Experimental Analysis on Heat Release of Pulsating Heat Pipe Phase Change Regenerator with Different Working Fluids

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Abstract: In order to improve the problems of serious energy waste and low utilization rate, this paper designs and builds an experimental platform for a pulsating heat pipe type phase change heat storage device. The temperature changes with time in the heat storage and release device of the barium hydroxide octahydrate phase change material under different working conditions is studied. The results show that during the heat release process, when the pulsating heat pipe is filled with water, the cooling water temperature rises to the highest, and the heat recovery rate is as high as 64%. Otherwise, the initial temperature of the cooling water during the heat release process is studied. Result shows that the initial temperature of the cooling water increases, the longer the latent heat of phase change and the total heat release time, and the higher the temperature rise of the cooling water. The experimental design of this paper can provide a reference for researchers in related fields.

1. Introduction

At present, carbon neutrality is the consensus of human development, but it still faces many challenges in resources, technology, energy structure in the process of implementation[1]. Among them, energy is the most important survival basis for human society. With economic growth and the gradual exhaustion of non-renewable energy sources, energy supply in China is insufficient for that of demand[2]. However, a large amount of industrial waste heat has caused serious energy loss and also caused certain pollution to the environment. For example, automobile exhaust, ship exhaust, and industrial boiler waste heat are everywhere. There is often a temporary gap between waste heat availability and heating demand. The problem of mismatching makes it difficult to use wasted energy effectively. As one of the storage methods to solve renewable energy, energy storage technology provides a powerful measure for the storage of waste heat[3–6].

Latent heat storage technology has become a popular trend in environmental protection and improving energy efficiency[7–9]. This technology stores and releases energy by absorbing or releasing latent heat during the phase transition. It has the characteristics of high energy storage density and approximately constant temperature, and the structure of stored energy is simple [10]. The phase change heat storage device has a broad application prospect in thermal energy storage due to its small size, large energy storage, and uniform exothermic temperature [11–14]. Early Japanese scholar Akachi proposed a pulsating heat pipe (PHP) device that can be used in small equipment with efficient heat transfer function, and it has simple structure, it is also economical and practical, and flexible[15,16]. Therefore, PHP can be used as a heat transfer element in a phase change heat...
accumulator. P Khalilmoghadam et al. [17] studied a new type of solar distiller latent heat recovery heat storage system that combines a phase change material and a pulsating heat pipe. Store heat in the material. The latent heat of evaporation is stored during the day, releasing after sunset for prolonging the running time of the system. Q Li et al. [18] established numerical simulations through computational fluid dynamics (CFD) technology, and the results showed that the MEPCM suspension can tellingly ameliorate the dry resistance of PHP. After using MEPCM suspension as filling working medium, the startup time and Rth of PHP also expanded, but the change was not obvious. R Xu et al. [19] showed that the filling work medium is an vital factor affecting the heat transfer capability of a PHP. They proposed an azeotropic immiscible working fluid and studied the heat transfer characteristics under different ratios and heating powers. The results showed that two of these working fluids are slurred and stirred to form an emulsion, which can promote the heat transfer characteristics of the device. Cui Kaixuan et al. [20] showed that barium hydroxide octahydrate is a type of crystalline hydration salt with the highest latent heat density in the low temperature range of 0-120℃, as a phase change material (PCM), it has a wide prospect for application.

In order to reduce heat loss and improve energy efficiency, different working fluids are selected in this paper to use barium hydroxide octahydrate as the phase change heat storage material filled in the device, and a set of PHP phase change heat storage and release experimental device is set up to make the device play a certain role in the heat transfer process. The heat release characteristics of different working fluids and different cooling water temperatures in the heat release process are experimentally studied.

2. Experimental set-up

2.1. Introduction of pulsating heat pipe heat accumulator

Figure 1 shows the PHP phase change heat accumulator. This heat accumulator mainly uses a combination of PHP and phase change heat storage, and uses the high thermal conductivity of the PHP to enhance heat transfer. The heat accumulator is mainly divided into three areas: the top is the cooling area; the middle is the heat storage area, and the lower part is the evaporation area.

In order to obtain the temperature of measurement points at different locations, 6 different measurement points are set on the PHP phase change heat accumulator. Among them, measuring point 1 and measuring point 2 in the regenerator are located at the same horizontal position, which is completely covered by the phase change material, and is located at the bottom end, closest to the bottom heating steel plate, used to measure the phase change material near the bottom of the heat storage tank temperature changes; measuring points 3 and 4 are located at the same horizontal position in the middle, and are closer to the cooling zone than measuring points 1 and 2, which are used to measure the temperature change in the middle of the phase change material; and measuring points 5
and 6 are at the same level in the upper part. The position, the material has just been covered, is at the critical position between the material and the air. In addition, a T-type thermocouple (the accuracy is 0.5 ℃) is used to insert the end of the blind hole for temperature testing. The other end is connected to the data acquisition instrument to observe the temperature change of the material.

2.2. Introduction to the test bench

![Fig.2 Schematic diagram of pulsating heat pipe experiment platform](image)

As shown in Figure 2, this design mainly uses the pulsating heat pipe as the core to build the experimental platform. The lower part of the PHP device is connected to a high temperature constant temperature oil bath, and the heating medium in the pot is high temperature resistant silicone oil. When the material in the device is heated to the phase change temperature, you need to close the high-temperature oil bath, and then open the low-temperature thermostat. The low-temperature thermostat is a water tank that can set the initial water temperature and has a certain amount of water. The water pump makes the cooling water circulate back and forth between the low temperature constant temperature tank and the heat release place of the heat accumulator to cool the barium hydroxide octahydrate phase change material in the device. The heat released by the phase change material during solidification is used to heat the cooling water in the water channel, and the time taken to heat the cooling water in the water channel to a certain temperature is analyzed, and the heat release rate is obtained to evaluate the PHP phase change heat storage and release device the exothermic performance.

3. Results and discussion

3.1. Analysis of temperature changes under different working fluids

The setting conditions are that the mass of the material barium hydroxide octahydrate is 4.5kg, the initial temperature of the cooling water is 20 ℃, the cooling water flow is 0.13m³/h, and the working fluid of the PHP is set to water and absolute ethanol and methanol, the filling rate is 0.3. The temperature change curve of the filled material at each measuring point during the entire heat storage process is shown in Figure 4 below:
Figure 3 shows that when the working fluids are different, the heat release time of the phase change latent heat stage are also different, but the heat release trend is basically the same. The measurement point 1 is selected here for experimental analysis. When the working fluid is methanol, the cooling water can be heated up to 41.8℃, and the phase change latent heat duration is 7500s; when the working fluid is absolute ethanol, the cooling water can be heated up to 41.2℃, the duration of the latent heat of phase change is 8200; when the working fluid is water, the cooling water can be heated up to 43.3℃, and the duration of the latent heat of phase change is 9550s. Therefore, the time consumed by the materials in the phase change coupling module in the heat release process is different for different working fluids. The reason is that the boiling points of different working fluids are different, the temperature difference they produce is different, and the oscillation effect induced is also different. Therefore, the time consumed by the phase change material when exothermic is also different.

3.2. Variation analysis of heat recovery rate under different working fluids

The heating fluid (high temperature silicone oil) of the PHP phase change heat storage and release appliance designed in this experiment is used to simulate industrial waste heat or engine exhaust, and the recovered heat is stored in the phase change material. The cooling water channel connected to the upper end of the heat storage device is used to simulate the heat extraction process on the user side. In this system, the total stored heat absorbed by the change of the phase change material is calculated as follows:

\[ Q = Q_1 + Q_2 + Q_3 = C_s \cdot M \cdot \Delta T_s + M \cdot Q_{pcm} + C_l \cdot M \cdot \Delta T_l \]  

(1)

Among them, \( Q_1 \) represents the solid state sensible heat storage capacity, \( Q_2 \) represents the latent heat storage capacity when the PCM changes in the liquid state, \( Q_3 \) represents the liquid sensible heat storage capacity of the PCM; \( C_s \) is the solid state specific heat capacity of the PCM, namely
1.17\,kJ/(kg\cdot ^\circ \! C) \); \( C_i \) is the phase the liquid specific heat capacity of the changeable material, 
1.17\,kJ/(kg\cdot ^\circ \! C) \); \( M \) is the mass of the PCM, that is, 4.5kg; \( Q_{pcm} \) is the latent heat of the PCM, that is 285\,kJ/kg; \( \Delta T_i \) is the temperature difference between the initial heating temperature and the temperature at the end of the phase change; \( \Delta T_f \) is the temperature difference from the end of the phase change to the final end of the material.

Heat recovery \( Q_w \) is the heat recovered from the heat accumulator in the water tank, which is,

\[
Q_w = C_w \cdot M_w \cdot \Delta T_w = C_w \cdot \rho_w \cdot V_w \cdot \Delta T_w \tag{2}
\]

Among them, \( C_w \) is the specific heat capacity of the cooling water, which is 4.2\,kJ/(kg\cdot ^\circ \! C); \( M_w \) is the material quality, which is kg; \( \rho_w \) is the density of the cooling water, which is 1kg/L; \( V_w \) is the volume of the cooling water, that is, the added cooling water is 10L; \( \Delta T_w \) is the difference between the initial and final temperature of the cooling water. The maximum heating temperature of the cooling water in the water tank under different working fluids is different, that is, the heat recovery rate is calculated as shown in the following table1:

| Working substance     | Maximum temperature of cooling water (℃) | Heat storage (\( Q/kJ \)) | Recoverable heat (\( Q_w/\text{k}J \) %) | Heat recovery rate (%) |
|-----------------------|------------------------------------------|----------------------------|------------------------------------------|-----------------------|
| Methanol              | 41.8                                     | 1536.3                     | 915.6                                    | 60                    |
| Anhydrous ethanol     | 41.2                                     | 1539                       | 890.4                                    | 58                    |
| Water                 | 43.3                                     | 1528.4                     | 978.6                                    | 64                    |

It can be seen from Table 1 that the heat recovery rate is the highest when water is used as the working medium, but the total heat storage is lower. This is due to the longer time spent in the heat storage process, which may reduce a certain amount of heat loss.

3.3. Analysis of the change of the initial cooling water temperature at different times

Fig.4 Variation curve at different initial temperature of cooling water
### Table 2. Change of different cooling water temperature and time

| Initial temperature of cooling water (℃) | Maximum temperature of cooling water (℃) | Latent heat release time (s) | Heat storage (Q/kJ) | Recoverable heat (Q_r/kJ %) | Heat recovery rate (%) |
|----------------------------------------|------------------------------------------|----------------------------|-------------------|-----------------------------|-----------------------|
| 10                                     | 38.2                                     | 7000                      | 1555.2            | 1184.4                      | 76                    |
| 20                                     | 43.5                                     | 9500                      | 1527.3            | 987                         | 65                    |
| 25                                     | 46.5                                     | 10600                     | 1527.3            | 987                         | 58                    |

As shown in Figure 4, change the initial temperature of the cooling water, set different cooling temperatures to 10℃, 20℃, and 25℃, complete 3 sets of experiments and obtain images.

It can be seen from Figure 4 and Table 2 that when the initial water temperature of the cooling water is set to 10℃, the phase change latent heat release time is about 7000s, the total heat release time is about 13,500s, and the maximum temperature of the cooling water can be raised to 38.2℃; when the initial water temperature of the cooling water is set to 20℃, the phase change latent heat release time is about 9500s, the total heat release time is about 16700s, and the maximum temperature of the cooling water can be raised to 43.5℃; when the initial water temperature of the cooling water is set to 10℃, the phase change latent heat release the heat duration is about 10600s, the total heat release duration is about 17900s, and the maximum temperature of the cooling water can be raised to 46.5℃. Through experimental analysis, it can be seen that when the initial temperature of the cooling water rises, the maximum temperature of the cooling water also increases, and the phase change latent heat duration and total heat release duration also increase.

### 4. Conclusions

In order to strengthen the heat transfer capability of the PHP, the temperature change of the phase change material during the heat release of the PHP phase change heat storage and release device was studied. By changing the initial temperature of the charging working medium and the cooling water, the different effects to heat transfer performance of device under different working conditions are studied, and the experimental analysis through the heat recovery rate, draw the following conclusions:

1. Methanol, anhydrous ethanol and water are used as the filling working fluid, the temperature rises the highest when using water as the works fluid, and the heat recovery rate is the largest, reaching about 64%.

2. When water is used as the filling working medium, the heat release of cooling water at different initial temperatures is studied. As the initial temperature of cooling water rises, the longer the PCM take for latent heat release the faster the water temperature increase. The heat recovery rate in the PHP heat storage device decreases with the increase of the initial temperature of the cooling water.

Therefore, when methanol, absolute ethanol and water are used as working fluids, the heat recovery rate of water is the highest, and the lower the initial water temperature of the cooling water, the higher the relative heat recovery rate. The duration to phase change latent heat release time is relatively short, but considering cost, management and other factors, setting initial water temperature to be 20℃ is recommended.

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