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Study on the Enhanced Heat Transfer of Cascade Phase Change Heat Storage Devices by the Filling Ratio of PCM

Yurao Li[1]， Jianjun Wen*
*[*1]Inner Mongolia University of Science and Technology, Baotou 014000, China*
Corresponding Author: Jianjun Wen, E-mail: 1042076584@qq.com

Abstract
In order to solve the problem of phase change material (PCM) melting asynchronous at all levels of cascade phase change heat storage device, this study used numerical simulation method to construct a physical model of five different PCM filling ratios, and quantitatively analyzed the liquid phase distribution characteristics, complete melting time and melt out of sync rate based on the enthalpy method. The results show that the cascade phase change heat storage device can optimize the complementarity and heat distribution between materials by adjusting the PCM filling ratio. In this process, the synergistic effect of low-temperature PCM and medium-temperature PCM is significant, the melt out of sync rate is reduced to 2.85%, and the overall complete melting time is shortened by 7.6% compared with other proportions, which effectively improves the stability and melting rate of the device, and provides a theoretical basis for the optimal design of the device.

Keywords: *Cascade phase change heat storage device, Numerical simulation, Enhanced heat transfer.*

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I. INTRODUCTION

Under the dual pressure of rising global energy demand and intensifying climate change, the international community is accelerating the construction of a "low-carbon, diversified and intelligent" new energy system. Due to its high energy storage density and isothermal energy release characteristics, phase change heat storage technology has shown unique advantages in scenarios such as building envelope [1], heating and air conditioning [2, 3], solar thermal photovoltaic utilization [4], and building waste heat recovery [5], which is helpful to solve the problem of mismatch between energy supply in time and space, and realize energy peak shift and valley filling.

The traditional single-stage phase change heat storage device has the disadvantages of low heat exchange efficiency and long heat storage cycle. Based on the principle of "temperature matching and cascade utilization", the cascade phase change heat storage device optimizes the heat transfer process through multi-stage phase change materials (PCM), and the thermodynamic performance is better [6]. In 1986, Farid [7] first proposed a cascade phase change heat storage device model, using three paraffin waxes with different melting points as PCM, and the study showed that the heat transfer rate during the storage/release process was significantly improved when PCM with different melting points was used. Adebiyi et al. [8] conducted numerical simulations of multi-stage and single-stage PCMs, and the results showed that when using five PCMs with stepwise decreasing phase transition temperatures, the energy storage efficiency can be improved by 13%-26% compared with the single-stage system, and the thermal stratification phenomenon can be reduced by 42%. Hu [9] found that compared with single-stage energy storage devices, the combined energy storage method can improve the energy utilization rate of the system, and through the method of thermodynamic effective energy combined with numerical analysis, it was concluded that when the four PCMs are combined, the effective energy utilization rate can reach more than 80%, which is 50% higher than that of a single PCM. Mujumdar et al. [10] constructed a multi-level PCM thermodynamic evaluation system,the system performance of 2 - stage, 3 - stage, and 5 - stage PCM configurations was systematically compared. The results show that compared with the single-stage system, the multi-stage PCM array can reduce the loss coefficient to 1/3, and the system efficiency reaches the peak of 72.4% when the proportional temperature gradient configuration is adopted, which is 8-12 percentage points higher than that of the linear distribution.

However, through the above studies, it is found that although the cascade phase change heat storage device can optimize the heat transfer process through multi-stage PCM synergy, and its thermodynamic performance is significantly better than that of the traditional single-stage phase change heat storage device, the melting time of each phase change interval of the cascade phase change heat storage device is different, and the complete melting time of the device mainly depends on the melting time of the PCM with the highest phase change temperature. Therefore, in order to improve the heat transfer performance and optimize the heat transfer effect, it is important to design the PCM filling ratio reasonably. In this paper, five cascade phase change heat storage devices with different filling ratios in different phase transition intervals are designed, and numerical simulations are carried out to analyze the influence of different filling ratios on heat storage performance, in order to provide theoretical support for practical application.

II. ESTABLISHMENT OF MATHEMATICAL MODELS

2.1. Physical Model

The cascade phase change heat storage device is shown in Figure 1, which is a 720mm×140mm×440mm cuboid, which is divided into three areas by two thin plates, which are filled with PCM1, 2, and 3 respectively. The unit is equipped with two sets of copper serpentine tubes that serve as heat transfer fluid (HTF) channels. The HTF inlet is the origin of the system, and the fluid (water) flows in from the left inlet and out from the right outlet through the serpentine tube. The serpentine pipe consists of a pipe with a diameter of 20 mm and a bending radius of 15 mm, with a straight pipe length of 330 mm and a pipe length of 380 mm. Composite PCM [11] was selected, and its thermophysical parameters are shown in Table 1.

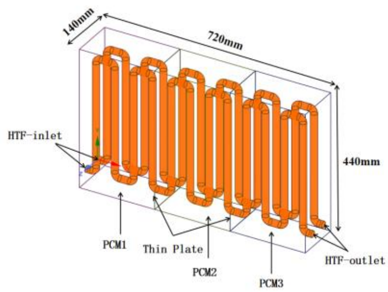


Figure 1: Schematic diagram of cascade phase change heat storage device

Table 1: PCM thermal performance parameters[93]

Parameter	70% (10% paraffin + 90% stearic acid): 30% graphite	70% (90% paraffin + 10% stearic acid): 30% graphite	70% (50% paraffin + 50% stearic acid): 30% graphite
Phase Change Temperature K	338	330	322
Latent Heat of Phase Change J/kg	190900	219200	241900
Density kg/m^3	1070.5	923.3	919.8
Thermal Conductivity W/（m·K）	1.143	1.207	1.292
Specific Heat J/（kg·K）	2202.40	2426.55	2326.55

2.2. Mathematical models

In order to simplify the calculation process, the following reasonable assumptions are made:

(1) The PCM at all levels inside the phase change heat storage device is uniformly distributed and isotropic.

(2) Using the Boussinesq approximation, it is considered that the density of PCM changes very little, and only changes with temperature in the buoyancy force.

(3) Ignore the thickness of the pipe wall of the heat storage device, and the thermal resistance is not counted.

(4) ignore the heat dissipation loss of the phase change heat storage device to the outside world and think that the heat storage of the device cylinder is very small, and can be ignored, according to the adiabatic treatment.

(5) There is no supercooling (heating) phenomenon in the phase transformation process.

Based on the above assumptions, the governing equations for PCM are as follows:

(1) Continuity equation:

$$\frac{\partial\rho}{\partial t} + \nabla(\rho\vec{V}) = 0 \tag{1}$$

where: ρ : the density of PCM, kg/m³; t : the time, s; $\vec{V}$: the flow velocity in the PCM liquid phase zone, m/s.

(2) Momentum equation:

$$\rho\frac{\partial(\vec{V})}{\partial t} + \rho\mu\nabla(\vec{V}) = -\nabla P + \mu\nabla(\vec{V}) + S \tag{2}$$

where: P : pressure, Pa; μ : the dynamic viscosity, Pa·s; S : the source term of the momentum equation and represents the loss of momentum, is expressed as:

$$S = \frac{(1-\beta)^2}{\beta^3+\varepsilon} A_{mush}(\vec{V} - \vec{V_{\mathrm{p}}}) \tag{3}$$

where: β : liquid fraction; A_{mush} : the constant of the paste region, and the value is between 10^4 and 10^7. ε : A number less than 0.0001 to prevent the denominator from being 0. $\vec{V_{\mathrm{p}}}$: the implication velocity, the index of continuous motion of the solidified material, m/s.

(3) Energy equation:

$$\frac{\partial(\rho H)}{\partial t} + \nabla(\rho\vec{V}) = \lambda\nabla^2 T + S_n \tag{4}$$

$$S_n = \frac{\partial(\rho T_{ref})}{\partial t} + div(\rho H T_{ref}) - div(\frac{\lambda}{c_p}\nabla T_{ref}) \tag{5}$$

where: λ : thermal conductivity, W/(m·K); H : is the total enthalpy, J; T_{ref} : reference temperature, K; c_p : the specific heat capacity of constant pressure, J/(kg·K)。

(4) Enthalpy equation:

$$H = \quad + \Delta H \tag{6}$$

$$= \quad {}_{ref} + \int_{T_{ref}}^{T} C_p \, dT \tag{7}$$

$$\Delta H = \beta L \tag{8}$$

$$\beta = \begin{cases} 0, & T < T_s \\ \dfrac{T - T_s}{T_l - T_s}, & T_s < T < T_l \\ 1, & T_l < T \end{cases} \tag{9}$$

where: T_s : the freezing point temperature of PCM, K; T_l : the melting point temperature of PCM, K.

2.3. Boundary conditions and initial conditions

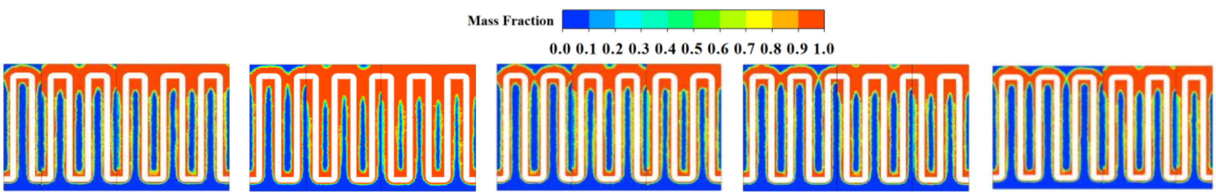
In the process of heat storage in the simulated heat storage unit, the HTF selects the velocity flow rate and temperature inlet boundary conditions, and the inlet temperature of the inner and outer tubes HTF is constant 359K, and the average inlet flow velocity is 1m/s, substituting the flow rate into Formula (10).The critical Reynolds number is Re>2600, and the HTF is turbulent. The HTF outlet boundary condition is the average static pressure outlet boundary condition, and the outlet relative pressure is Pout=0. The outer walls are set as adiabatic walls, and the heat exchange walls of HTF and PCM, as well as the thin plates separated by two stages of PCM, are set as coupled walls for heat exchange coupling calculation. The initial temperature of the unit as a whole is set to 305 K.

$$Re = \frac{d_e v_{in}}{\nu} \tag{10}$$

where: d_{e} : the equivalent diameter of the pipeline where the HTF is located, m; v_{in} : the HTF inlet flow rate, m/s; ν : the kinematic viscosity of HTF, m^2/s.

III. LIQUID PHASE CONTOUR ANALYSIS

By changing the filling ratio of PCM1 and PCM3 to keep the PCM2 filling ratio constant, five cascade phase change heat storage devices with PCM filling ratios of 2:4:6, 3:4:5, 4:4:4, 5:4:3 and 6:4:2 were designed. According to the liquid phase cloud at different times, the melting state in the cascade phase change device can be clearly displayed, and Figure 2 shows the liquid phase cloud of five PCM filling ratios at 900s.



(a) 2:4:6 (b) 3:4:5 (c) 4:4:4 (d) 5:4:3 (e) 6:4:2

Figure 2: Liquid contour diagram of five PCM filling ratios at 900s

As can be seen from Figure 2, among the five devices, PCM3 has the lowest phase change temperature and the fastest melting rate, and its filling ratio directly affects the significance of the difference in melting rate. When the proportion of PCM3 increases (e.g., 2:4:6), the proportion of PCM3 is higher, but because the proportion of PCM1 is too small, the inlet heat is underutilized, resulting in an imbalance in heat distribution. The 3:4:5 filling ratio achieves a more reasonable heat distribution, and at the beginning of the 900s melting, the filling is more efficient than the heat transfer and utilization of the unit, and the overall melting process is more harmonious.

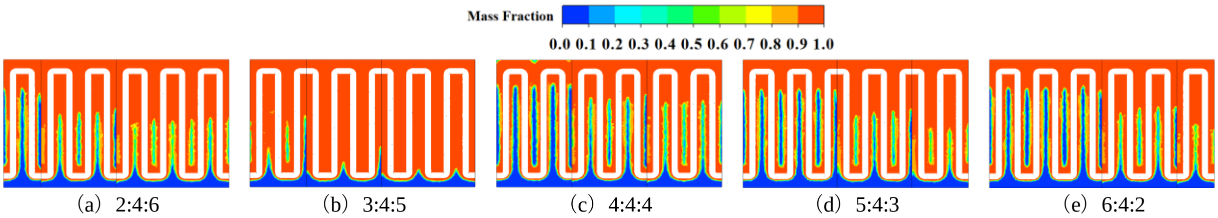


Figure 3: Liquid contour diagram of five PCM filling ratios at 1800s

From Figure 3, it can be intuitively found that the melting degree and uniformity of each PCM at a filling ratio of 3:4:5 are higher than those of the other four filling ratios, which further highlights the advantages of a filling ratio of 3:4:5: the leading effect of PCM3, the buffering effect of PCM2 and the inlet advantage of PCM1, that is, in the structure with a filling ratio of 3:4:5, it is manifested as a synergistic effect between PCM performance and heat distribution. In the process of cascade phase change heat transfer, because the phase transition temperature of PCM3 is the lowest and the thermal conductivity is the largest, it forms the "engine" of heat diffusion, and the boundary surface of PCM2 and PCM3 uses coupled boundary conditions, so part of the heat is conducted from PCM3 to PCM2 at the junction, resulting in an increase in the melting degree of PCM2, and the high latent heat energy of PCM2 makes it absorb more heat without heating up quickly, balancing the heat distribution. Similarly, there is some heat transfer at the junction of PCM1 and PCM2, and the HTF has a high water temperature at the inlet, so PCM1 is in direct contact with the high-temperature fluid, taking advantage of the heat transfer efficiency at the inlet to further promote the coordination of the overall melting process. As a result, PCM1 is more melted. The complementary performance of the PCM results in efficient heat transfer in units with a 3:4:5 filling ratio. In the filling ratio of 2:4:6, the proportion of PCM3 is too much, resulting in excessive concentration of heat and uneven melting, and the proportion of PCM1 is too small, and the inlet heat cannot be fully utilized. When the filling ratio is 4:4:4, although the proportion of each PCM is evenly distributed, it lacks the complementary effect between the PCMs in the filling ratio of 3:4:5, and the heat transfer and; The utilization rate is relatively low, resulting in the overall melting degree and uniformity is not as good as 3:4:5. In the filling ratios of 5:4:3 and 6:4:2, the proportion of PCM3 is relatively small, which cannot fully play the role of "engine", and cannot achieve an optimal state in heat distribution and transmission, which affects both melting rate and uniformity.

IV. ANALYSIS OF MELT OUT OF SYNC RATE

As can be seen from Table 4.1, the overall melting time of the filling ratio of 3:4:5 is 3.48%, 2.00%, 7.00% and 7.60% faster than that of the other four respectively, and the filling ratio can make the whole cascade phase change heat storage device carry out the melting process more efficiently and realize the overall efficient heat storage and heat transfer.

Table 2: PCM complete melting time at different filling ratios

Fill ratio	2:4:6	3:4:5	4:4:4	5:4:3	6:4:2
PCM1	6494s	8170s	6584s	6740s	6782s
PCM2	4098s	6097s	5115s	3923s	3958s
PCM3	4779s	5923s	4504s	4717s	4753s
Overall	6489s	6263s	6392s	6736s	6780s

It can also be found from Table 4.1 that the melting process of all levels of PCM is not completed at the same time during the melting process, when one kind of PCM is completely melted, its temperature rises rapidly, and the heat storage rate decreases greatly, and when only one type of PCM is left is not completely melted, the overall heat storage rate of the heat storage device decreases more obviously. In order to maintain the stability of the unit as much as possible during the heat storage process and to absorb more heat in the same amount of time, the cascade PCM should be completely melted at the same time as possible. Define the melt out of sync rate (OS) to reflect the difference in the time of complete melting of the PCM during the melting process, calculated as:

$$O_S = \frac{T_E - T_s}{T_E} \tag{11}$$

where : T_S : the complete melting time of the first melted PCM, s; T_E : the complete melting time of the last melted PCM, s.

According to Eq. 11, the O_S between the stages under the five phase change filling ratios is calculated and summarized, as shown in Table 3.

Table 3: O_S at all levels

Fill ratio	2:4:6	3:4:5	4:4:4	5:4:3	6:4:2
PCM1、2O_S	36.89%	25.37%	22.30%	41.79%	41.64%
PCM2、3O_S	14.25%	2.85%	11.90%	16.83%	20.93%
PCM1、3O_S	0.07%	27.50%	31.59%	30.01%	29.90%

As can be seen from Table 3 and Figure 4, when the filling ratio is 3:4:5, PCM2 and 3O_S are the smallest, only 2.85%, which is significantly lower than the other ratios. On the other hand, in the ratio of 5:4:3 and 6:4:2, the PCM1 and 2O_S exceed 41%, resulting in insufficient heat accumulation and supply, which seriously affects the heat storage efficiency. Although PCM1 and 3 have good melting synchronization at the 2:4:6 ratio, the imbalance of other PCMs is obvious, and the stability of heat storage cannot be guaranteed. From the perspective of heat storage stability and heat storage rate, the cascade phase change heat storage device pursues stable heat storage and absorbs more heat at the same time, and too high O_S will completely melt the PCM in advance, resulting in a sudden increase in temperature and a significant decrease in heat storage rate. As can be seen from Figure 4, the O_S is the lowest under the 3:4:5 filling ratio, which can make the PCM at all levels approach the ideal state of complete melting at the same time, so that the heat distribution in the device is uniform, and the heat storage rate can be continuously and efficiently stored, effectively avoiding the problem of reducing the heat storage rate due to the premature melting of some PCMs, and has significant advantages in heat storage stability and efficiency.

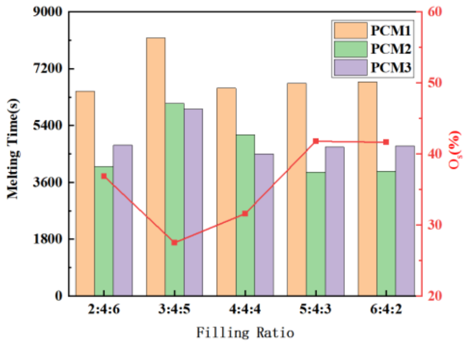


Figure 4: The melting time and O_S of each PCM under different filling ratios

V. CONCLUSION

In order to solve the problem of melting asynchronization between the stages of the cascade phase change heat storage device, the PCM filling ratio of the cascade device is optimized, and the physical model of five different filling ratios is established by numerical simulation method, and the performance difference is evaluated by the liquid phase cloud diagram, melting time and melt out of sync rate, aiming to select the structure with the best heat storage efficiency to provide theoretical guidance for practical application. The study found that by keeping the proportion of PCM2 constant, the device with a filling ratio of 3:4:5 performed best by adjusting the filling ratio of PCM1 (high temperature PCM) and PCM3 (low temperature PCM). By reducing the proportion of PCM1 (high-temperature PCM) and increasing the proportion of PCM3 (low-temperature PCM), the scheme maximizes the synergistic effect of PCM3 and PCM2, avoids heat accumulation, effectively balances heat distribution, and significantly shortens the melting time of PCM1, with the melt out of sync rate of PCM2 and 3 only 2.85%, and the overall complete melting time is 6263s, which is shortened by 7.6% at most. It is confirmed that the cascade phase change heat storage device can optimize the complementarity and heat distribution between materials by adjusting the filling ratio of phase change materials, thereby effectively enhancing the stability of the device and increasing the melting rate, which provides theoretical support for the optimal design of the cascade phase change heat storage device.

REFERENCES

[1] 刘永虎. PCM 在建筑围护结构中的热管理应用研究 [J]. 居舍, 2025, (01): 53-55.
[2] 陈兰鑫. 用于供暖的相变储能单元蓄放热特性数值模拟研究[D], 2023.
[3] 王彩霞, 胡之剑. 中低温相变储热技术在供暖领域的研究应用 [J]. 中外能源, 2018, 23(02): 82-88.
[4] 陈颖, 裴浩斐, 陶进, et al. 光热+市电相变蓄热地板供暖在建筑中的设计及应用 [J]. 能源研究与管理, 2023, 15(02): 118-126.

[5] 刘佳豪. 用于烟气余热回收的相变蓄热装置特性研究[D], 2022.
[6] 张仁元. 《PCM 与相变储能技术》 [J]. 科学通报, 2009, (4): 1.
[7] Farid M M, Kim Y, Kansawa A. Thermal Performance of a Heat Storage Module Using PCM's With Different Melting Temperature: Experimental [J]. Journal of Solar Energy Engineering, 1990, 112:2(2).
[8] Adebiyi G A, Hodge B K, Steele W G, et al. Computer simulation of a high-temperature thermal energy storage system employing multiple families of phase-change storage materials [J]. Journal of Energy Resources Technology, 1996, 118(2): 102.
[9] 胡芃, 卢大杰, 赵盼盼, et al. 组合式 PCM 最佳相变温度的热力学分析 [J]. 化工学报, 2013, 64(7): 6.
[10] Gong Z X, Mujumdar A S. Thermodynamic optimization of the thermal process in energy storage using multiple phase change materials [J]. Applied thermal engineering, 1997, 17(11): 1067-1083.
[11] 王晨羽. 基于梯级相变的储能换热器的研究[D]: 北京建筑大学, 2021.