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ORIGINAL RESEARCH ARTICLE

Study on heat transfer characteristics of regenerative shell-and-tube heat exchangers

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ABSTRACT

A new type of regenerative shell-and-tube heat exchanger is designed to solve the problems that the generation load of cogeneration units is limited by the amount of heat supply during the heating period, the peak shaving capacity of units decreases, and the phenomenon of wind and light abandonment in the power system is serious. Considering the advantages of nearly constant temperature and large potential heat release during the heat storage/release process of phase change materials, paraffin is selected as the phase change material, and the phase change area of the heat exchanger is selected as the heat exchange unit. The control variates method is used to simulate the heat storage/release process of the heat exchange unit according to the key factors such as the flow rate of heat transfer fluid, the thermal conductivity of phase change materials and the thickness of phase change layer. The results show that increasing the flow rate of heat transfer fluid can enhance the heat storage capacity of the heat exchange unit and shorten the complete melting time of phase change materials. In order to control the heat at the output end of the heat exchanger during the heat release process, the flow rate of heat transfer fluid should be appropriately selected; using composite materials to improve the thermal conductivity of phase change materials can enhance the heat transfer capacity of the heat exchange unit, and the average heat transfer coefficient of the heat exchange unit is more than 2 times higher than that of pure paraffin at the same heat transfer fluid flow rate; increasing the thickness of phase change layer can prolong the time of maintaining the outlet temperature of heat transfer fluid in the process of heat release.

Keywords: Cogeneration; Phase Change Material; Numerical Simulation; Regenerative Heat Exchanger

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1. Introduction

The cogeneration unit adopts the operation mode of “determining electricity by heat” during the heating period, resulting in poor flexibility of peak load regulation, which will aggravate the phenomenon of wind and light abandonment in the power system. Using heat storage technology in the heating system to realize “thermoelectric decoupling” is an effective technical way to improve the load peak shaving capacity of cogeneration units during the heating period[1-5]. Local heat exchange stations generally use plate heat exchangers and shell-and-tube heat exchangers, without the ability to adjust the heat load. The regenerative heat exchanger takes the phase change material as the core, and makes use of its advantages such as large latent heat absorbed and released during the phase change process and nearly constant phase change temperature, so that the heat exchanger encapsulated with phase change material has the functions of heat storage and maintaining the stability of cold source outlet temperature, so as to improve the unit heat storage density and heat supply stability of the heat exchanger.

Domestic and foreign scholars’ research on regenerative heat exchanger mainly focuses on two parts: using CFD software to simulate the heat transfer characteristics of regenerative heat exchangers and design effective ways to enhance heat transfer; the heat transfer process in the simulation is verified by experiments, and the practical application of regenerative heat exchangers in cogeneration unit is studied. Wang *et al.*[6] established two kinds of shell-and-tube heat storage units, namely light tube and finned tube, analyzed the changes in heat transfer characteristics of phase change material after adding aluminum finned tubes, and found that using finned heat exchange tubes can shorten the complete melting and heat release time to 68.0% and 85.5% of that of light tube heat exchange units, respectively. Zhang and Zheng[7] studied the heat transfer behavior on the paraffin side of phase change material through experiments and found that when the heat source temperature is 65 ℃, the total heat storage time of finned tubes is 22.5% of that of smooth tubes. Murray and Groulx[8] used dodecanoic acid as phase change material to establish a shell-and-tube phase change heat storage unit, and studied the effect of the speed of heat transfer fluid on the heat storage and release performance. It was found that the melting time decreased with the increase of flow rate during the heat storage process, and the flow rate did not affect the solidification time during the heat release process. Liu and Groulx[9] conducted experimental research on a cylinder latent heat storage system and found that heat conduction was the main heat transfer mechanism at the initial stage of heat storage, and natural convection was dominant when enough phase change material melted. Wang *et al.*[10] designed a vertical shell-and-tube heat storage device using erythritol as phase change material. The experiment shows that increasing the inlet temperature and mass flow of the heat transfer fluid during the heat storage and release process can significantly enhance the internal heat transfer of the phase change material and shorten the heat storage and release time. Yang *et al.*[11,12] proposed to fill the phase change material into foam metal copper and conduct numerical simulation of the heat storage system encapsulated with composite materials in view of the low thermal conductivity of phase change materials. The research shows that adding fins and foam metal can significantly accelerate the melting process and alleviate the phenomenon of overheating at the top and non-melting at the bottom caused by natural convection. Xu *et al.*[13] added an energy storage device to the cogeneration unit and established a new thermoelectric integrated system, which realized thermoelectric decoupling and improved the flexibility of peak load regulation of the cogeneration unit. Haeseldonckx *et al.*[14] proposed a scheme for the combined use of multiple small-scale cogeneration devices and heat storage tanks. Through simulation, it was found that the installation of heat storage tanks can prolong the service life of cogeneration devices, and the use of small-scale heat storage devices can reduce CO_2 emissions to 1/3 of ordinary cogeneration units. Zhang *et al.*[15] proposed to install heat storage devices in the combined electric heating system and wind power heating system at the same time, and formulate a reasonable start-up and stop control strategy considering the comprehensive coordination of the power grid, the lagging characteristics of the thermal parameters of the heat storage system and the daily regulation plan.

The literature review found that regenerative heat exchangers used in the thermoelectric decoupling of cogeneration process can be further optimized in terms of structural design and operation mode. Based on the existing work, this article proposes a new type of regenerative shell-and-tube heat exchanger suitable for the heating network of thermal power stations, and carries out performance simulation research for the structure and process design.

2. Design and physical model of the regenerative heat exchanger

As shown in **Figure 1**, the regenerative heat exchanger is divided into the phase change zone and heat exchange zone by the shunt. During heat storage, the hot fluid flows into the heat flow tube, and the heat is transferred to the phase change material through the wall and fins as the heat source in the phase change area. After the phase change material melts, the hot fluid flows into the heat exchange zone to exchange heat with the cold fluid. During heat release, due to the reduction of hot fluid flow, the heat exchange of cold fluid in the heat exchange zone is insufficient, and the outlet temperature is lower than the solidification temperature of phase change material. Phase change material exchanges heat with cold fluid through pipe wall and fins in the phase change zone. Considering the heating temperature of the heating station, latent heat of phase change material, thermal conductivity, chemical stability, whether it is non-toxic, corrosive, cheap and easy to obtain and easy to package, paraffin is selected as the phase change material of the heat storage heat exchanger.

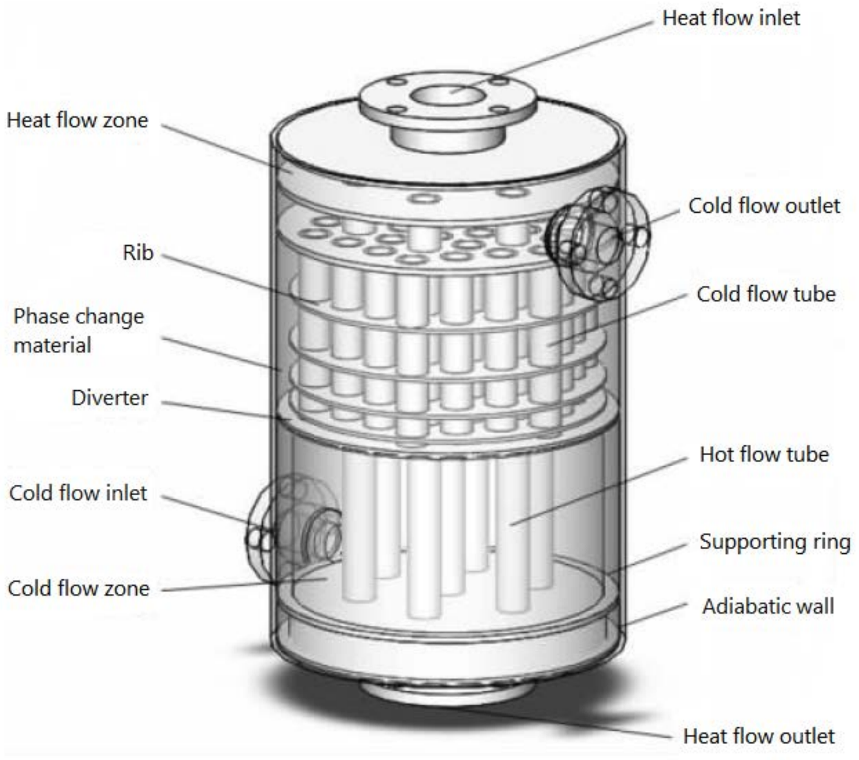
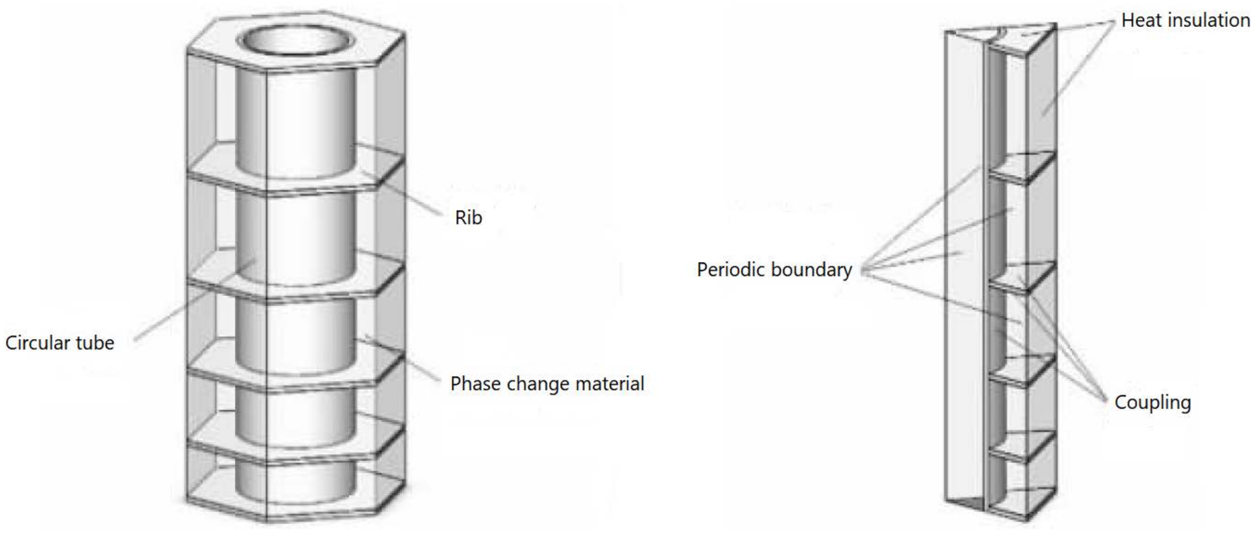


Figure 1. Schematic diagram of the regenerative heat exchanger.

Take the partial structure of the phase change zone of the regenerative heat exchanger to establish the regenerative heat exchange unit, as shown in **Figure 2(a)**. The outer annular ribs of the circular tube wall are arranged parallel to the upper end face and the bottom face with unequal spacing[16], and the closer to the inlet end of the heat fluid, the greater the spacing of the adjacent fins. In the traditional equidistant rib heat accumulator, due to that the heat transfer temperature difference along the flow direction of high-temperature heat transfer fluid is becoming smaller and smaller in the heat storage process, the phase change material in the inlet section is easy to overheat, the phase change material in the outlet section cannot be completely melted, and the overall utilization rate of phase change material is low. The resulting uneven distribution of temperature and thermal stress reduces the service life of phase change material and container material. The arrangement of ribs with unequal spacing is adopted to make the overall heat exchange temperature difference of the heat exchange unit close, and the heat exchange effect is uniform, so as to alleviate the overheating of the phase change material at the inlet of the hot fluid, reduce the local overheating of the phase change material and the excessive thermal stress of the heat storage container, and improve the overall utilization rate of the phase change material. According to the adiabatic characteristics of the symmetrical boundary, the intercepted regenerative heat exchange unit is a regular hexagonal prism. Considering the periodicity of the equipment, the interaction between the unit structure and the heat storage unit in the direction of gravity, the 1/6 structure of the intercepted heat exchange unit is taken as the simulation calculation domain. As shown in **Figure 2(b)**, in the central 1/6 cylinder is the heat transfer fluid, and the phase change material is stored between the two adjacent ribs. In the process of heat storage/release, because the thermal resistance of the circular tube wall is much smaller than that of the phase change material, the thickness of the circular tube wall is ignored to simplify the structure of the heat exchange unit and the complexity of the simulation operation.



(a) (b)

Figure 2. Schematic diagram of the regenerative heat transfer unit.

Table 1. Material physical properties of the heat transfer unit[17]

	Density/(kg·m^{-3})	**Specific heat capacity/(J·kg^{-1}·K^{-1})**	**Thermal conductivity/(W·m^{-1}·K^{-1})**	**Latent heat of phase change/(kJ·kg^{-1})**	**Dynamic viscosity/(kg·m^{-1}·s^{-1})**
Phase change material	760	2,100.00	0.25	170	0.00324
Water	1,000	4,182.00	0.60	-	0.00100
Rib	2,179	871.00	202.40	-	-
Side plate	8,030	502.48	16.27	-	-

The regenerative heat exchanger designed in this article is mainly used in the secondary heat supply network heater. When the heat is sufficient, the phase change material absorbs the heat of the primary heat supply network water for heat storage; when peak shaving is required, the phase change material releases heat to maintain the water outlet temperature of the secondary heat supply network. The phase change material selected in the simulation is paraffin, the heat transfer fluid is tap water, the installed annular rib is aluminum rib, and the side plate is steel. The physical parameters are shown in **Table 1**.

3. Mathematical model

3.1. Numerical methods and control equations

The phase change regenerative heat exchange unit is established, and the unsteady phase change heat transfer is simulated by FLUENT software. The solidification and melting processes of the heat storage medium are simulated mainly by using the solidation/melting model, VOF method and "enthalpy porosity" model. The porosity is used to represent the volume share of liquid phase material in the calculation domain, and the porosity is 1 when it is completely melted. The enthalpy method model is used to calculate, and the continuity equation, momentum equation and energy equation are solved to track the phase interface. In order to simplify the calculation, assumptions are made for the model: (1) the paraffin filled into the heat exchange unit is evenly distributed and isotropic; (2) the density of paraffin phase change material is constant and does not change with temperature. Both solid and liquid paraffin are considered as constant physical properties; (3) paraffin, cold and hot fluids have no axial heat conduction; (4) ignoring the natural convection of paraffin in the process of heat storage/release; (5) paraffin does not have supercooling and overheating during solid-liquid phase transition; (6) neglecting viscous dissipation effect; (7) there is no internal heat source and internal heat sink.

According to the assumption, the control equations of the regenerative heat exchange unit are as follows.

Continuity equation:

$$\nabla(\rho v) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho v)}{\partial t} + \nabla(\rho v v) = -\nabla p + \nabla(\mu v) \tag{2}$$

Energy equation:

$$\rho \frac{\partial h_i}{\partial t} = \lambda \nabla^2 T \tag{3}$$

Where

$$h_i = h + \Delta h_i \tag{4}$$

$$h = h_{\mathrm{ref}} + \int_{T_{\mathrm{ref}}}^{T} c_p \, \mathrm{d}T \tag{5}$$

$$\Delta h_i = \varphi L \tag{6}$$

In equtations (1)–(6): ρ is the density, kg/m^3; V is the material flow rate, m/s; T is the temperature, K; t is the occurrence time of phase transition, s; p is pressure, N/m^2; μ is the dynamic viscosity, kg/(m·s); λ is the thermal conductivity, W/(m·K); h_i is the specific enthalpy of the material at any time, J/kg; h_{ref} is the initial specific enthalpy, J/kg; T_{ref} is the initial temperature, K; c_p is the specific constant pressure heat capacity, J/(kg·K); L is the latent heat of phase transition, J/kg; φ is the volume fraction of liquid phase, specifically defined as

$$\varphi = \begin{cases} 0 & T < T_s \\ \dfrac{T - T_s}{T_l - T_s} & T_s < T < T_l \\ 1 & T > T_l \end{cases} \tag{7}$$

Where: T_s is the melting point of the material, K; T_l is the freezing point of the material, K.

3.2 Boundary conditions and initial conditions

In the simulation of heat storage shell-and-tube heat exchange unit, during heat storage, the inlet boundary condition of water is velocity inlet boundary condition; the velocity is 0.300 m/s, the turbulence intensity is 4.67%, the hydraulic diameter is 0.02 m, and the inlet temperature is 363.15 K; during heat release, the flow rate of water is 0.030 m/s, and the inlet temperature is 293.15 K.

The initial conditions are as follows: setting the temperature of paraffin and ribs at 324.15 K during heat storage; setting the temperature of paraffin and ribs at 330.15K during heat release.

3.3 Model validation

In this article, the heat storage experiment of the tube-rib phase change regenerator in [7] is selected for simulation verification. The temperature of the heat transfer fluid is 338.15 K, and the initial temperature of paraffin and ribs is 298.15K. The temperatures of the experimental measurement points R2 and R3 are selected as the simulation monitoring values, and the influence of natural convection is ignored in the simulation. **Figure 3** shows the curve of the simulated value and the experimental measured value of the temperature of tube-rib phase change accumulator points R2 and R3 calculated by the numerical model with time, as shown in **Figure 3**, the relative error between the simulated calculation results and the experimental results is less than 5%, and the change trend of the simulated value and the experimental measured value is basically consistent, which verifies the accuracy of the numerical model selected in this article. The grid sensitivity test is carried out for the exothermic process of the regenerative heat exchange unit. **Figure 4** shows the time-varying curve of the liquid volume fraction of phase change material in the exothermic process. From **Figure 4**, we can see 7.0611 × 10^5 is the optimal grid number.

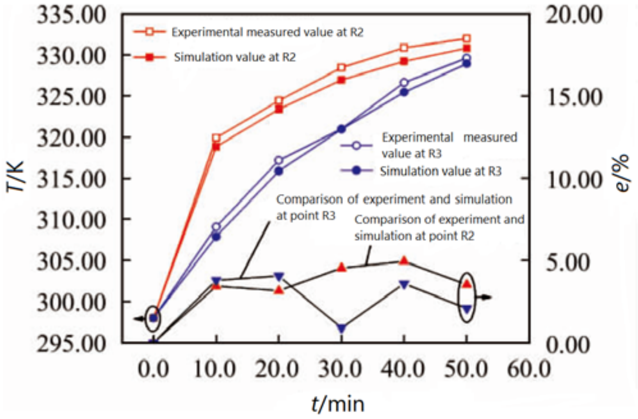


Figure 3. Comparison of the experimental results and numerical simulation results.

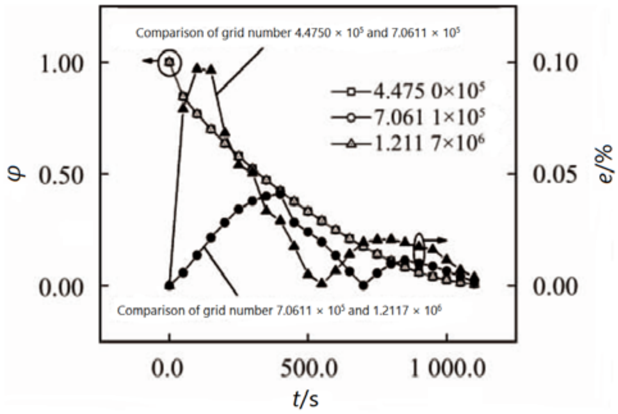


Figure 4. Results of the grids sensitivity test.

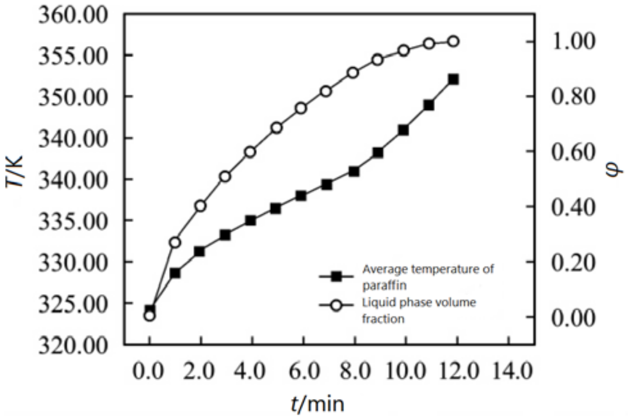


Figure 7. Variations of average temperature of paraffin and liquid phase volume fraction with time.

4. Results and discussion

Using FLUENT software and single variable method, the heat transfer characteristics of heat exchange unit under different working conditions are simulated by changing the flow rate of heat transfer fluid, the thermal conductivity of phase change materials and the structural size of equipment.

4.1 Simulation of heat storage/release process of heat exchange unit

In the process of heat storage, as shown in **Figures 5** and **6**, the inlet temperature of the heat transfer fluid is 363.15 K and the speed is 0.300 m/s. It flows in the circular tube from top to bottom and releases heat to the phase change area. The phase change layer is heated and melted, the solid-liquid phase change interface moves to the backheat area, and the temperature and volume integral number of the liquid paraffin continue to rise. With the continuous enlargement of the liquid phase area of paraffin and the continuous increase of temperature, the heat transfer temperature difference between paraffin and hot fluid decreases, the heat transfer intensity decreases, and the volume fraction of liquid paraffin and the temperature rise rate decrease, as shown in **Figure 7**. Until the paraffin is completely melted, the total heat storage capacity of the heat storage and heat exchange unit is 255.01 kJ.

During the exothermic process, the inlet temperature of the cold fluid is 293.15 K, and the flow rate is 0.030 m/s. As shown in **Figures 8** and **9**, the paraffin solidification releases the latent heat of phase change, and the temperature gradually decreases. Due to the enhanced heat transfer effect of the fins, the solidification process of the liquid paraffin near the fins progresses rapidly. As can be seen from **Figure 10**, with the passage of time, the cold fluid continuously absorbs heat, the average outlet temperature increases, and the maximum temperature reaches 307.14 K; then the solidification process advances, and the solid-liquid phase transition interface moves away from the cold fluid until the paraffin is completely solidified, and the average outlet temperature of the cold fluid drops to the initial temperature.

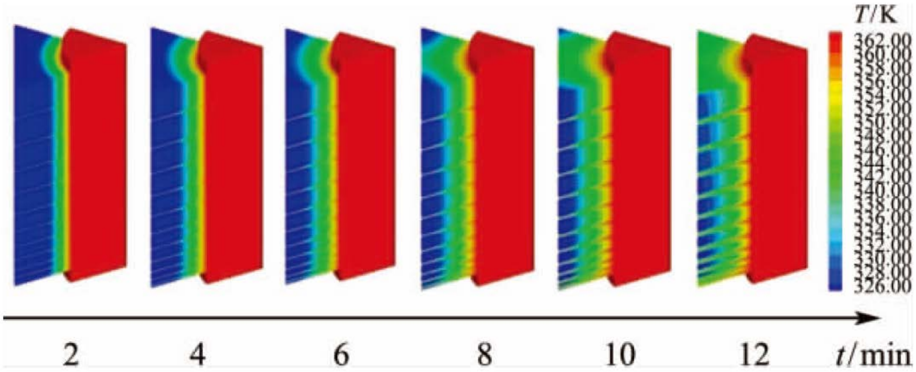


Figure 5. Temperature nephogram of heat transfer unit.

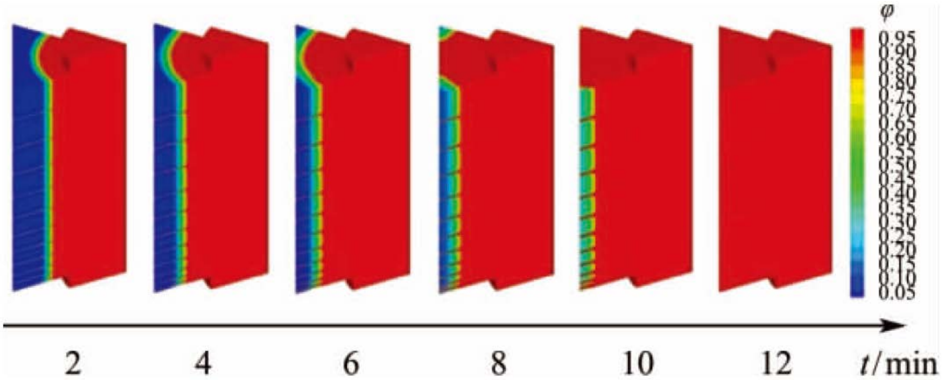


Figure 6. Liquid phase volume fraction nephogram of paraffin.

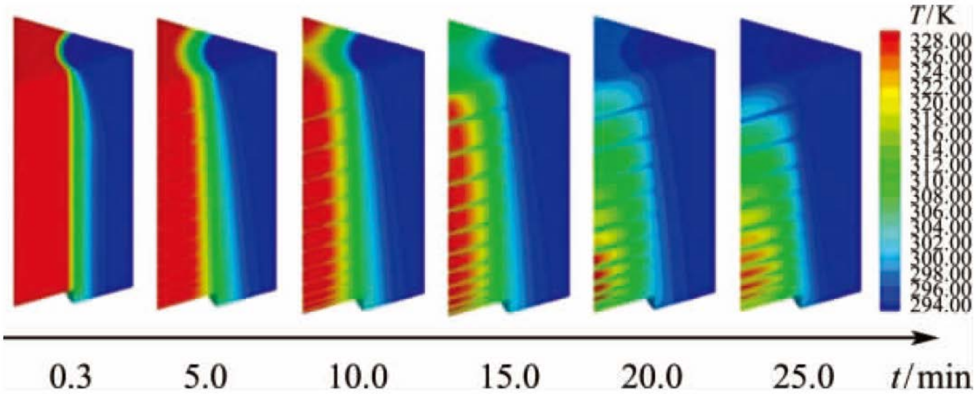


Figure 8. Temperature cloud diagram of heat exchange unit.

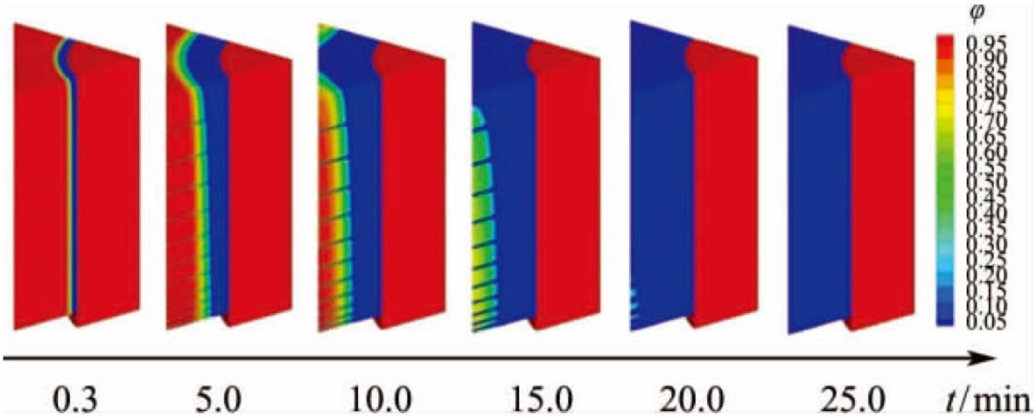


Figure 9. Liquid phase volume fraction nephogram of paraffin.

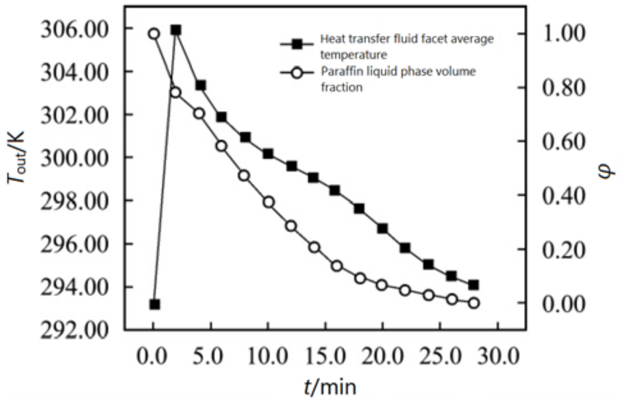


Figure 10. Variations of heat transfer fluid facet average temperature and paraffin liquid phase volume fraction with time.

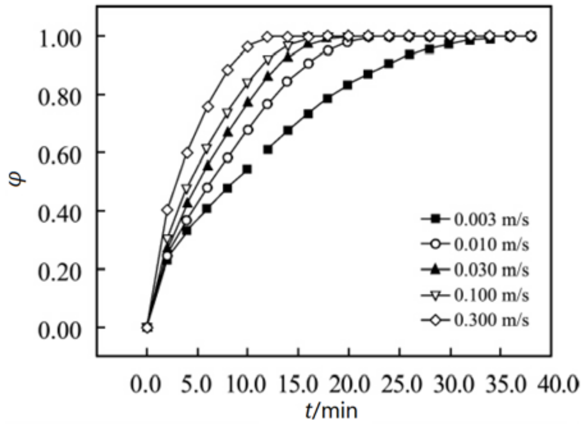


Figure 11. Variations of paraffin liquid volume fraction with different heat transfer fluid velocity.

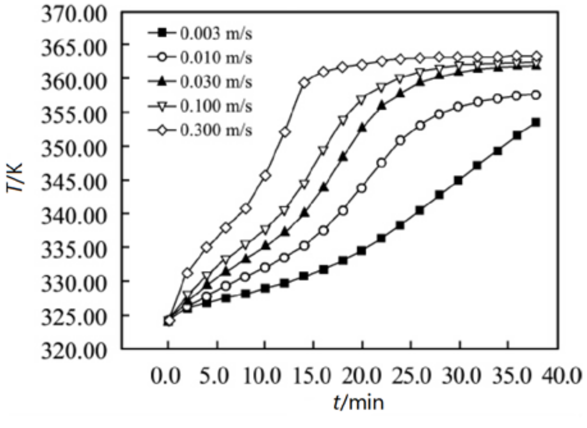


Figure 12. Variations of paraffin average volume temperature with different heat transfer fluid velocity.

4.2 Effect of heat transfer fluid flow rate on heat transfer capacity of heat exchange unit

Figure 11 shows that the flow rate of heat transfer fluid has a great influence on the heat storage process. The faster the flow rate of heat transfer fluid, the shorter the time required for the complete melting of paraffin. The time required for the complete melting of paraffin at the flow rate of 0.300 and 0.030 m/s is 0.32 and 0.53 times that at the flow rate of 0.003 m/s, respectively.

It can be seen from **Figure 12** that at the initial stage of heat storage, the exothermic temperature of hot fluid decreases, the heat absorption temperature of paraffin melting rises, the heat transfer temperature difference between the two gradually decreases, and the temperature rise rate of paraffin gradually decreases; with the expansion of the liquid region, the effect of the increase of the temperature in the liquid region on the increase of the average temperature rise rate in the phase change region is more than that of the decrease of the heat transfer temperature difference on the inhibition of the average temperature rise rate in the phase change region, and the temperature rise rate of paraffin gradually increases; finally, when the temperature difference between paraffin and heat transfer fluid is small enough, the temperature rise rate of paraffin decreases further.

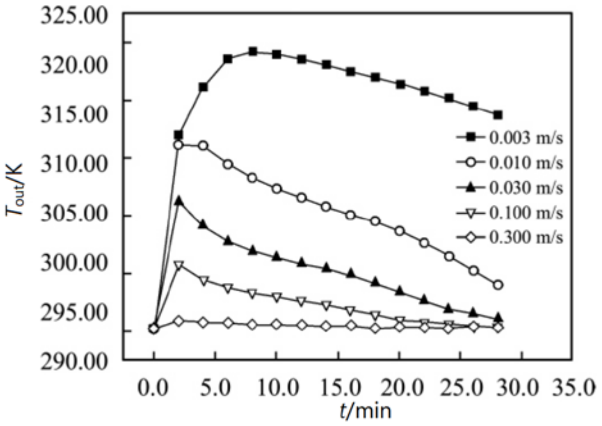


Figure 13. Variations of heat transfer fluid facet average temperature with different velocity.

During the heat release process, the average outlet temperature of the heat transfer fluid is greatly affected by the fluid flow rate, and the outlet temperature increases with the decrease of the fluid flow rate, as shown in **Figure 13**. When the flow rate is 0.003 m/s, the maximum temperature rise of the heat transfer fluid is 5.79 times that of 0.300 m/s. Because the lower the flow rate of heat transfer fluid, the longer the heat absorption time in the heat exchange unit, and the problem of reducing the mass flow of fluid and the total heat provided by the output end of the heat exchanger, it is necessary to reasonably select the flow rate of heat transfer fluid according to the actual situation to ensure the optimization of system performance.

Figure 14 shows that the paraffin solidification process is greatly affected by the flow rate of heat transfer fluid. It can increase the average outlet temperature by reducing the fluid speed, but the heat carried by the cold fluid decreases at the same time. As the reduction of heat transfer temperature difference and convective heat transfer coefficient weakens the heat transfer capacity of the heat exchange unit, the paraffin solidification process slows down and the released latent heat decreases.

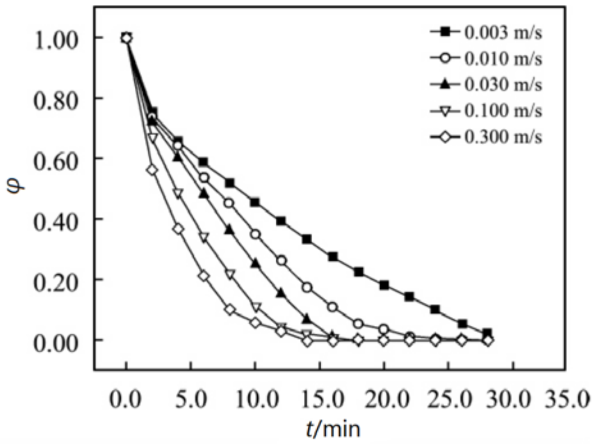


Figure 14. Variations of paraffin liquid volume fraction with different heat transfer fluid velocity.

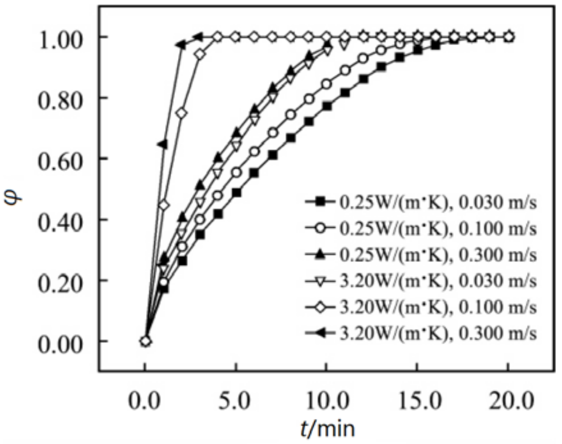


Figure 15. Variations of paraffin liquid volume fraction.

4.3 Effect of thermal conductivity of phase change material on heat transfer capacity of heat exchange unit

It can be seen from section 4.2 that the heat transfer fluid can get a good temperature rise only under the condition of low flow rate in the process of heat release, which is unrealistic in actual working conditions. The composite material of expanded graphite and paraffin in document[18] is selected as the heat storage medium, and the thermal conductivity is increased from 0.25 of pure paraffin to 3.20 W/(m·K).

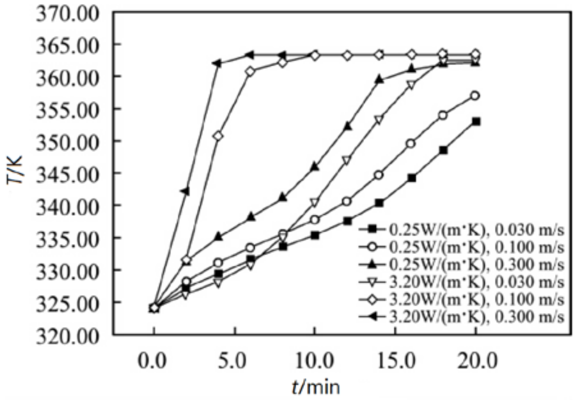


Figure 16. Variations of paraffin average volume temperature.

In the process of heat storage, three different flow rates are selected at the inlet of the heat transfer fluid: 0.030, 0.100 and 0.300 m/s. It can be seen from **Figures 15** and **16** that the completion time of the heat storage process of the heat exchange unit installed with composite materials at the same flow rate is much shorter than that of the pure paraffin heat exchange unit. In the three working conditions with flow rates of 0.030, 0.100 and 0.300 m/s, the time for the complete melting of the composite is 0.46, 0.40 and 0.33 times that of pure paraffin, respectively.

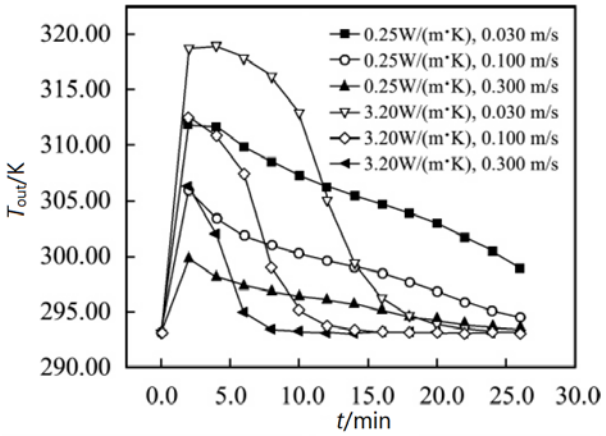


Figure 17. Variations of heat transfer fluid facet average temperature.

It can be seen from **Figure 17** that in the early stage of the heat release process, under the same flow rate and time, the average temperature of the heat transfer fluid outlet under the condition of high thermal conductivity is higher than that under the condition of low thermal conductivity。 In the three working conditions of flow rate of 0.030, 0.100 and 0.30 m/s, the maximum outlet temperature of the heat exchange unit installed with composite material is 6.50, 6.70 and 6.40 K higher than that installed with pure paraffin. With the advance of the exothermic process, the phase change material with high thermal conductivity solidifies rapidly, the solid layer thickens, the heat transfer resistance increases, the heat transfer temperature difference decreases, and the heat flow decreases due to the depletion of phase change latent heat. At the same flow rate and time, the average outlet temperature of the heat transfer fluid is gradually lower than that of pure paraffin.

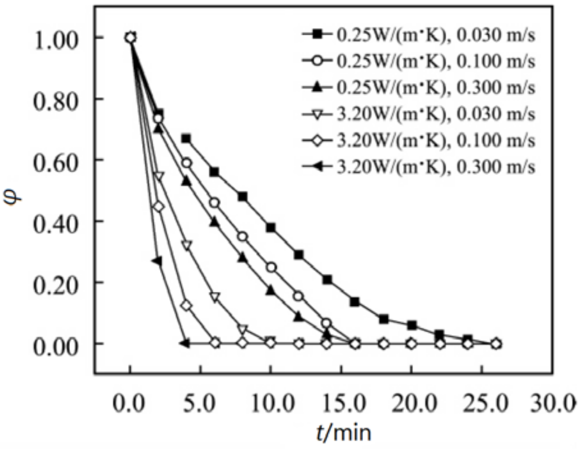


Figure 18. Variations of paraffin liquid volume fraction.

Figure 18 shows the change trend of paraffin liquid volume fraction during the exothermic process. It can be seen from **Figure 18** that phase change material with high thermal conductivity solidifies faster at the same flow rate and time. Use equations (8)–(10) to calculate the average heat transfer coefficient of the regenerative heat exchange unit.

$$\dot{Q} = c_{\mathrm{p}}\Delta\bar{T} + m_{\mathrm{p}}\Delta L \tag{8}$$

$$q = Q/\Delta t \tag{9}$$

$$q = \bar{k}\Delta T_m A \tag{10}$$

Where: $\dot{Q}$ is the heat release of the heat exchange unit in the calculation period, kJ/kg; c is the specific heat capacity of paraffin, kJ/(kg·K); m_{p} is the mass of paraffin, kg; $\bar{T}$ is the average heat exchange temperature difference of paraffin, K; ΔL is the latent heat released during paraffin solidification, kJ/kg; Δt is the time interval, s; k is the average heat transfer coefficient of the heat exchange unit, W/(m^2·K); ΔT_m is the average heat exchange temperature difference, K; A is the area of heat exchange surface, $\bar{k}$.

In the calculation, the time of completing the solidification process is rounded, and the maximum error is 2.0 min. After calculation, the average heat transfer coefficient of the heat exchange unit with composite material is more than twice that of the heat exchange unit with pure paraffin at the same flow rate.

4.4 Effect of phase change layer thickness on heat transfer capacity of the heat exchange unit

Improving the thermal conductivity of phase change material plays a great role in strengthening the heat transfer capacity of the heat exchange unit, but in the process of heat release, the solidification of phase change material is too fast, resulting in the decrease of heat output at the outlet of heat transfer fluid.

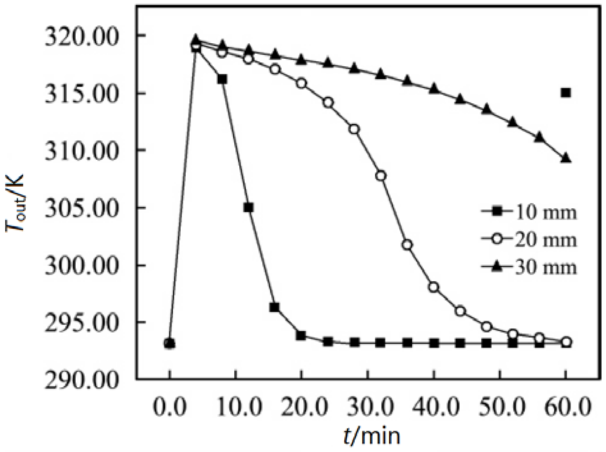


Figure 19. Variations of heat transfer fluid facet average temperature.

As shown in **Figure 19**, considering the heat supply quality at the outlet of the heat exchange unit, the heat transfer fluid flow rate of 0.030 m/s and the thermal conductivity of phase change material of 3.20 W/(m·K) are selected to simulate the heat release process. The results show that the thickness of the phase change layer has little effect on the heating stage of heat transfer fluid; in the cooling stage, the greater the thickness of the phase change layer, the more latent heat of phase change that can be provided to the heat transfer fluid, and the slower the temperature decay of the heat transfer fluid. For heat exchange units with phase change layers of 10, 20 and 30 mm, the average temperature of the heat transfer fluid outlet is maintained above 315.00 K for 9.5, 20.3 and 38.7 minutes respectively, effectively ensuring the heating quality of the output end of the regenerative heat exchanger.

5. Conclusion

In this article, a regenerative shell-and-tube heat exchanger is designed. In order to alleviate the uneven heat exchange temperature difference of the traditional equidistant rib structure heat exchanger and the high thermal stress of the heat storage container, the unequal spacing rib arrangement structure is adopted, the phase change area of the heat exchanger is selected as the heat exchange unit, and the control variates method is used to discuss the heat transfer characteristics of the heat exchange unit and draw a conclusion.

(1) The velocity of heat transfer fluid has a great influence on the heat storage process. The faster the velocity of heat transfer fluid is, the shorter the time for paraffin to melt completely.

(2) Improving the thermal conductivity of phase change materials plays a great role in strengthening the heat transfer capacity of the heat exchange unit. Under the three working conditions of flow velocity of 0.030, 0.100 and 0.300 m/s, the time of complete melting of the composite is 0.46, 0.40 and 0.33 times that of pure paraffin respectively; at the same flow rate in the exothermic process, the average heat transfer coefficient of the heat exchange unit with composite material is more than 2 times higher than that with pure paraffin.

(3) Increasing the thickness of the phase change layer can prolong the maintenance time of the average outlet temperature of the heat transfer fluid, and effectively ensure the heating quality in the process of heat release.

Conflict of interest

The authors declared no conflict of interest.

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