APPLICATION OF PERFORMANCE DYNAMIC EQUATION IN NUMERICAL SIMULATION AND OPTIMIZATION OF WASTE HEAT UTILIZATION AND STORAGE SYSTEM

by

Feng LI *

Yellow River Conservancy Technical Institute, Kaifeng, Henan, China

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In order to improve the current situation of double energy loss in waste heat recovery and utilization, according to the factors such as phase change temperature, thermal conductivity, phase change latent heat, economy, and safety of thermal storage materials, 70# phase change thermal storage balls produced by XX company were selected as phase change thermal storage materials, and differential scanning calorimetry was used to test and analyze them, and the melting point, freezing point and phase change latent heat value of PCM were obtained, provide data reference for simulation in the following text. The shell and tube heat exchanger is selected as the core component of the mobile heat storage system, and its heat storage and release processes are simulated using FLUENT software. The results show that when the heat transfer equipment is charged for 7 hours, almost all of the inner-heat exchangers have completed the heat supply, and only the phase change products at both sides and bottom of the heat supply have "dead zone", which is the major effect of heat storage. In order to improve the heat storage and release rate and break the "bottleneck" of heat storage, the heat transfer was strengthened by changing the diameter size, arrangement, and adding fins of the heat exchange tube. The effects of straight fins, T-shaped fins, as well as the number, height, thickness, and width of fins on the heat storage performance were explored. The results indicate that, adding fins cannot only improve heat transfer efficiency, but also inhibit natural-convection. The heat storage and release time decreases to varying degrees with the increase of fin width, thickness, height, and the number of circumferential fins in a single heat exchange tube.

Key words: *phase change heat storage, numerical simulation, enhanced heat exchange, economy*

Introduction

Energy is the foundation for human life to survive. Development and utilization of energy are the driving force for the development of human society. The level of energy development is one of the important signs of human civilization. It can be seen that energy is closely related to the development of human society. The history of human being is a gradual understanding and exploitation of energy, which has driven the development of the whole human society [1]. With the rapid development of the world economy, energy consumption has also sharply increased. Since the 1970's, energy issues have been included in one of the world's five major issues (energy, population, food, resources, and environment), and global conflicts and contradictions caused by energy issues have been frequent. According to Report B, the world's proven coal reserves can only be

* Author's e-mail: fl_1142@163.com

exploited for another 200 years, oil reserves can be exploited for about 34 years, and natural gas reserves can be exploited for about 60 years. Therefore, in the future, people will have to save fossil energy as much as possible and develop a new energy system based on renewable energy and sustainable development [2]. With the rapid development of world population, the scale of human society in the world has become smaller and smaller. Environmental degradation and depletion are two swords hanging from the human head. In order to accelerate economic development and meet the needs of people's daily life, the massive use of oil, firewood, coal and other resources has not only caused resource depletion, but also caused great damage to the human living environment. Land desertification, iceberg melting, flooding, and thinning of the ozone layer have all seriously affected human survival, and the main culprit causing these disasters is excessive energy consumption by humans. Therefore, the topic of energy conservation, such as continuously developing new energy and effectively utilizing existing energy, has emerged. Various forms of energy in nature provide energy directly or indirectly, statistical data show that the energy provided in the form of thermal energy accounts for a significant proportion of the energy consumed by human. In a sense, the development and utilization of energy is the use of thermal energy. However, there is still a significant gap in the current level of thermal energy utilization technology compared to developed countries in the world, mainly manifested in outdated thermal energy utilization systems, low thermal energy utilization rates, and poor economic efficiency. How to develop new energy and improve its utilization rate has become an urgent problem that needs to be solved [3]. At present, heat storage technology, as an important aspect of effective energy utilization, has received widespread attention. In the existing energy structure, thermal energy is one of the most important sources of energy. Most of the renewable and non-renewable energy sources, such as solar energy, geothermal energy, wind energy, industrial waste heat and waste heat, which make people unable to consume energy in many cases. For example, when there is no need for heating, generate a lot of heat, but cannot provide timely response to sudden emergencies, or a significant part of it disappears because of waste heat. Heat storage technology is an effective way to solve this energy consumption contradiction, utilizing specific devices, temporarily unused or excess heat energy is stored through certain thermal storage materials and reused when needed. Analytical and numerical methods are the main methods for solving phase change heat transfer problems. The analytical method includes accurate analysis and approximate analysis. The accurate analysis is mainly based on Neumann method and the generalized Neumann method. The approximate analysis is mainly based on integration method, metastability method, successive approximation method and thermal resistance method. Numerical methods include fixed step method, independent variable

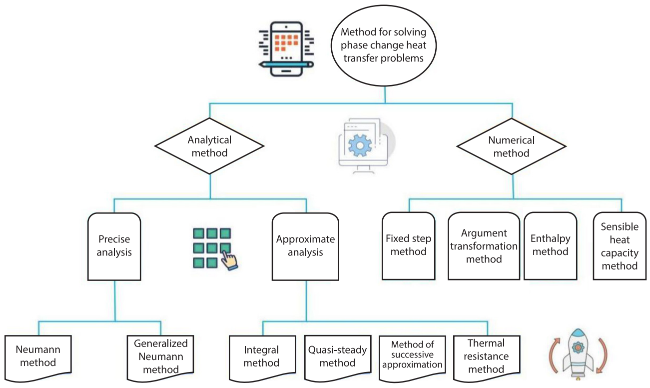

Figure 1. Solution method for phase change heat transfer problem

transformation method, enthalpy method, and sensible heat capacity method, as shown in fig. 1 [4, 5]. In order to improve the disposal of waste heat current and present the situation of two energy losses, as phase change temperature, thermal conductivity, phase change latent heat, economy and safety of heat storage equipment, phase change heating equipment made of 70 phase change heat storage package XX company is selected and differential scanning calorimetry test analysis, get the phase change material melting point, setting point and phase change latent heat value, provide data reference for the simulation.

Methods

Numerical simulation of phase change heat storage

The heat transfer function of phase change heat exchanger directly affects the heat transfer performance of the whole heat storage system. This article chooses the shell and tube phase heat exchanger as the core of the mobile heat storage system, and designs the physical model of the phase change heat storage system using GAMBIT.

The length of heat box is 1640 mm, diameter is 380 mm, and the box is made of 2 mm thick stainless steel plate material. The outermost layer of the box is covered by an 18 mm thick insulation layer. It consists of 925 mm diameter copper pipes inside, which are fixed by a baffle plate. Phase shifting material is encapsulated between a heat pipe and a shell of a heat exchanger. The inside of the heat pipe is heat exchanger (HTF), and both the end of furnace and the shell surface are insulated, meaning there is no heat exchange with the outside world. Considering the thermal expansion problem of PCM, when adding PCM, the area of about 15% is reserved on the top of the heat exchanger. The thermal fluid and the pipe wall transfer heat in the form of convection, while the thermal storage material obtains heat from the thermal fluid through thermal conduction and stores it in the form of latent heat.

In order to simplify the author's analysis and ensure the accuracy of numerical simulation, we propose the following viewpoints on the physical model: the phase change data are isotropic and consistent. When there is temperature, phase change occurs, and the thermal conductivity and specific heat coefficient of solid-liquid phase show a series of changes. The speed of liquid phase follows Busynesk theory. Both ends and shells of the heater are used as insulation walls, with no external temperature. The thermal resistance at the contact point between the PCM and the pipe-line, as well as the thickness of the heat exchange tube wall, are ignored. When phase change occurs in phase PCM, only solid-liquid phases exist, and there is no performance degradation or undercooling phenomenon. Neglection of the friction of fluid during flow process in heat pipe system. The thermophysical parameters of the phase change data obtained from the dynamic measurement analysis (DSC) and the related data analysis, as shown in tab. 1 [6, 7].

Table 1. Main thermophysical parameters of phase change materials

Thermal properties	Numerical value
Density [kgm^{-3}]	1300 (140 °C), 1480 (20.1° C)
Specific heat capacity [$Jkg^{-1}K^{-1}$]	2.74 (140 °C), 1.35 (20 °C)
Thermal conductivity [$wm^{-1}K^{-1}$]	2.74 (140 °C), 1.35 (20 °C)
Dynamic viscosity [$kgm^{-1}s^{-1}$]	0.01602 (140 °C), 0.02895 (20 °C)
Latent heat [$kJkg^{-1}$]	335.61
Phase transition temperature [°C]	124.51

The treatment of the solid-liquid two-phase region of PCM is a difficult point in numerical calculation research during the phase change process. In order to describe the flow and heat transfer problems of thermal storage materials during melting and solidification within a certain temperature range, the author selected the FLUENT solidification/melting model and used the *Enthalpy Porosity* technique to uniformly treat the solid-liquid two-phase region of thermal storage materials. When $0 < \beta < 1$, it indicates that the phase change material is in a solid-liquid coexistence state:

$$\beta = \begin{cases} 0 & \text{if}, \ T < T_{\text{solidus}} \\ \dfrac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} & \text{if}, \ \ T_{\text{solidus}} < T < T_{\text{liquidus}} \\ 1 & \text{if}, \ T > T_{\text{liquidus}} \end{cases} \tag{1}$$

where T_{solidus} is the solidification temperature of the thermal storage material, T_{liquidus} – the melting temperature, T – the temperature at any time, and the porosity model assumes that the liquid phase ratio is equal to the porosity.

The control equation for the phase transition region is:

– Continuous equation

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

– Momentum equation

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z}\right) = \mu\left(\frac{\partial^2 u}{\partial x^2} + w\frac{\partial^2 u}{\partial z^2}\right) - \frac{\partial p}{\partial x} + s_u \tag{3}$$

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z}\right) = \mu\left(\frac{\partial^2 w}{\partial x^2} + w\frac{\partial^2 w}{\partial z^2}\right) - \frac{\partial p}{\partial z} + s_w \tag{4}$$

– Energy equation

$$\rho\left(\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + w\frac{\partial h}{\partial z}\right) = \frac{\lambda}{c_p}\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2}\right) + s \tag{5}$$

where ρ [kgm^{-3}] is the density of the thermal storage material, U [ms^{-1}] – the velocity of the fluid in the x-direction, W [ms^{-1}] – the velocity of the fluid in the z-direction, and λ – the thermal conductivity of phase change materials. Energy equation source term:

$$s = \frac{\rho}{c_p}\frac{\partial(\Delta H)}{\partial \Delta t} \tag{6}$$

$$H = h + \nabla H \tag{7}$$

$$h = h_{\text{ref}} + \int_{T\text{ref}}^{T} c_p \mathrm{d}T \tag{8}$$

$$\Delta H = \beta L \tag{9}$$

where H [kJkg^{-1}] is the enthalpy value at any time, T_{ref} [K] – the reference temperature, H_{ref} [kJkg^{-1}] – the corresponding enthalpy value at the reference temperature, β – the liquid phase rate, L [kJkg^{-1}] – the latent heat of phase change of phase change materials, and ΔH [kJkg^{-1}] – the latent enthalpy value. The source terms S_u and S_w of the momentum equation:

$$s_u = \frac{(1-\beta)^2}{(\beta^2+\varepsilon)} u A_{\text{mush}} \tag{10}$$

$$s_w = \frac{(1-\beta)^2}{(\beta^2+\varepsilon)} w A_{\text{mush}} + \frac{\rho_{\text{ref}}\,\mathrm{g}(h-h_{\text{ref}})}{c_p} \tag{11}$$

where ε is the constant less than 0.0001, prevent β being too small causes the denominator to be 0, A_{mush} – the continuous number of partially solidified regions during the phase transition process, taken as 0.00001, ρ_{ref} [kgm^{-3}] – the density of the thermal storage material corresponding to the reference temperature, and g [ms^{-2}] the gravitational acceleration.

Optimization of the arrangement of heat exchanger tube bundles in a heat accumulator

In order to improve heat transfer efficiency, shorten heat storage time, and increase heat transfer area, it is an important way to improve heat transfer efficiency. Therefore, without changing the equation of phase change data in the heat exchanger, the heat exchanger system can be optimized by decreasing the diameter of the inner heat exchanger and increasing the number of heat exchangers to increase the heat exchanger area. However, when there are a large number of heat exchange tube bundles, it will also increase the difficulty and economic cost of the heat exchanger process production, or there is a risk of phase change material leakage outward. Therefore, in engineering projects, the diameter and lay-out of heat exchange pipes should be carefully selected:

$$V = n\frac{\pi d^2}{4} l \tag{12}$$

According to eq. (12), the internal heat exchange tube volume of the heat storage structure mentioned is $6.359 \cdot 10^{-3}$ m^3. Do not change the proportion of phase change products in heat exchangers. When the diameter of the heat pipe is 13 mm, there are many pipe-lines. This article selects 22 mm, 19 mm, and 16 mm as the research object. It can be seen from the numerical simulation result of melting and solidification of the phase change heat storage equipment that almost all the internal combustion equipment in the heat exchanger have finished the hot work after 7 hours of charging. Only the *dead zone* of thermal storage materials at both sides and bottom of the thermal storage material appears, which is an important part of the thermal storage material. Therefore, in order to solve this problem, when preparing the heat exchanger tube, the position of the bottom of the heat exchanger tube must be moved downward, so that the heat storage device under the heat exchanger can be completed in contact with the heat exchanger tube. Properly adjust the heat exchange tube in the middle to both sides of the heat accumulator to improve the phenomenon that the heat storage materials on both sides are far away from the central heat exchange tube, and the heat conduction and natural-convection are weak. The arrangement of DN22 tube bundles, DN19 tube bundles, and DN16 tube bundles is carried out according to this principle. The arrangement and diameter of DN22, DN19, and DN16 tube bundle phase change heat exchangers have only changed, the flow and heat transfer models have not changed, so the mathematical model and related parameter settings established are still applicable. Similarly, the heat storage system is first divided into blocks for grid division, followed by grid independence verification. Finally, the grid numbers of the DN22 tube bundle, DN19 tube bundle, and DN16 tube bundle phase change heat storage models are determined to be 1.15 million, 1.22 million, and 1.3 million, respectively, the internal $z = 0$ cross-section is selected to illustrate the grid division of the three tube bundles.

Physical model: The effect of increasing heat transfer rate solely by reducing the pipe diameter and increasing the number of heat exchange tubes is limited. Based on the previous research, this section conducts numerical simulation research on the heat accumulator with fins, which are made of copper. Select the DN19 pipe-line's phase change heat model as the research object, and choose $z = 0$ cross-section illustrate the physical model of heat storage in four different operating conditions. Through numerical simulation, the influence of different models on the heat release of phase change products during heating process is analyzed. Specific parameters of fins are shown in tab. 2.

Table 2. Fin types and structural parameters under different operating conditions

Name	Fin type	Number of fins (piece)	Rib height [mm]	Fin thickness [mm]	*T*-shaped arc length [mm]
Condition 1	Straight fin	2×16	15	1	–
Condition 2	Straight fin	4×16	15	1	–
Condition 3	*T*-shaped fins	2×16	15	1	25.7
Condition 4	*T*-shaped fins	4×16	15	1	25.7

Results and analysis

Numerical simulation results and analysis

Observing the movement of the three solid-liquid interfaces separately, it can be observed that the melting and heat storage conditions of DN19 and DN16 tube bundle phase change heat exchangers are generally consistent, and the optimization effect is better than that of DN22 tube bundle phase change heat exchangers, but the *bottleneck* of heat storage has not been completely broken. As shown in fig. 2, the curve of liquid composition over time during heating process of four diameter heat exchangers is presented. From the curves, it can be seen that during thermal storage stage from 0-360 minutes, DN19 tube bundle phase change thermal storage device has the shortest time to achieve thermal storage. Compared with the DN16 tube bundle phase change heat storage device, its changes are basically the same. But in cases where the heat storage effect is similar, in order to avoid the risk of outward leakage of PCM due to the large number of welded joints in the tube bundle, priority should be given to selecting optimization methods with larger tube diameters and fewer tube bundles.

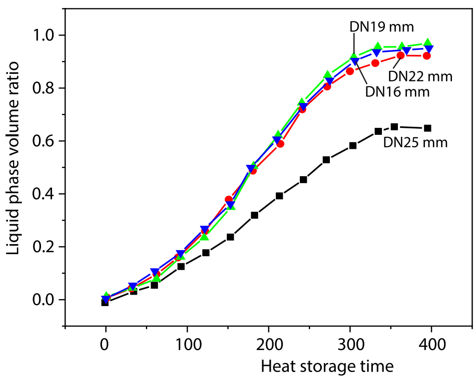

Figure 2. Liquid fraction in four different diameter heat accumulators

Exothermic process: The liquid phase rate distribution during the solidification process of DN22, DN19 and DN16 tube bundle phase change heat accumulators can be obtained that the heat release rate of three different tube diameter heat accumulators in the exothermic process is different. After the heat release of DN22 pipe-line's heat exchanger is finished, the heat storage device on both sides and top cannot change the temperature. The reason is that the diameter of DN22 heat pipe heat exchanger decreases, and the heat flow rate of heat pipe also decreases accordingly. Although the heat transfer area increases compared to DN25 heat pipe heat exchanger, its overall heat transfer performance is better than DN25 pipe-line heat exchanger. The heat transfer efficiency of DN19 and DN16 tube bundle phase change heat exchangers is better than that of DN25 tube bundle heat exchangers. Therefore, in practical engineering applications, the impact of heat exchange pipe diameter and heat exchange area on heat transfer efficiency should be comprehensively evaluated.

Figure 3 shows the liquid phase volume ratio of four different pipe diameter heat accumulators during the heat release process. That after the heat release process is completed, about 10% of the internal heat storage materials have not completely completed heat release, resulting in unsatisfactory heat transfer effect. It can be seen that only reducing pipe diameter and increasing the number of pipe-lines to strengthen heat transfer cannot. Therefore, based on the research in this part, it is advisable to improve the heat transfer performance and the performance of the heat exchanger by adding fins.

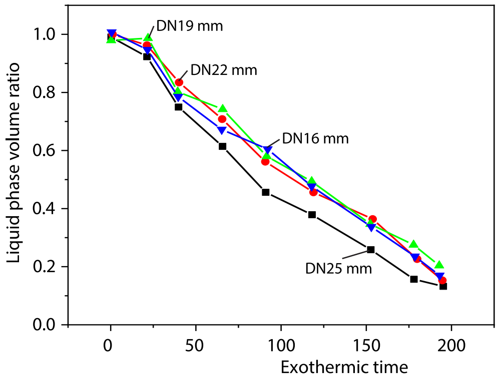

Figure 3. Liquid fraction in four different diameter heat accumulators

Simulation results and analysis

Figure 4 shows the liquid to liquid ratio curve of phase change data during solidification under four operating conditions. From the different structure curves in the diagram, it can be seen that in the initial stage of heat release, there are different temperature distribution between the material phase change and the wall temperature change. Heat storage material near a finned tube before releasing heat and power. However, due to the exothermic solidification of PCM, the gap between liquid phase composition and heat transfer surface of thermal storage materials becomes more and more serious, making it more difficult to replace the additional heat of liquid PCM, and the corresponding solidification rate gradually decreases.

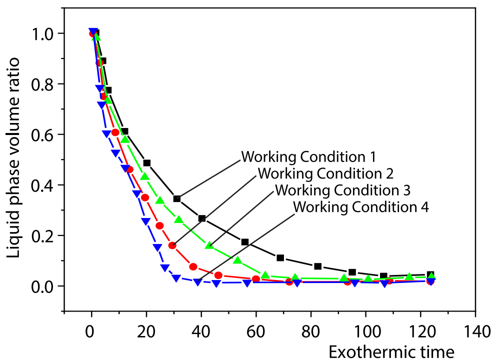

Figure 4. Changes in liquid phase ratio of PCM under four operating conditions

Among the four conditions mentioned, Condition 1 takes the longest complete solidification time, approximately 125 minutes. Compared with Condition 1 with the addition of straight fins, Condition 3 with the addition of *T*-shaped fins takes about 92% of Condition 1 to fully solidify due to the increase in some heat transfer area. Compared with Condition 4, Condition 2 takes almost the same time for complete solidification, about 98 minutes. In the early and early stages of exothermic solidification, the solidification rate of Condition 4 is significantly better than that of Condition 2, because the total area of the *T*-shaped fin heat exchange tube in Condition 4 is slightly larger than that of the straight fin heat exchange tube in Condition 2. However, in the middle and later stages of exothermic solidification, compared with straight fin heat exchange tubes, *T*-shaped fin heat exchange tubes, due to their own structural characteristics, have weakened the impact of Natural-convection on heat transfer, thus reducing the solidification rate of Condition 4, and its complete solidification time tends to be the same as that of Condition 2 [8, 9].

After holding 180 minutes under Conditions 1 and 3, the heat supply around the heat accumulator almost did not evaporate, indicating that adding some fins could not destroy the *bottleneck* of heat storage. The time needed to complete the melting under Condition 2 is about 135 minutes, and the time needed to complete the melting under Condition 4 is about 155 minutes. and the time required to complete the melting under Condition 4 is about 155 minutes. Compared with the experimental results under Conditions 1 and 2, the results show that increasing heat transfer area can improve heat transfer efficiency and Compared with the experiments under Conditions 2 and 4, the finned tube structure also has a great effect on heat transfer performance [10].

Conclusion

Based on the analysis of the principle of phase change equipment, the heat storage device with high latent heat value and suitable phase change temperature was finally selected as the heat storage device for the mobile heat storage system. A heat exchanger with high latent heat value has been designed. The DSC test and analysis were made to it, and the results showed that the physical parameters of phase change products were easily selected according to the police regulations. The phase change temperature is 134.5 °C, and the latent heat of phase change is 335.6 kJ/kg, providing a reference for numerical simulation in this article. The simulation results of exothermic process of phase change data show that during melting, the liquid phase change the flow data to the upper part of the heat transfer tube, that causes the data transfer phase at the top of the node. *Dead area* appears on both sides and bottom of heat exchanger, which is a major influence on heat storage. During the solidification process, natural-convection affects the phase transition of PCM, making the lower of PCM solidify faster than the upper in heat exchanger. Moving the role of tubular heat transfer to the bottom and side effectively improves the heat release rate of phase change products. The heat transfer performance and configuration of DN19 pipe are the best: through four operating conditions, adding fins can enhance the heat transfer efficiency while inhibiting the role of natural-convection. Through the heat transfer period of phase transfer products, the heat transfer efficiency of fins is about twice of that of naked tubes: fin width, thickness and height, and the number of heat exchangers per cycle all affect the heat storage and storage time of heat exchangers. The influence of fin thickness on heat transfer rate is very small, while the influence of fin height is the most important. In practical engineering, selecting four or five fins is more economical and reasonable.

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