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HEAT TRANSFER MATCHING DESIGN AND OPTIMIZATION OF SOLID-STATE ELECTRIC HEATING THERMAL STORAGE SYSTEM

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ABSTRACT

The solid-state electric heating thermal storage system is an emerging large-capacity peak shaving technology in the power grid. The studying of the heat transfer matching characteristics is of great significance for improving reliability and heat transfer performance of the solid-state electric heating thermal storage system. In this paper, by establishing the heat transfer rate balance equation and the performance evaluation criteria, the correlation between the design parameters and heat transfer matching of the thermal storage system is analyzed. The results show that the temperature of the thermal storage unit increases linearly with the increase of electric model heating power, decreases exponentially with the increase of hole ratio and circulating wind speed. The reduction of the electric heating power and the increase of the circulating wind speed can enhance the heat efficiency and the temperature uniformity. However, the turn-on of the circulating wind will cause a sudden change of heat efficiency and the temperature uniformity. Changing the hole ratio has little effect on the heat transfer matching performance. The experimental verification proves that through the Multi-parameter collaborative optimization, better heat transfer matching performance can be achieved.

Keywords: solid-state electric heating thermal storage; heat transfer matching; heat transfer rate balance; performance evaluation criteria.

NOMENCLATURE

A	surface area (m^2)
c	specific heat (J kg^{-1} K^{-1})
C	cross-section area (m^2)
h	heat transfer coefficient (W m^{-1} K^{-1})
J	mechanical equivalent of heat (J K^{-1})
m	mass (kg)
n	number of measuring points (-)
P	heating power (W)
Q	migration energy (J)
t	heating time (s)
T	temperature (K)
$\bar{T}$	average temperature (K)
v	circulating wind speed (m s^{-1})
W	storage energy (J)
Greek abbreviations	
γ	temperature uniformity (1)
Δ	the single-step average variation of the temperature
η	heat efficiency (%)
θ	step contribution degree (%)
ρ	density (kg m^{-3})
φ	hole ratio (%)
Subscripts	
a	air
e	electric heating wire
f	convective heat transfer
i	measuring point
r	radiation heat transfer
s	thermal storage masonry
t	heat exchanger

1. INTRODUCTION

High temperature solid-state thermal storage technology is a new type of large-capacity peak shaving technology developed in recent years. Because of the excellent flexibility and thermo-electricity decoupling capacity, it has become one of the research hotspots of large capacity energy storage technology [1]. Under normal operating conditions, the high temperature solid-state thermal storage system transfer heat in the fluid-structure interaction model. Because of the limited heat transfer rate [2], the heat transfer mismatch between the electric heating wire and the thermal storage masonry is common to occur in the heating process. As a result, on the one hand, a large amount of heat accumulated in the electric heating wire, and the high temperature will shorten the service life of the electric heating wire or even blown them [3]. On the other hand, the larger temperature difference of the thermal storage masonry will cause deformation or cracking of the thermal storage masonry. Therefore, in the design process of the solid-state electric heating thermal storage system, it is necessary to optimize the heat transfer matching of the electric heating wire and the thermal storage masonry.

For the past few years, with the development of various thermal storage technologies, research on heat transfer and heat transfer characteristics has gradually received attention. For example, Yang Xiaoping [4] analyzed the heat transfer temperature difference of the packed bed storage system by numerical analysis, Belusko M [5] studied the heat transfer characteristics of air in a phase change thermal storage device, Andreozzi A [6] [7] simulated the transient heat transfer of parallel square-slot thermal storage structures and parallel-plate thermal storage structures, and provided a thermal storage heat transfer model.

In order to study the heat transfer matching design method between the electric heating wire and the thermal storage masonry, the key design parameters affecting heat transfer matching of the thermal storage system are obtained by analyzing the heat transfer rate balance relationship between electric heating wire and the thermal storage masonry. And the correlation equation and heat transfer matching performance evaluation criteria between heat transfer matching target and design parameters of the electric heating thermal storage system are established. On this basis, the matching design law of heat transfer matching target and thermal storage design parameters is analyzed by the Fluent numerical simulation software. And the reliability of the heat transfer matching optimization design method is verified through experiments.

2. HEAT TRANSFER MATCHING CALCULATION

The heat transfer mode mainly includes convection heat transfer and radiation heat transfer. And the heat loss rate of the air in the heat exchanger should be extra considered. The heat transfer rate and direction between the parts of the solid-state electric heating thermal storage system are shown in Fig 1.

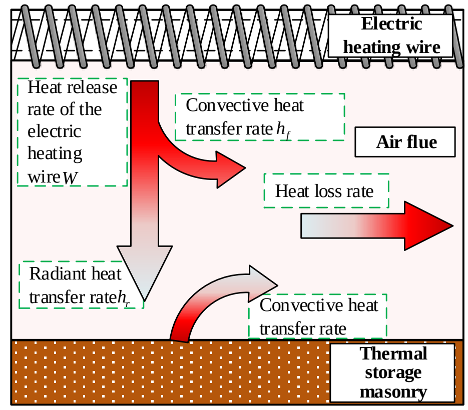


Fig 1 Schematic diagram of heat transfer

According to the basic principle of heat transfer, the heat transfer rate balance equation between every part of high temperature solid-state thermal storage system can be expressed as:

$$\begin{aligned}\frac{P}{J} &= A_e h_r (T_e^4 - T_s^4) - 2A_s h_f (T_s - T_a) \\ &+ h_t \rho_a v_a C_t \frac{\partial T_a}{\partial t} + m_a c_a \frac{\partial T_a}{\partial t} + m_e c_e \frac{\partial T_e}{\partial t}\end{aligned} \tag{1}$$

The heat power P, the air flue surface area A_s and the circulating wind speed v_a are selected as variables to perform heat transfer matching design.

In order to be consistent with the actual situation of the project, it is assumed that the length of the air flue is invariant. Therefore, the air flue surface area A_s can be converted into the hole ratio φ which be more often used as an engineering standard amount.

$$\varphi = \frac{\textit{cross section area of air flue}}{\textit{cross section area of heat storage masonry}} \tag{2}$$

In order to evaluate the thermal storage performance of the thermal storage system, the heat efficiency η and the temperature uniformity γ are introduced respectively to characterize the heat dissipation capacity of the electric heating element and the temperature difference of the heat storage masonry. The calculation formula is as follows:

$$\begin{cases} \eta = \dfrac{Q}{W} \times 100\% \\ \gamma = 1 - \dfrac{1}{2n} \sum_{i=1}^{n} \dfrac{\sqrt{(T_i - \bar{T}_s)^2}}{\bar{T}_s} \end{cases} \tag{3}$$

When η approaches to 100%, the temperature of the heating element rises slowly. When γ approaches to 1, the temperature distribution of the heat storage masonry is more uniform.

Affected by the structure of the thermal storage masonry, when the heat transfer matching design is optimized, the parameters such as heating power, hole ratio, and circulating wind speed can only be adjusted stepwise. In order to judge the optimization of each parameter, this paper introduces the step contribution degree to characterize the influence of parameters on the temperature of the thermal storage masonry:

$$\theta = \frac{\Delta}{T_{tmax} - T_{tmin}} \times 100\% \tag{4}$$

3. NUMERICAL PROCEDURE

3.1 Problem Description

This paper simulates the solid-state electric heating thermal storage system through Fluent. Since the electric heating wires are evenly distributed, and the heat transfer characteristics around the electric heating wires are similar, the electric heating wire, the surrounding air, and the thermal storage masonry are regarded as one thermal storage unit. Since the screw pitch of the electric heating wire is much smaller than the length of the air flue, the spiral electric heating wire is assumed to be a circular tube. Table 1, Table 2, Table 3 show the key parameters of the thermal storage unit. In order to simplify the analysis, the following assumptions are made for the high temperature solid-state thermal storage unit:

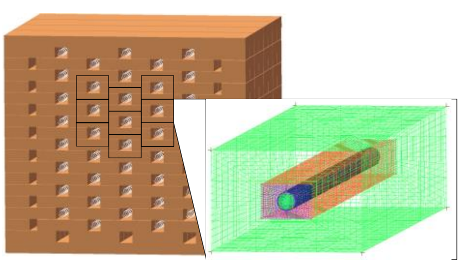


Fig.2 Thermal storage unit structure and mesh generation

1) The gas flow in the air flue of the thermal storage unit is an unsteady, incompressible flow;

2) The gas viscous diffusion is negligible;

3) The thermal property parameters of the material are constant and do not change with temperature.

Table 1 Thermal storage unit geometrical parameter

Hole ratio	Unit section size	Air flue section size	Length	Unit
11%	240*160	80*54		
15%	250*160	110*54		
18%	260*160	140*54	1000	mm
21%	270*160	170*54		
24%	280*160	200*54		

Table 2 Electric heating wire geometrical parameter

Wire outer diameter	Wire inner diameter	Length	Unit
30	27	1000	mm

Table 3 Thermal storage unit thermophysical parameter

Parameter	masonry	wire	Unit
Density	2900	7100	kg m^{-3}
Specific heat	960	460	J kg^{-1} K^{-1}
Heat conductivity Coefficient	3	13	W m^{-1} K^{-1}
Emissivity	0.8	0.7	

3.2 Initial and Boundary Conditions

The initial conditions: the thermal storage unit and the air initial temperature are both 573K.

The boundary conditions: the inlet boundary adopts the velocity inlet boundary condition, the outlet boundary adopts the free outflow boundary condition, and the surrounding wall of the thermal storage unit adopts the second type of heat transfer boundary condition.

4. SIMULATION RESULTS AND DISCUSSION

Under different heating powers, hole ratios and circulating wind speeds, the temperature comparison of the electric heating wire and the thermal storage masonry are shown in Fig. 3 and Fig. 4.

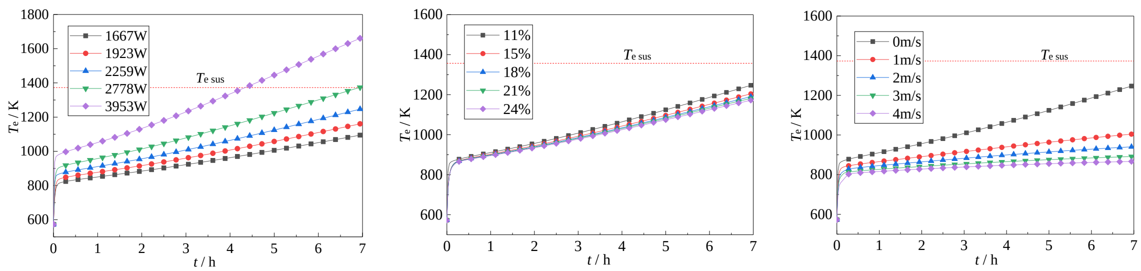
When the hole ratio of the thermal storage unit is 11% and the circulating wind speed is 0 m/s, the temperature curve of the electric heating wire and the temperature of the thermal storage masonry under different heating powers is shown in Fig. 3(a) and Fig. 4(a). As the power of the electric heating wire increases, the electric heating wire temperature and the thermal storage masonry temperature value increase linearly. The step contribution degree of the heating power to the temperature of the thermal storage masonry was 148.99%.

It is calculated that when the thermal storage unit with the power of 1677W, 1923W, 2259W, 2778W and

3953W is heated for 7h, the heat efficiency of the electric heating wire is 98.02%, 97.87%, 97.66%, 97.28%, and 96.32%, respectively. It is proved that the lower the heating power, the less the storage energy increment. When heating for 7h, the temperature uniformity of the thermal storage masonry is 0.9817, 0.98, 0.9778, 0.9848 and 0.9689, respectively, which proved that the lower the heating power, the more uniform the temperature distribution of the heat storage masonry.

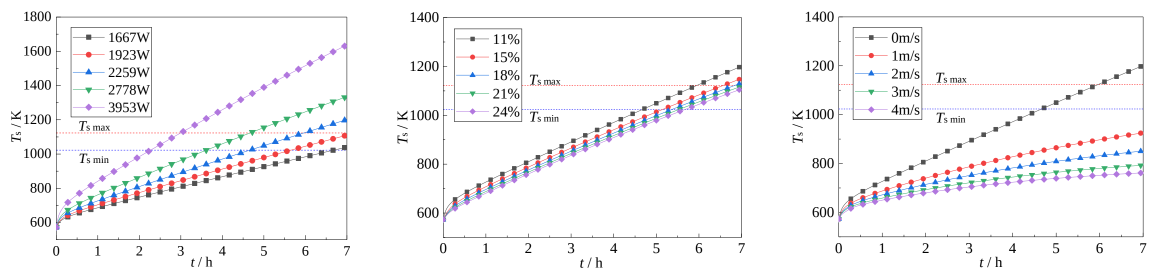
When the electric heating wire power is 2259W and the circulating wind speed is 0m/s, the heating curve of the electric heating wire and the thermal storage masonry temperature at different hole ratios is shown in Fig. 3(b) and Fig. 4(b). As the hole ratio increases, the temperature of the heating element and the temperature of the thermal storage masonry decrease exponentially. This is because when the ratio of the pores increases, the distance between the electric heating wire and the thermal storage masonry increases at the same time, and the heat absorption of the thermal storage masonry decreases due to the existence of the air temperature gradient. The step contribution of the hole rate to the temperature of the thermal storage masonry was 23.41%.

It is calculated that when the thermal storage unit with the hole ratio of 11% and 24% is heated for 7h, the heat efficiency of the electric heating wire and temperature uniformity of the thermal storage masonry is increased by no more than 1%. It is proved that only changing the hole ratio has little effect on the heat transfer matching of the thermal storage unit.



(a) (b) (c)

Fig 3 Electric heating wire temperature: (a) different powers (b) different hole ratios (c) different wind speeds



(a) (b) (c)

Fig 4 Thermal storage masonry temperature: (a) different powers (b) different hole ratios (c) different wind speeds

When the electric heating wire power is 2259W and the hole ratio is 11.25%, the heating curve of the electric heating wire and the thermal storage masonry temperature at different circulating wind speeds is shown in Fig. 3(c) and Fig. 4(c). As the circulating wind speed increases, the temperature of the heating element and the temperature of the thermal storage masonry decrease exponentially. This is because as the circulating wind speed increases, the heat exchange rate of the heat exchanger increases at the same time, and the thermal storage masonry receives less heat. The step contribution of the circulating wind speed to the temperature of the thermal storage masonry was calculated to be 109.81%.

It is calculated that when the thermal storage unit with circulating wind speeds of 0m/s, 1m/s, 2m/s, 3m/s, and 4m/s is heated for 7h, the heat efficiency of the electric heating wire is 96.12%, 99.73%, 99.86%, 99% and 99%, respectively. It is proved that when there is a circulating wind, the heat efficiency of the electric heating wire is rapidly increased, and the temperature of the electric heating wire is substantially unchanged. When heating for 7h, the temperature uniformity of the thermal storage masonry is 0.9778, 0.9732, 0.9784, 0.981 and 0.9828, respectively. It is proved that when there is circulating wind, the temperature uniformity of the heat storage masonry will decrease rapidly, and then the temperature uniformity of the heat storage masonry will gradually increase as the circulating wind speed increases.

5. EXPERIMENTAL VERIFICATION

In order to verify the accuracy of the numerical simulation results, as shown in Fig. 5, the experimental

Fig.5 Experimental facility

facility has designed with a design power of 100 kW and a rated voltage of 400 V. HM-92 type magnesia bricks and Kanthal A-1 type electric heating wires are used as thermal storage masonry and electric heating wire. The

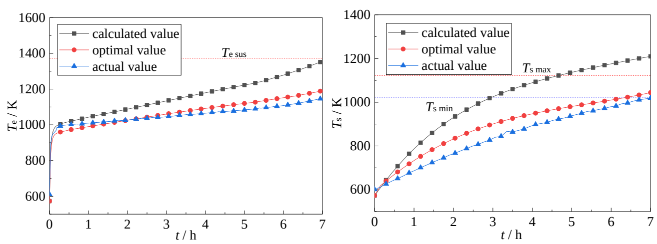


Fig.6 Experimental verification curve

experimental results as shown in Fig. 6.

Comparing the optimal value with the actual value, the actual value agrees well with the optimal value. When heating for 7h, the temperature error of the thermal storage masonry is 25K, and the temperature error of the electric heating wire is 42.82K.

6. CONCLUSION

In this paper, the heat transfer matching characteristics of the solid-state electric heating thermal storage system is studied by numerical simulation method, and the following conclusions are drawn:

(1) The heat transfer rate balance equation is established, and the analysis shows that the heating power, the hole ratio, and the circulating wind speed are the main influencing parameters of the heat transfer matching design. The step contribution degree, the heat efficiency, and the temperature uniformity are introduced as the performance evaluation criteria of the heat transfer matching optimization degree.

(2) The temperature of the heating element and the thermal storage masonry increases linearly with the increase of the heating power and decreases exponentially with the increase of the hole ratio or the circulating wind speed. The step contribution of heating power, hole ratio and circulating wind speed are 148.99%, 23.41%, and 109.81%, respectively.

(3) Reducing the heating power can increase the heat efficiency of the electric heating wire and the temperature uniformity of the heat storage masonry. Increasing the circulating wind will cause the sudden increase of the temperature uniformity and the sudden decrease of the heat efficiency, but as the circulating wind speed increases, the heat efficiency of the electric heating wire and the temperature uniformity of the heat storage masonry will gradually increase. Changing the hole ratio has little effect on the heat efficiency and temperature uniformity of the heat storage unit.

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REFERENCE

[1] Dai Y, Chen L, Min Y, et al. A General Model for Thermal Energy Storage in Combined Heat and Power Dispatch Considering Heat Transfer Constraints[J]. IEEE Transactions on Sustainable Energy, 2018, PP(99):1-1.

[2] HU Zhipei, SUN Zhigao, LI Angui. Numerical Investigation of Melting Heat Transfer Enhancement of Enclosure Geometry[J]. Journal of Engineering Thermophysics, 2018 39(07):1532-1537.

[3] Lim S H, Oh J S, Kong Y M, et al. High Temperature Oxidation Behaviors of Fe-Cr-Al Based Powder Porous Metal and a Strip[J]. Journal of Korean Institute of Metals & Materials, 2013, 51(10):743-751.

[4] Yang Xiaoping, Yang Xiaoxi, Zuo Yuanzhi, et al. The Transfer Temperature Difference Study Between Fluid and Solid During the Charging Process of a High Temperature Packed Bed Storage System[J]. Journal of Korean Institute of Metals & Materials, 2015, 36(4):825-828.

[5] Belusko M, Sheoran S, Bruno F. Effectiveness of direct contact PCM thermal storage with a gas as the heat transfer fluid[J]. Applied Energy, 2015, 137:748-757.

[6] Andreozzi A, Buonomo B, Manca O, et al. Transient analysis of heat transfer in parallel squared channels for high temperature thermal storage[J]. Computational Thermal Sciences, 2015, 7(5-6):477-489.

[7] Andreozzi A, Buonomo B, Pasqua A D, et al. Heat Transfer Behaviors of Parallel Plate Systems in Sensible Thermal Energy Storage[J]. Energy Procedia, 2017, 126:107-114.