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Dynamic temperature variation of insulation materials for solid-phase cold storage tank of liquid air energy storage

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ABSTRACT. The cold storage tank is a vital component within the liquid air energy storage system, enabling the transfer of cold energy between the processes of air liquefaction and gasification. Solid-phase cold storage, distinguished by its lack of operating temperature constraints, environmental friendliness, and cost-effectiveness, stands out as a highly promising method for cold storage in liquid air energy storage systems. The solid-phase cold storage tank undergoes periodic cycles of heating and cooling during the processes of air liquefaction and gasification. To explore the dynamic temperature variations in the external insulation material of the solid-phase cold storage tank and improve its insulation performance, this study developed a dynamic computational model for the tank's insulation system. It simulated the temperature distribution and dynamic changes of the insulation material in the first-stage (173~300K) cold storage tanks under periodic temperature fluctuations within the tanks. The dynamic temperature changes of the insulation material were examined with a focus on the effects of insulation material type, thickness, and the cycle time.

1. Introduction

As a new type of energy storage technology, liquid air energy storage has become a solution to mitigate the volatility and intermittency of renewable energy sources due to its high energy density, flexible arrangement, and lack of geographical constraints [1,2]. The solid-phase cold storage tank is an important part of the cold storage device in the liquid air energy storage system, in which the solid-phase cold storage medium is in direct contact with the circulating gas to complete the cold storage and cold release process [3,4].

Solid-phase cold storage tank in the process of cold storage and release of cold unit will experience cyclical cooling and heating cycle [5]. Fig. 1 shows the cold storage stage of solid-phase cold storage tank, Ⅰ ～ Ⅲ for the low-temperature circulating gas from the bottom to the top of the solid-phase cold storage tank, cooling the process of cold storage medium. The solid-phase cold storage tank operates below ambient temperature and is usually filled with insulating materials such as expanded perlite on its exterior to reduce heat leakage. It can be seen that in addition to the circumferential temperature is uniform, the insulation layer in the axial and radial direction there is a temperature gradient, and its temperature distribution also undergoes cyclic changes with the temperature distribution of the solid-phase cold storage tank. All of the above makes the quantitative study of the temperature of the outer insulation layer of the cold storage tank difficult.

In order to simplify the problem, the temperature gradient of the insulation layer in the axial direction is neglected in this paper, and a microelement intercepted from it is the object of study. Numerical simulation was used to study the dynamic temperature change of the outer insulation material of solid-phase cold storage tank under the cyclic fluctuation of the temperature inside the tank, which provides a basis for improving the thermal insulation performance of solid-phase cold storage tank.

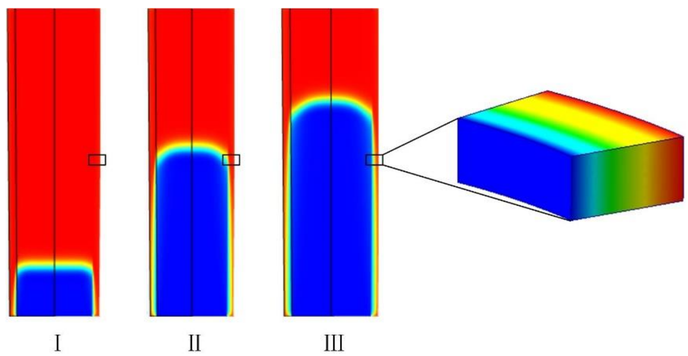

Figure 1. Solid-phase cold storage tank temperature distribution diagram.

2. Boundary condition

Using the finite volume method for numerical solving, the solid's temperature distribution is typically described by the heat conduction equation based on the fundamental principles of heat transfer:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \tag{1}$$

where ρ is the density, c is the specific heat capacity, k is the thermal conductivity, T is the temperature, and Q is the internal heat source.

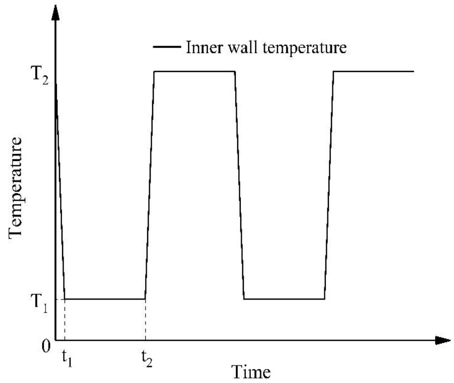

Figure 2. Temperature change of the inner wall of the insulation layer.

To ensure that the simulation results are independent of the grid resolution, three different grid sizes 84,652, 139,248, and 184,265 were tested. The dynamic response of the outer wall temperature was evaluated under the same conditions of inner wall temperature variation. When the grid sizes were 139,248 and 184,265, the temperature difference was less than 0.3%. Therefore, a grid size of 139,248 was selected for subsequent simulations.

The inner wall of the insulation is a constant wall temperature boundary condition, the outer wall is a convective heat transfer boundary condition, the interior is approximated as a one-dimensional thermal conductivity, the ambient temperature is 300 K, and the convective heat transfer coefficient is set to 10W/(m^2·K).

This study focuses on the first stage of cold storage tank in liquid air energy storage. It is obvious from Fig. 1 that the temperature of the inner wall of the microelement of the studied insulation changes only when the front end of the circulating gas passes through it, and remains at the corresponding high or low temperature for the rest of the time. Fig. 2 shows the temperature change of the inner wall of the insulation layer, the initial temperature of the inner wall T_2=300K, which decreases to T_1=173K at t_1 and then stays at a low temperature, and starts to rewarm at t_2 and then stays at a high temperature, thus completing a cold storage and cooling release cycle in $2t_2$ time. In this study, the temperature change of the insulation material in the two cycles is simulated.

3. Result and discussion

3.1 The effect of insulation thickness

This study firstly analyses the influence of the thickness of the insulation layer on the dynamic temperature change of the outer wall. The temperature distribution when the thickness of the insulation layer is 0.1m, 0.15m and 0.2m is simulated, and the results are shown in Fig. 3 When the thickness increases, the volume and mass of the material increase accordingly, which means that the heat capacity of the material increases and the thermal inertia is enhanced, so the response of the outer wall of the insulation layer to the temperature change of the inner wall becomes slower and the delay is enhanced. The outer wall temperature may even continue to decrease for a period of time when it enters the release time after the end of the holding time. The slower the cooling rate within a certain period of time, the less the temperature is reduced, so the

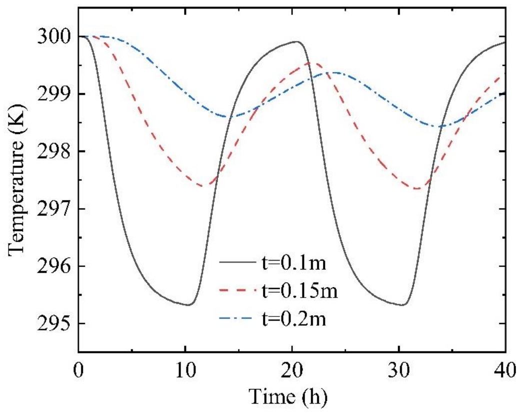

Figure 3. Influence of insulation thickness.

increase in thickness will make the minimum temperature reached by the outer wall of the insulation layer is greatly improved, and the change in temperature also becomes smoother, and the insulation effect is better. For example, when the thickness increases by 0.1m, the minimum temperature can be increased by about 3K.

At the end of the two cooling storage and release processes, the temperature of the outer wall of the insulation layer with thicknesses of 0.1m, 0.15m and 0.2m decreased by about 0.1K, 0.6K and 1K respectively compared to the beginning, which shows that this hysteresis also has negative effects. If the outer wall temperature does not recover to 300K before entering the next storage cooling cycle, this will result in a lower outer wall temperature at the end of each cycle than at the start. The stronger the hysteresis, the more the temperature decreases.

3.2 The effect of insulation material type

In thermal insulation applications, the thermophysical properties of materials are crucial for their thermal performance. This study provides an insight into the laws affecting the dynamic temperature variation of the outer wall of different insulation materials in terms of their physical parameters while keeping the thickness of the insulation layer constant. Table 1 lists the data on density, thermal conductivity and specific heat capacity of three commonly used insulation materials. Among these materials, glass wool has the lowest density and thermal conductivity, while expanded perlite has the highest specific heat in the range of temperature fluctuations, which indicates that it is able to absorb and store more heat and therefore shows greater thermal stability during temperature changes.

From the heat capacity point of view, expanded pearlite is able to store the most heat for the same volume, followed by foam glass and glass wool the least. This is reflected in the dynamic temperature variation of the outer wall shown in the Fig. 4. Glass wool has the fastest response rate to temperature changes, which may be due to its low density and low thermal conductivity resulting in rapid heat transfer. In contrast, expanded pearlite showed the slowest response to temperature changes due to its higher specific heat capacity, showing a stronger delay in temperature changes.

It is worth noting that even though glass wool has the fastest response to temperature changes, the minimum temperature it reached in the experiment was the highest of the three materials. The temperature change of the outer wall of the glass wool is very similar to that of the

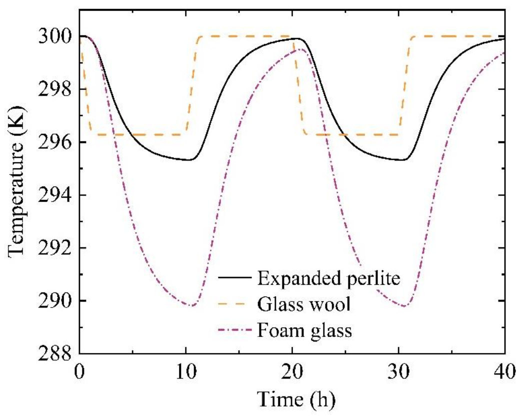

Figure 4. Influence of insulation material type.

inner wall, and that it can maintain a relatively stable temperature during the time of cold preservation, which suggests that the heat conduction inside the insulation material and the convective heat transfer on the outer wall surface reached a thermal equilibrium state in that time

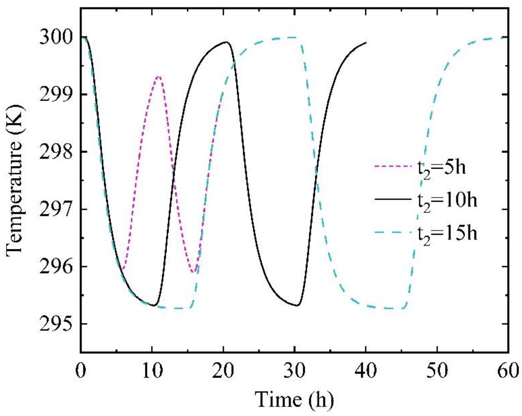

Figure 5. Influence of cycle time.

period, so as to bring the temperature distribution to a steady state.

Table 1. Physical parameters of the three insulation materials.

Insulation materials	Density (kg/m3)	Thermal conductivity (W/(m·K))	Specific heat capacity (J/(kg·K))
Expanded perlite	760	0.0424	0.451*(2.44T+128.44)
Glass wool	90	0.033	0.498*(2.97T-120.668)
Foam glass	160	0.099	0.498*(2.97T-120.668)

3.3 The effect of cycle time

In this study, the influence of different cycle times on the dynamic temperature change of the outer wall of the insulation layer is further investigated. Keeping the cooling time of the inner wall constant, i.e., t1=1h, and at the same time changing the time of keeping it cool, i.e., t2-t1. Fig. 5 shows the changes of the temperature of the outer wall of the insulation layer within two cycles under different cycle times. It can be clearly seen that in the first 5h, the temperature change curves for different cycle times almost overlap, which indicates that the temperature response of the insulation layer has some consistency in a short period of time. The longer the cycle time, the longer the cooling and warming time of the outer wall, and therefore the correspondingly lower and higher temperatures can be achieved. This trend of temperature fluctuations shows the possibility of the system moving towards a state of thermal equilibrium. On the contrary, when the cycle time is shorter, the time for cooling and rewarming of the outer wall is correspondingly shorter. This leads to the fact that at the end of a cycle, the temperature of the outer wall has not had enough time to return to its initial state. In particular, when t2 = 5 h, the temperature of the outer wall at the end of two cycles decreased by about 1 K. This result indicates that if the cycle time is set too short, it will result in a gradual decrease of the temperature of the outer wall in consecutive cycles, which may affect the thermal insulation effect and the stability of the system.

4. Conclusion

Numerical simulation of the dynamic temperature variation of the outer insulation material of the first stage solid-phase cold storage tank of liquid air energy storage under cyclic fluctuation of the temperature inside the tank. The influence of the thickness of the insulation layer, the type of insulation layer material and the cycle time on the temperature change of the outer wall of the insulation layer within two cycles is mainly studied, and the following conclusions are drawn:

1) Increasing the thickness of the insulation layer can significantly increase the minimum temperature of the outer wall and improve the insulation performance, but it also leads to a delay in the temperature response and a decrease in the temperature at the end of the cycle.

2) The density, thermal conductivity and specific heat capacity of the material together affect its thermal properties. The thermal capacity of expanded perlite gives it greater thermal stability during temperature fluctuations, but also results in a delay in temperature change. Glass wool has the fastest response to temperature changes due to its low density and thermal conductivity, but it also reaches thermal equilibrium more quickly.

3) Longer cycle times will have larger temperature fluctuations and help the system reach thermal equilibrium. Too short cycle times prevent the outer wall temperature from returning to its initial state, and continuous cycling may lead to a gradual drop in temperature, affecting the insulation performance and system stability.

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