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The effect of changing PCM distribution on thermal performance of latent heat storage

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Abstract—In previous studies on thermal performance of solid-liquid phase change thermal energy storage (TES), it could be found that the lower phase change material (PCM) of TES was difficult to melt due to the influence of natural convection. Therefore, many scholars improved the overall thermal performance by enhancing the heat transfer in the lower region, increasing the distribution of the lower fins, increasing the length of the lower fins, or changing the porosity of the lower metal foam to improve the lower heat transfer. However, it had not been found that by changing the ratio of the upper and lower PCM to improve the heat storage performance. Therefore, this paper designed ten cases to study the effect of different ratios of the upper and lower PCM on the heat storage performance and finally found that the case 2 performed best, and the full melting time is 17240 s, reduced 39.05% compared with 28290 s of case 6.

Keywords: improve heat transfer, shell-and-tube heat storage tube, numerical simulation

NONMENCLATURE

Abbreviations

LTES	Latent thermal energy storage
PCMs	Phase change materials
HTF	Heat transfer fluid

Symbols

f_m	Melting fraction

I INTRODUCTION

Energy storage is an effective method to solve the problem of clean energy intermittency and the mismatch between the time and place of waste heat generation and use. The current heat storage methods mainly include three methods: sensible heat storage, phase change heat storage, and chemical reaction heat storage. Among the above list, phase change heat storage is widely used, thanks to its weak temperature fluctuation and high energy density. And mainly due to the small variation range of volume change, the solid-liquid phase transition has been widely used. And in order to improve the low conductivity of organic PCM, the methods of increasing area of heat transfer [1], and adding some material to make the high conductivity PCM [2] have been widely studied. And the phenomenon suggests a direction to further improve the speed of melting, that is by improving the heat transfer of lower phase change materials will increase the overall thermal effect and reduce the overall complete melting time.

Therefore, many researchers increased the proportion of the lower fins by changing the arrangement of the fins to strengthen the melting of the lower phase change material, and improve the melting uniformity and overall thermal performance of latent heat storage system. Wu et al. [3] explored the influence of position and length of the single fin on the melting and solidification of the phase change material in the latent heat storage unit through transient numerical simulation. The comparison of four indexes, the liquid-solid interfaces, temperature distributions, velocity vector and phase change rate, were analyzed, and the conclusion was that increasing the fin length and lowing the fin position would both decrease the total melting time significantly. Sodhi et al. [4] studied the effect of annual fins distribution on the charging and discharging processes. The conclusion was that the employment of non-uniformly distributed fins in the single PCM system led to a 24.5% and 16.5% reduction in the melting and solidification times.

In addition, some researchers increased the proportion of the lower fins by changing the angle between the fins to enhance the strengthening effect of the fin on the phase change material. Yu et al. [5] designed gradient fins with gradient thickness and gradient central-angle, and developed the simulation to investigate the melting behaviors of latent heat storage unit with gradient fins. The optimal gradients of fin thickness and central angle can be gotten through the RSM optimization, the value in their paper are 2.846 mm and 14.96°, respectively. And the complete melting time is reduced by 30.5% for the optimized LHS unit as compared with the corresponding uniform fin. Moreover, some researchers increase the proportion of the lower fin by changing the shape of the fins. Tiari et al. [6] compared the thermal characteristic of the latent heat storage system with different fin heights, whose volume were kept constant. And the result showed that the charging time of latent heat storage system in the configuration with 20 fins of varying length with the longer fins on the bottom tapering to the top. decreased the most, and the total decrease in time for this configuration was 73.7%.

Except the research on the improvement of the fins, some people promote the melting of the phase change material in the region where the phase change material was more difficult to melt by increasing the porosity of the metal foam, thereby achieving the effect of promoting the overall melting performance. Marri et al. [7] compared the thermal characteristic of different composite PCM made of an open-cell aluminum metal foams with different porosities of 0.9, 0.94 and 0.97 and PPI of 8, 14 and 20. The results showed that time to reach a setpoint temperature of the case of non-uniform variation in porosity with constant PPI density and the case of non-uniform PPI density with constant porosity show superior performance up to 28% and 45% compared with uniform porosity and PPI density respectively in the charging cycle. Wang et al. [8] experimentally compared the thermal performances of commonly used homogeneous copper foam and a gradient copper foam. And the experimental results presented that the gradient porosity copper foam improved temperature uniformity in the thermal energy storage system and the overall melting time reduced by 37.6% compared to the embedded homogeneous metal foam in the phase-change material.

In addition to the above-mentioned methods of improving the melting uniformity by improving the distribution or shape of fins and porosity of the metal foam, this article proposed that through changing the shape of the LHTES to satisfy the need. In order to alleviate the phenomenon that the phase change material under the latent heat storage system melts faster than the phase change material above, this paper designed a trapezoid LHTES and tried to improve the melting uniformity by decreasing the quality of phase change material in the low part.

II. Physical Models And Computational Domains

In this paper, a series of novel vertical shell-and-tube regenerators are designed. The basic accumulator is designed by two concentric circles. The outer cylinder is made of Perspex with a diameter of 45mm, and the inner cylinder is made of copper tubes, with a diameter of 22mm and a thickness of 1mm. And the other cases were improved by changing the ratio of upper and lower radius of storage, and ratios are listed in TABLE 1.

Since the phase transition interface, temperature distribution, and flow velocity distribution contours obtained by sectioning the heat accumulator along different diameters of the model are always the same, and the model is an axisymmetric graph, the numerical calculation area of the model is selected as half of the above-mentioned section surface. The computational domain contains half of the inner copper tube and phase change material along the water flow direction, this solution also saved computational space on the premise that the same phase change law can be observed.

III. Model Validation

To validate the present numerical simulations, the experimental results of a basic model case6 are compared with. The experiment were performed for a vertical concentric tube heat exchanger, incorporating an organic PCM (Paraffin RT35). Water was employed as the heat transfer fluid and injected from the top. To record the temperature evolution in PCM, a fixed point at one radial position was chosen. Fig. 1 compared the temperature history from the measurement and the numerical results. A good agreement between numerical and experimental data can be noted (with a maximum deviation of 5.4%), confirming the feasibility of the computational models developed in the present study.

TABLE I THE SIZE OF TEN CASES

	Length of upper boundary / mm	**Length of lower boundary / mm**
case 1	71.858	11.000
case 2	69.994	13.999
case 3	68.034	17.008
case 4	64.852	21.617
case 5	58.919	29.459
case 6	45.000	45.000
case 7	29.459	58.919
case 8	21.617	64.852
case 9	17.008	68.034
case 10	13.999	69.994

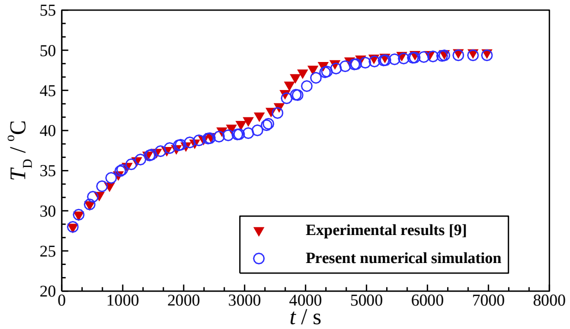

Fig. 1. The comparison of temperature between experimental and numerical.

IV. RESULTS AND DISCUSSION

A. *Melting fraction*

Fig. 2 depicted the detailed changes of each case in the whole melting process, and the result showed that the melting fraction curves of the ten cases coincided before about 500 s. This was mainly because at the beginning of melting, only the PCM near the copper tube was heated up rapidly by conduction and melted. Therefore, the different distribution of PCM has no effect on the melting of PCM, so the melting fraction of each case is almost the same. From 500 s to 7500 s, the melting fraction curves of ten cases showed great difference, among which case 2 melted fastest, case 6 melted slowest, and the difference between two cases was large. From 500 s and 7500 s, case 1, case 2, case 3, case 9, case 10 exhibited faster melting rates than case 4, case 5, case 6, case 7, case 8. This could be accounted that the proportion of upper and lower boundaries in case 1, case 2, case 3, case 9, and case 10 was large, so there was an area with little PCM in the upper or lower region of the LHTES and it had small area in contact with the low temperature solid PCM. So the temperature of this small solid PCM rose fast and the melting rate was faster in the initial stage. After 7500 s, the melting rate of case 7, case 8, case 9 and case 10 began to slow down, which could be demonstrated by the gradient decrease of the melting fraction curve. This phenomenon could be explained that the natural convection moved the high temperature liquid PCM to the upper region of LHTES increased the distance between high temperature liquid PCM and large proportion unmolten PCM in the lower part of LHTES, which increased the difficulty of delivering heat to low temperature unmolten PCM. But the melting rate of case 5 and case 6 was accelerated, so the slope of the melting fraction curve became steeper. At about 11800s, the melting rate of case 5 and case 6 exceeded the melting rate of case 7, case 8, case 9 and case 10, and continued until melting ending. This could be explained that as the melting processed, the liquid PCM continued to increase, and the natural convection in the LHTES strengthened. In general, the melting rate of case 1, case 2, case 3, case 4, and case 5 is higher than the melting rate of case 6, and increasing the PCM proportion of lower region will slow down the melting rate. And the case 2 melted fastest, the full melting time was 17240 s, reduced 39.05% compared with 28290 s of case 6.

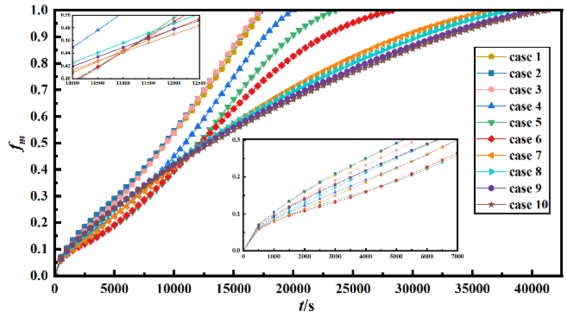

Fig. 2. The melting rate curves of ten cases

B *The melting front contour*

In order to clearly reflect the internal melting process of each case, Fig. 3 showed the melting front of ten cases at 1000 s, 8000 s and 15000 s. It could be seen from Fig. 3 that the melting front of the ten cases had shown difference at 1000 s. For every case, there was a very thin liquid PCM near the copper tube and a small area of liquid phase in the upper region of LHTES formed by erosion of natural convection. But for case 1, case 2, case 3, case 9, and case 10, there existed less PCM regions that was easily to heat up, so these regions became complete molten regions at 1000 s. At 8000 s, the difference of the melting front was further enlarged. For case 7, case 8, case 9 and case 10, since the PCM distributed in the upper region of LHTES sequentially decreased, so at 8000 s the melting front of case 7, case 8, case 9 and case 10 was lower and lower sequentially. In case 1, case 2 and case 3, due to the less PCM in the lower part, there were not only a large area of liquid PCM appeared in the upper region of LHTES, but also a large area of liquid PCM in the lower part at 8000s. At 15000s, the liquid area in the lower part of case 1, case 2 and case 3 expanded compared with 8000 s, and the natural convection was also strengthened, and the PCM in the middle part became difficult area to melt. But by accepting the convective heat transfer from the upper and lower liquid PCM, the PCM in the middle part also melted rapidly.

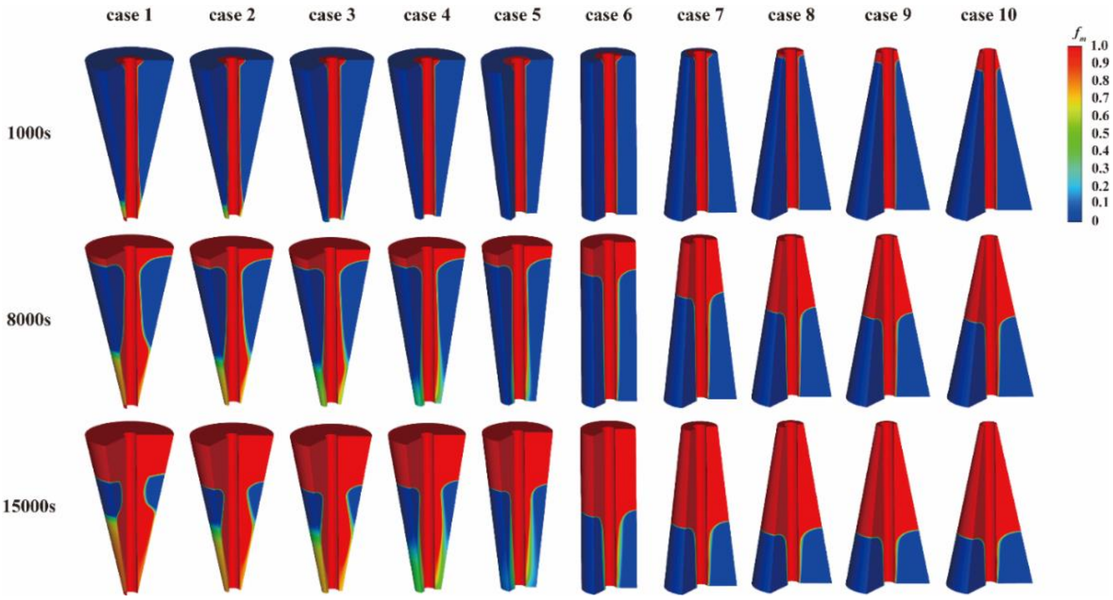

Fig. 3. Melting front interface

V. Conclusion

This article discussed the effect of changing the distribution of PCM on the heat storage performance of the heat storage. By observing the heat storage performance of ten cases, the following conclusions are drawn:

1. By increasing the proportion of PCM located in upper zone will improve the heat transfer. And increasing the proportion of PCM located in lower zone will slow down the heat transfer process.

2. The case 2 performed best, and the full melting time is 17240 s, reduced 39.05% compared with 28290 s of case 6.

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