freezing point. The simulation numerical model used in condition 1 was adopted, with the exception that the valve stem moved downward to close the valve outlet. The external environmental temperature was also set to the historical extreme minimum temperature of Delingha City, which is -30℃. The boundary conditions were set as a speed inlet of 5m/s and a pressure outlet of 0 Pa. As shown in Figure 6, the temperature distribution of the symmetrical plane section of the molten salt regulating valve is uniform. Since the molten salt domain is a heat source, the overall temperature is the highest, and it is greatly affected by the temperature of the molten salt domain. The temperature of the solid domain changes, and the overall temperature is between 267.11℃ and 300.12℃. There is a significant temperature stratification. The air domain is also greatly affected by the temperature of the molten salt domain. The temperature of the air near the valve outer wall changes, and a large part of the air temperature is higher than 36.02℃. The temperature of the molten salt domain is basically between 267.11℃ and 300.12℃. At 300℃, the freezing point of the molten salt is 220℃ - 238℃. In condition 2, the lowest temperature of the molten salt domain is higher than the freezing point of the molten salt. As shown in Figure 7, the temperature distribution of the valve outer wall is reasonable. The molten salt in the middle cavity flows less, resulting in little influence on the wall temperature. The temperature of some outer wall surfaces is lower than 9.96℃. From the velocity distribution in Figure 8, the molten salt enters from the upper right and exits from the lower left. Due to the influence of the valve structure, the maximum velocity is 54.27m/s - 60.3m/s at the valve opening position. There are also most low-velocity areas, which are prone to vortexes, and this may have an impact on the freezing of the molten salt. In conclusion, under condition 2, the freezing of the molten salt will not occur.

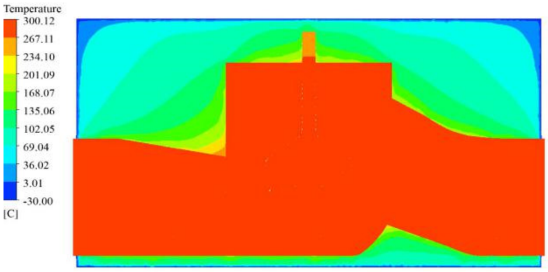


Fig 6. Temperature distribution on the symmetry plane

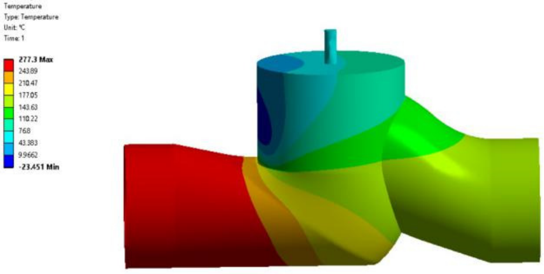


Fig 7. Temperature distribution in the solid domain

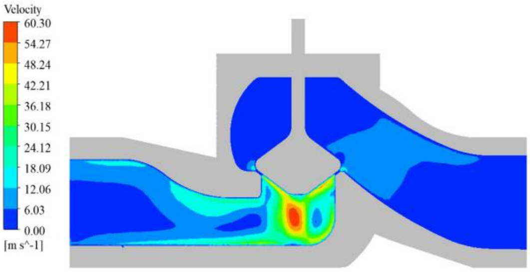


Fig 8. Velocity distribution symmetry plane

3.3. Valve Simulation for Condition 3

Condition 3 simulates the scenario where the solenoid valve is fully open, and the pipeline equipment suddenly breaks down, resulting in a reduced flow of molten salt to the molten salt regulating valve, a decrease in the flow velocity of the molten salt, and a complete cessation of the molten salt flow. Meanwhile, the photothermal power station system still operates normally. The boundary conditions set the inlet speed at 0.01 m/s and the pressure outlet at 0 Pa. As shown in Figure 9, the temperature distribution across the symmetrical plane of the molten salt regulating valve is uniform. Due to the molten salt domain being the heat source with the highest overall temperature, it is significantly affected by the heat transfer from the molten salt domain. The temperature of the solid domain changes, and there is a distinct temperature stratification. The air domain is also greatly influenced by the temperature of the molten salt domain. The temperature of the air near the valve outer wall changes, with some air temperatures exceeding 6.43℃, while the temperature of the molten salt domain is generally between 297.86℃ and 334.29℃. At 300℃, the molten salt solidifies at 220℃ - 238℃. In Condition 3, the lowest temperature of the molten salt domain is higher than the molten salt solidification temperature. As shown in Figure 10, the temperature distribution of the valve outer wall is reasonable. The molten salt flowing in the middle cavity is less, resulting in little influence on the wall temperature. Some outer wall temperatures are lower than -21.69℃. From the velocity distribution in Figure 11, the molten salt enters from the upper right and exits from the lower left. Due to the valve structure, its maximum velocity is at the valve opening position. Most areas are at low flow rates, prone to vortices, and may have an impact on the molten salt solidification. In conclusion, Condition 3 will not result in the solidification of the molten salt.

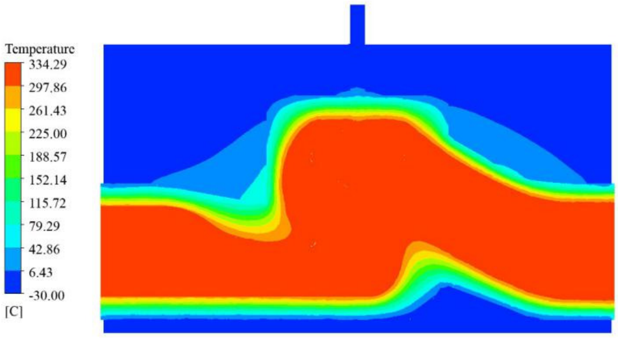


Fig 9. Temperature distribution on the symmetry plane

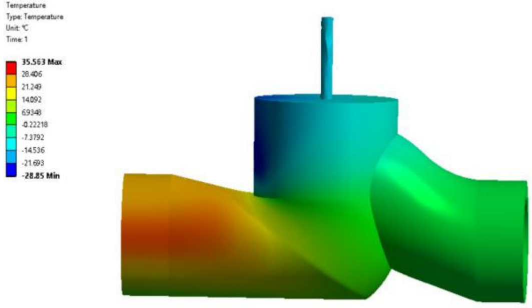


Fig 10. Temperature distribution in the solid domain

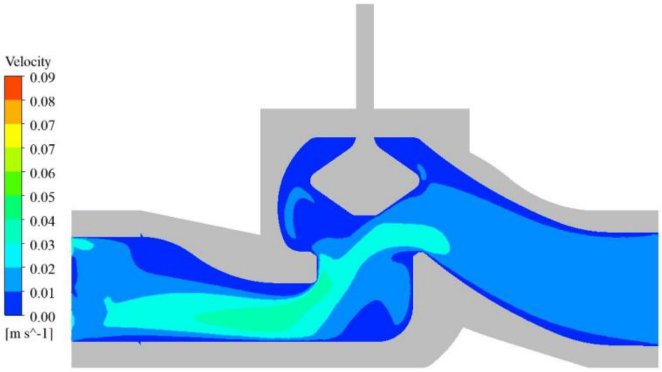


Fig 11. Velocity distribution symmetry plane

4. CONCLUSION

This study employed the three-phase coupling heat transfer method of fluid-solid-gas to investigate whether the molten salt would solidify under the extreme environmental conditions at the lowest temperature of the regulating valve under three different working conditions. The simulation results yielded the following conclusions: 1) In condition 1, which simulated the normal operating situation, the temperature in the molten salt area ranged from 267.08℃ to 300.09℃, which was higher than the molten salt's freezing point, and thus no molten salt solidification occurred. 2) In condition 2, which simulated the sudden closure of the molten salt regulating valve and the simultaneous filling of the entire valve cavity without complete discharge, the temperature in the molten salt area was between 267.11℃ and 300.12℃, and no molten salt solidification occurred either. 3) In condition 3, which simulated the full opening of the molten salt valve, the sudden damage to the pipeline equipment led to a reduced flow of molten salt towards the molten salt regulating valve, resulting in a lower flow velocity and a cessation of the molten salt flow. The temperature in the molten salt area was between 297.86℃ and 334.29℃, which was also higher than the molten salt's freezing point. In summary, under the extreme lowest temperature conditions, the lowest temperature of the molten salt in the regulating valve under all three conditions was higher than the freezing point of the molten salt, and no molten salt solidification occurred. This provides a reference direction for the subsequent optimization design of molten salt regulating valve anti-icing.

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