

Research on Performance Optimization of Phase Change Thermal Storage Electric Heating Device

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Abstract

At present, the main heating method for reducing crude oil viscosity is electric heating, and the all-day electric heating method has the problems of high energy consumption and high cost. In order to meet the needs of environmental protection and industrial production, a new type of phase change thermal storage electric heating device was designed by combining the crude oil viscosity reduction heating method with valley price and phase change materials. The results indicate that as the inlet flow rate of the working fluid increases, the outlet temperature continuously decreases. And when the outlet temperature rises to 10°C, the inlet flow rate of the device can meet the flow range of 1.413 - 2.120 m³/h. At the same time, the addition of foam nickel makes the internal temperature of PCM more uniform, and the internal temperature of PCM decreases with the decrease of porosity of foam metal. By increasing the number of electric heating rods and reducing the power of individual electric heating rods, the structure of the device was optimized to significantly improve local high-temperature phenomena. The use of this device can maintain high heat exchange efficiency and reduce production costs.

Keywords

Crude Oil Viscosity Reduction, Phase Change Thermal Storage, Electric Heating, Valley Electricity Price

1. Introduction

With the increasing demand for oil in China, more effective extraction, storage, and transportation of crude oil have become a focus of attention in the oil field, including heating methods for reducing crude oil viscosity. At present, there are

mainly two types of heating methods: gas or oil boiler heating, and electric heating [1]. However, gas or oil-fired heating furnaces not only have high heating costs and low efficiency, but also have high exhaust emissions, causing great waste and irreversible pollution to resources and the environment. Therefore, electric heating has become the mainstream heating method [2]. In addition, to alleviate the problem of insufficient urban power supply, China has introduced the “valley peak electricity price”, which means that the daytime electricity price is higher during peak electricity consumption, and the nighttime electricity price is lower during low peak electricity consumption [3]. Therefore, the function of storing energy at night and using energy during the day has gradually entered the industrial field.

Phase change material is a substance that can change its physical state and provide latent heat at a constant temperature. It is widely used in energy storage technology due to its ability to absorb or release a large amount of latent heat by changing its physical state within a certain temperature range [4] [5]. Wang *et al.* [6] tested latent heat reservoirs using trihydrate sodium acetate-based composite materials for variable heating systems. Sensible heat is used for short-term heat storage, while latent heat is used for long-term heat storage. The results indicate that the phase change material maintains stable undercooling in 66% of the test cycles. Compared with traditional heating systems, the heat storage effect is significantly improved. However, the thermal conductivity of most phase change thermal storage materials is very low, so it is necessary to enhance heat transfer to meet industrial production requirements. At present, methods to enhance heat transfer in phase change materials include adding ribs, adding metals to phase change materials, and injecting phase change thermal storage materials into porous metal layers. Agyenim *et al.* [7] found that the system with longitudinal fins has the best heat transfer effect. Zhang *et al.* [8] found that foam metal composite phase change material is more effective than single phase change material in enhancing heat transfer. Huang *et al.* [9] found that compared with a single phase change material, the thermal conductivity of foam nickel composite phase change material and foam copper composite phase change material increased by 1.8 times and 7.51 times, respectively.

The above research focuses on the performance of phase change materials and does not involve the complementary effects of phase change energy storage with other energy sources. However, relevant studies have shown that multi energy complementarity can effectively reduce energy consumption and improve energy utilization efficiency. Therefore, by combining crude oil heating and viscosity reduction methods, valley electricity, and composite phase change material technology, a new type of phase change thermal storage electric heating device was designed and developed by efficiently combining thermal energy storage and electrical energy. The thermal storage performance of the device was simulated and optimized, providing new ideas for the design and operation of crude oil viscosity reduction processes.

2. Device System and Modeling

2.1. Device Introduction

The phase change thermal storage electric heating device designed is shown in **Figure 1**. The device mainly consists of a thermal storage furnace shell, heat exchange coils, electric heating rods, and composite phase change materials. Among them, the tank body is about 4 meters long, with a circular cross-section and an inner diameter of 1.55 meters. The furnace body is divided into two parts from the middle by a dividing plate, with two 8-kilometer coils and multiple electric heating rods inside each part. The total length of the coils is about 29 m. Phase change composite materials are distributed between the heating coils and heating rods inside the shell.

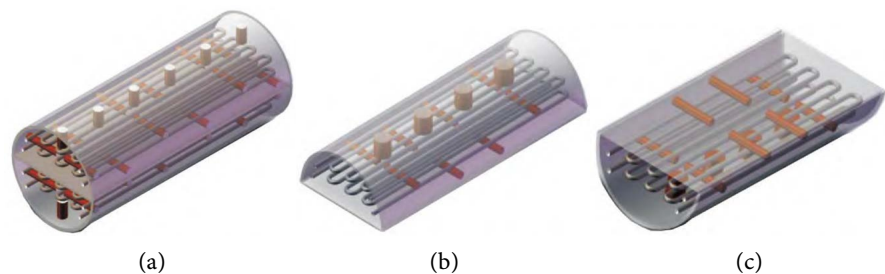


Figure 1. Model of Phase Change Thermal Storage Electric Heating Device. (a) The whole model; (b) The upper part of the model; (c) The lower part of the model.

The shell and internal coil of the unit are made of carbon steel. The phase change material is ammonium aluminum sulfate dodecahydrate ($\text{NH}_4\text{Al}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$) and foam metal nickel with different porosity is added. This composite phase change material can not only prevent the coking of crude oil when viscosity is reduced, but also has good stability, high thermal conductivity and recyclability. The physical properties of the materials used are shown in **Table 1**.

Table 1. Material property parameters.

Material type	Specific heat/ ($\text{kJ} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}$)	Latent heat/ ($\text{kJ} \cdot \text{kg}^{-1}$)	Thermal conductivity /($\text{W} \cdot \text{m}^{-2} \cdot \text{K}$)	Density/ ($\text{kg} \cdot \text{m}^{-3}$)	Coefficient of expansion/ K^{-1}	Kinematic viscosity/($\text{m}^2 \cdot \text{s}^{-1}$)
$\text{NH}_4\text{Al}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$	1.40	254	0.53	1600	0.0012	-
Oil-water mixture	2.94	-	0.476	943	-	0.003
Carbon steel	0.47	-	50	3000	-	-
Nickel	0.46	-	91.74	8900	-	-

During the period of 23:00-7:00, both the upper and lower parts of the device undergo heat storage, but the upper part releases heat while storing heat. Therefore, during this period, there is a phenomenon of working fluid flow in the upper part of the tube; During the time period of 7:00-15:00, both the upper and lower parts of the device stop the heat storage process. The upper part of the phase

change material releases heat to heat the working fluid inside the tube, while the lower part stores heat; During the time period of 15:00-23:00, the heat stored in the upper part of the device can no longer meet the temperature requirements of the working fluid outlet inside the pipe. Therefore, the working fluid is transferred to the lower part of the coil for heating, and the upper part is no longer in use. This cycle is repeated to heat and reduce the viscosity of the crude oil. Focus on discussing the thermal storage performance of the device during the period of 23:00-7:00.

2.2. Physical Model

Based on the operation of the device during the period of 23:00-7:00, CFD method was used to conduct numerical simulation analysis on the thermal storage performance of the upper and lower parts of the device, and structural optimization was carried out based on the results.

The physical models of the upper and lower parts are shown in **Figure 1(b)** and **Figure 1(c)**, where the area inside the coil is the heat transfer fluid region, and the gap between the coil and the heating rod inside the shell is the phase change material region.

In order to accurately and conveniently study the thermal storage performance of the device, based on literature [10]-[13], the following assumptions are made: ① The working fluid oil-water mixture inside the pipe is an in-compressible fluid; ② The thermal storage material is isotropic and chemically stable, ignoring super-cooling and precipitation phenomena during the phase transition process; ③ The flow of working fluid at the inlet of the coil is fully developed; ④ Neglecting the heat dissipation of the device casing; ⑤ The foam metal nickel is distributed as a three-dimensional skeleton.

2.3. Mathematical Model

The heat transfer fluid region adopts three major control equations for flow heat transfer, namely the mass conservation equation, momentum conservation equation, and energy conservation equation.

According to the melting and solidification model provided by ANSYS Fluent, the phase change material region adopts three major control equations based on porosity enthal method.

2.4. Parameter Settings

In non-steady state calculations, the energy equation, $k-\varepsilon$ turbulence model, and melting solidification model are selected as the solving models, and the pressure based solver is chosen as the solver. The PISO algorithm is used as the algorithm. In the boundary conditions, the thermal storage shell is an adiabatic wall, and the coil and the heat transfer fluid, as well as the coil and the phase change material, are all coupled interfaces. The inlet of the heat transfer fluid area is the velocity inlet, and the outlet is the free outflow.

3. Simulation Results and Discussion

3.1. Thermal Storage Performance

In the process of heat storage, the foam metal nickel with porosity of 0.8 is added to make phase change composites, and the heat storage process is divided into the upper half and the lower half, and the heat storage time is 23:00-7:00.

There are 12 heating rods in the upper part of the furnace, each with a power of 500 kW/m^3 . Among them, 4 rods are evenly arranged between the furnace wall and the coil, 4 rods are arranged between the coil, and 4 rods are arranged between the coil and the dividing plate. After 8 hours of heat storage and release, the outlet temperature curve of the working fluid in the upper half of the coil is shown in **Figure 2**. The liquid phase distribution inside the coil and the phase change composite material, as well as the temperature distribution inside the furnace, are shown in **Figure 3**.

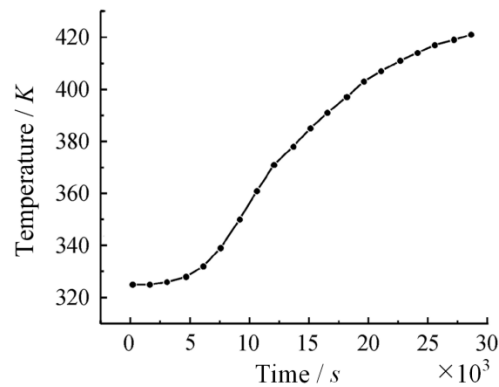


Figure 2. Temperature curve of working fluid outlet in the upper part of the coil.

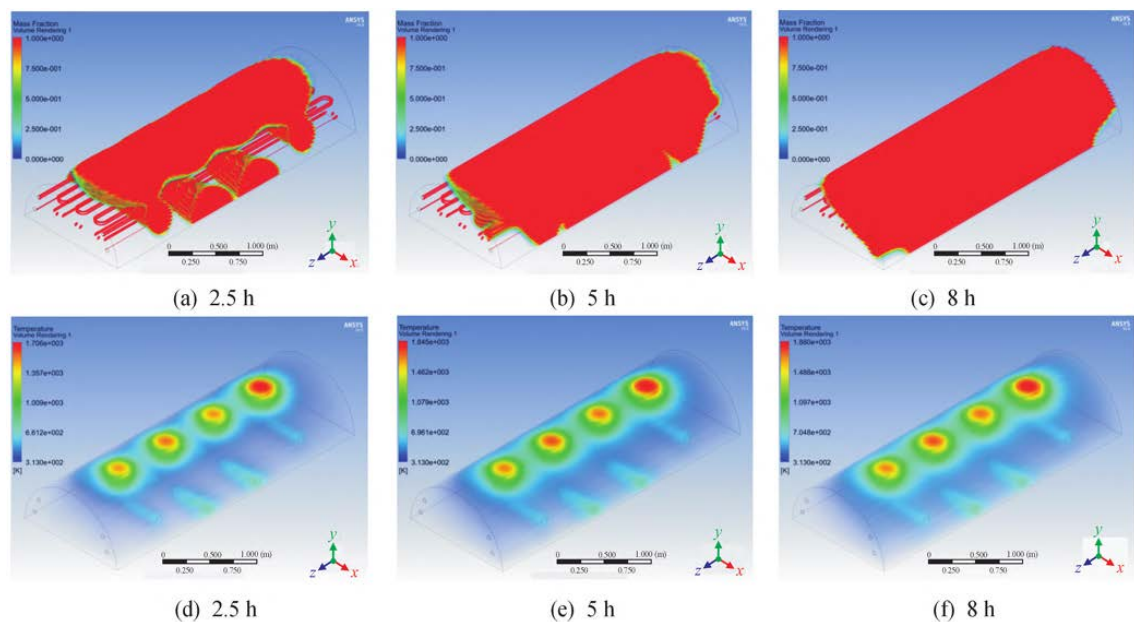


Figure 3. Liquid phase distribution in the upper half of the coil and phase change composite material at different times [(a)-(c)] and temperature distribution cloud map inside the furnace [(d)-(f)].

As shown in **Figure 2**, the outlet temperature of the working fluid in the upper half of the coil meets the temperature rise condition. As shown in **Figure 3**, with the passage of heat storage time, the phase change composite material in the upper part of the furnace basically melts into liquid after 8 hours, and the overall temperature of the phase change composite material reaches 403 K, which is the initial temperature of the phase change material during the heat release process. Therefore, the device meets the production requirements. However, there are still a few materials near the furnace wall that have not completely melted. In addition, although the temperature of phase change composite materials meets production requirements, the temperature distribution is uneven and there is a significant difference between the internal and external temperatures. Therefore, although the upper part of the device is feasible, it still needs improvement.

The arrangement of heating rods in the lower part of the furnace is similar to that in the upper part, with 12 heating rods with a power of 1000 kW/m^3 . After 8 hours of heat storage, the liquid phase distribution and temperature distribution of the phase change composite material in the lower part of the furnace are shown in **Figure 4**. According to **Figure 4**, after 8 hours, the phase change composite material near the wall in the lower half of the furnace basically melted into liquid, and at this time, the overall temperature of the phase change composite material in the furnace had reached 403 K, but a small part of the phase change composite material near the wall showed incomplete melting. Therefore, the lower part of the device needs improvement.

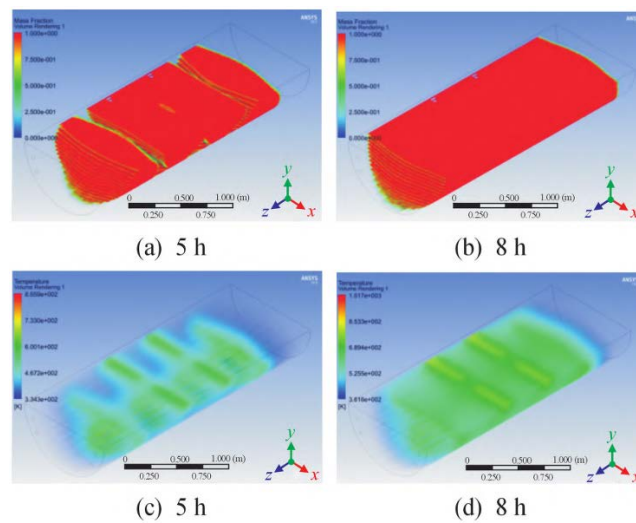


Figure 4. Liquid phase distribution of phase change composite materials in the lower half at different times [(a), (b)] and temperature distribution cloud map inside the furnace [(c), (d)].

The above simulation results show the phenomenon of incomplete melting of phase change composite materials and uneven temperature distribution inside the furnace after heat storage. The reason may be that firstly, the uneven distribution of heating rods inside the furnace may lead to incomplete melting and lower

temperature of phase change composite materials near the outer wall side. Secondly, during the time period of 23:00-7:00, the upper part releases heat while storing heat in the phase change composite material, while the lower part only stores heat during this time period. Therefore, the upper part requires a more powerful heating rod to meet the temperature requirements for heat storage and release.

Therefore, the furnace structure can be adjusted according to the position and power of the heating rod to optimize the heat storage performance of the device and meet market demand.

3.2. Structural Optimization

During the heat storage process of the device, first, the temperature of the phase change composite near the heating rod is heated by the heating rod, and the temperature rises, and begins to melt. As time goes by, under the catalysis of foam metal with high thermal conductivity, the heat accelerates to spread outward, until all the phase change composite materials in the furnace become liquid. At this time, the heat storage process ends. For the heat storage process, the power and arrangement of the electric heating rod are related to whether the heating is uniform and whether the temperature of the phase change material can rise uniformly. Therefore, based on the simulation results in section 3.1, the position and power of the heating rod in the furnace are optimized and adjusted, and the optimized model is numerically simulated and analyzed.

To ensure that the phase change composite material and the outlet temperature of the working fluid inside the coil meet the design conditions during the heat storage and release process in the upper part, a heating rod with a power of 2800 kW/m^3 is used for heating, and the number of heating rods is increased to 18. Corresponding adjustments were made to the position of the heating rods, with 6 evenly arranged between the furnace wall and the coil, 6 between the coil, and 6 between the coil and the dividing plate. After 8 hours of heat storage and release, the temperature curve of the working fluid outlet in the upper part of the coil is shown in **Figure 5**, and the liquid phase distribution and furnace temperature distribution in the coil and phase change composite material are shown in **Figure 6**.

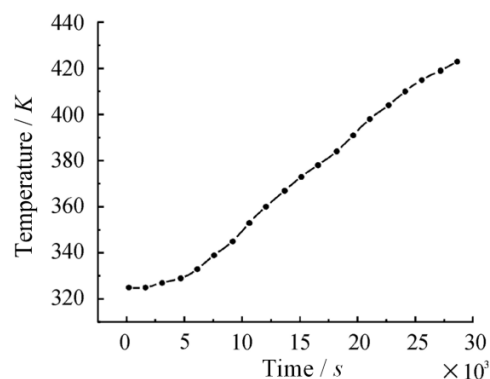


Figure 5. Optimized outlet temperature curve of working fluid in the upper half of the coil.

As shown in **Figure 5**, the outlet temperature of the working fluid in the upper half after optimization is slightly different from before optimization, but it meets the temperature rise condition. Meanwhile, as shown in **Figure 6**, after 8 hours of heat storage and release, the optimized phase change composite material in the upper half of the furnace completely melted, and the overall temperature reached 403 K. Therefore, the optimization plan is reasonable.

To avoid incomplete melting of the phase change composite material in the lower part, the number of heating rods in the lower part is increased to 18, arranged similarly to the upper part. At the same time, adjust the power of heating rods 13 and 18 to 500 kW/m^3 , and adjust the power of the remaining heating rods to 900 kW/m^3 . After 8 hours of heat storage, the liquid phase distribution and temperature distribution of the phase change composite material in the lower part of the furnace are shown in **Figure 6**. According to **Figure 6**, after 6.5 hours of

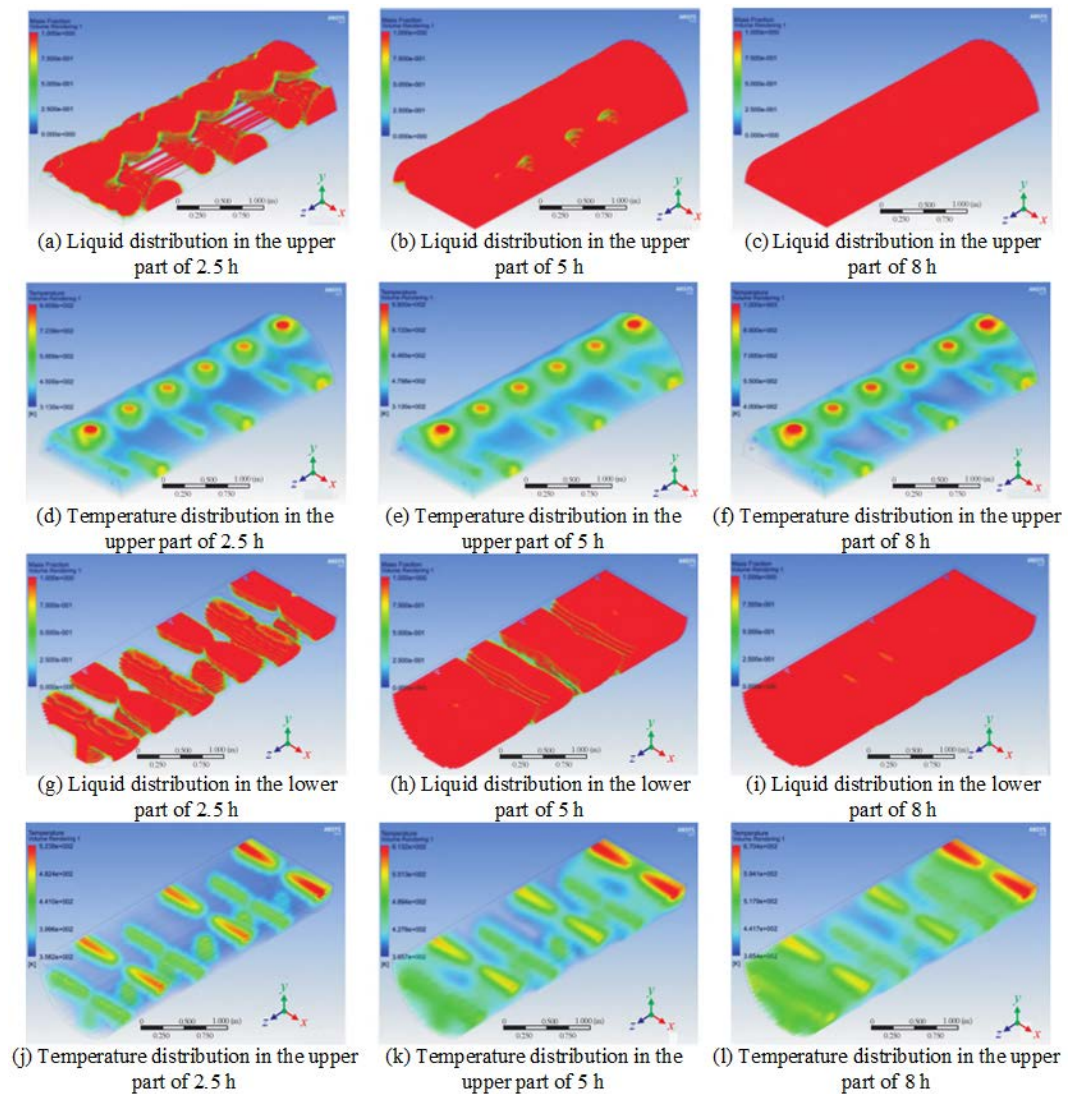


Figure 6. Cloud map of liquid phase distribution and furnace temperature distribution in the coil [(a)-(c) and (g)-(i)] and phase change composite material optimized at different times [(d)-(f) and (j)-(l)].

heat storage process, the phase change composite material in the lower part of the furnace completely melted, and the temperature distribution was relatively uniform. At this time, the overall temperature of the phase change composite material had reached 403 K. Compared with before optimization, using this heating power and heating arrangement can not only ensure that the phase change composite material in the furnace is completely melted and the temperature meets production requirements after the heat storage process is completed, but also reduce the second half of the heat storage time, that is, the heat storage can be completed after 6.5 hours of operation.

In summary, after optimizing the device, due to the more uniform and reasonable arrangement of heating rods inside the device, the phase change composite material not only has a more uniform solid-liquid transition during the heat storage process, but also has a more uniform temperature rise in each region. At the same time, due to the increase in the number of electric heating rods and the decrease in the power of a single electric heating rod, the occurrence of local extreme high temperatures in phase change composite materials after the heat storage process is avoided, thereby efficiently utilizing energy.

4. Conclusions

In this paper, the structural design and optimization of a new phase change thermal storage electric heating device were carried out through numerical simulation, achieving the use of valley electricity price for thermal storage and uniform temperature rise of the thermal storage structure, resulting in significant improvement of local high-temperature phenomena. The specific conclusion is as follows:

1) During the heat storage process, the phase change material near the electric heating rod melts first, and the heat diffuses to the surrounding phase change material with the help of foam metal with high thermal conductivity. The melting trend is radial.

2) Although phase change materials store a large amount of heat, there is a phenomenon of uneven distribution of released heat. With the addition of foam nickel, the porosity of foam metal decreases, and the internal temperature of phase change material is more uniform, and the internal temperature of phase change material decreases with the decrease of porosity of foam metal.

3) The more uniform the distribution of electric heating rods, the more uniform the temperature rise of phase change materials. Increasing the number of electric heating rods and reducing the power of a single electric heating rod can avoid local high temperatures in phase change materials, thereby reducing energy consumption.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

- [1] Amrouche, F., Blunt, M.J., Iglauer, S., Aiouache, F. and Short, M. (2024) A Novel

- Hybrid Enhanced Oil Recovery Technique to Enhance Oil Production from Oil-Wet Carbonate Reservoirs by Combining Electrical Heating with Nanofluid Flooding. *Materials Today Sustainability*, **27**, Article ID: 100915. <https://doi.org/10.1016/j.mtsust.2024.100915>
- [2] Rangel-German, E.R., Schembre, J., Sandberg, C. and Kovscek, A.R. (2004) Electrical-heating-Assisted Recovery for Heavy Oil. *Journal of Petroleum Science and Engineering*, **45**, 213-231. <https://doi.org/10.1016/j.petrol.2004.06.005>
- [3] Zhang, H., Zhang, X., Wang, Q., Ma, Y., Zhao, S., Wang, C., et al. (2023) A Method for Sizing Air Source Heat Pump and Electric Boiler Considering the Peak and Valley Electricity Prices. *Journal of Building Engineering*, **78**, Article ID: 107647. <https://doi.org/10.1016/j.jobbe.2023.107647>
- [4] Farid, M.M. and Kanzawa, A. (1989) Thermal Performance of a Heat Storage Module Using PCM's with Different Melting Temperatures: Mathematical Modeling. *Journal of Solar Energy Engineering*, **111**, 152-157. <https://doi.org/10.1115/1.3268301>
- [5] Li, Z., Chang, J., Li, W., Zhao, Y. and Gao, J. (2019) Experimental Study of Heat Transfer Performance of the Solar Collector-Automatically Multiple Phase Change Thermal Storage. *IOP Conference Series: Earth and Environmental Science*, **218**, Article ID: 012134. <https://doi.org/10.1088/1755-1315/218/1/012134>
- [6] Wang, G., Dannemand, M., Xu, C., Englmaier, G., Furbo, S. and Fan, J. (2021) Thermal Characteristics of a Long-Term Heat Storage Unit with Sodium Acetate Trihydrate. *Applied Thermal Engineering*, **187**, Article ID: 116563. <https://doi.org/10.1016/j.applthermaleng.2021.116563>
- [7] Agyenim, F., Eames, P. and Smyth, M. (2009) A Comparison of Heat Transfer Enhancement in a Medium Temperature Thermal Energy Storage Heat Exchanger Using Fins. *Solar Energy*, **83**, 1509-1520. <https://doi.org/10.1016/j.solener.2009.04.007>
- [8] Zhang, Z., Cheng, J. and He, X. (2017) Numerical Simulation of Flow and Heat Transfer in Composite PCM on the Basis of Two Different Models of Open-Cell Metal Foam Skeletons. *International Journal of Heat and Mass Transfer*, **112**, 959-971. <https://doi.org/10.1016/j.ijheatmasstransfer.2017.05.012>
- [9] Huang, X., Lin, Y., Alva, G. and Fang, G. (2017) Thermal Properties and Thermal Conductivity Enhancement of Composite Phase Change Materials Using Myristyl Alcohol/Metal Foam for Solar Thermal Storage. *Solar Energy Materials and Solar Cells*, **170**, 68-76. <https://doi.org/10.1016/j.solmat.2017.05.059>
- [10] Liu, Z., Zeng, L., Sheng, M., Yan, Y., Li, W. and Su, H. (2024) Experimental and Numerical Research on Thermal Characteristics of Phase Change Thermal Storage Device. *Case Studies in Thermal Engineering*, **58**, Article ID: 104358. <https://doi.org/10.1016/j.csite.2024.104358>
- [11] Liu, S., Wang, H., Ying, Q. and Guo, L. (2024) Numerical Study on the Combined Application of Multiple Phase Change Materials and Gradient Metal Foam in Thermal Energy Storage Device. *Applied Thermal Engineering*, **257**, Article ID: 124267. <https://doi.org/10.1016/j.applthermaleng.2024.124267>
- [12] Xu, Y., Ren, Q., Zheng, Z. and He, Y. (2017) Evaluation and Optimization of Melting Performance for a Latent Heat Thermal Energy Storage Unit Partially Filled with Porous Media. *Applied Energy*, **193**, 84-95. <https://doi.org/10.1016/j.apenergy.2017.02.019>
- [13] Ghahremannezhad, A., Xu, H., Salimpour, M.R., Wang, P. and Vafai, K. (2020) Thermal Performance Analysis of Phase Change Materials (PCMs) Embedded in Gradient Porous Metal Foams. *Applied Thermal Engineering*, **179**, Article ID: 115731. <https://doi.org/10.1016/j.applthermaleng.2020.115731>