



Article Thermal Performance of a Vertical U-Shaped Thermosyphon Containing a Phase-Change Material Suspension Fluid

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Abstract: This study investigated the thermal performance of a vertical U-shaped thermosyphon containing a phase-change material (PCM) suspension fluid via experimentation. The heating and cooling sections were located at the top and bottom of the loop, respectively. The lengths of the heating and cooling sections each accounted for one fifth of the height of the loop. Pure water and a PCM (octadecane) suspension fluid were used to fill the loop to compare the thermal performance of the thermosyphon under different heating power, cooling temperature, and PCM suspension concentration conditions. The results showed that, when the PCM suspension concentration was higher than a critical value, the addition of the PCM suspension had no positive effect on reducing the highest temperature of the fluid in the loop but instead resulted in an increase in fluid temperature. More detailed experiments are needed to observe the phenomena and decide critical values under different experimental parameters.

Keywords: phase-change material suspension; thermal performance natural circulation loop; thermosiphon; octadecane

1. Introduction

Thermosyphons for various configurations and operating conditions have been the subject of numerous investigations because of their wide range of technological applications. A thermosyphon removes heat from a heated section and transports the heat to a cooled section at a higher elevation by means of fluid flow driven by thermally induced density gradients. Such a loop can serve as a low-cost and highly reliable passive heat transfer device. Studies of the performance of single-phase natural convection loops and the effects of various parameters can be found in the existing literature [1–9].

The thermal performance of natural circulation loop systems can be improved not only by modifying the loop itself but also by enhancing the heat-exchange performance of the heated or cooled end or by changing the working fluid. The thermal performance of a natural circulation loop can be significantly enhanced by utilizing the latent heat as the working fluid changes phase. Adding a phase-change material (PCM) to the working fluid to increase the heat transfer efficiency of a natural circulation loop is currently a topic of interest [10]. An effective heat transfer enhancement medium that incorporated microencapsulation and emulsion technologies was proposed by Hart and Thornton [11], where fine solid–liquid PCM particles were dispersed in a carrier or suspending fluid (PCM slurries or suspensions).

Microencapsulation technology encapsulates a PCM using a macromolecular material, thereby separating the dispersed phase (the PCM) from the dispersion medium (water or glycerol) and enabling

the PCM particles to be suspended in the dispersion medium. The advantages of microencapsulation technology [12] are that the produced PCM particles have a relatively fixed size and shape and relatively stable physical properties. However, microencapsulation technology also has some disadvantages; it is relatively expensive and difficult to process. In addition, the macromolecular material used in the microencapsulation process to coat the PCM prevents heat transfer and can expand and fracture after repeated heating and cooling cycles. Emulsion technology can reduce the surface tension between the dispersed phase and the dispersion medium by adding a suitable emulsifier, thereby enabling the PCM to homogeneously suspend in the dispersion medium in the form of particles and form a stable emulsion. Compared to microencapsulation technology, emulsion technology is advantageous due to its low cost and mass production capability. From an economic perspective, emulsion technology is more suitable to be industrially developed to improve the heat transfer properties of working fluids.

A PCM suspension fluid can serve as a dual-functional medium for sensible and/or latent heat transport. The heat transfer enhancement obtained using PCM suspensions as working fluids has been extensively demonstrated in forced convection [13–15]. However, few studies have been conducted on heat transfer characteristics when PCM suspensions are used in a natural circulation loop; one such study is [16], which numerically investigated the efficacy of using a PCM suspension as the heat transfer fluid in a rectangular natural circulation loop. The melting/freezing processes experienced by the PCM particles in the heated/cooled sections were found to be closely interrelated in terms of the mutual effect of their inlet suspension on the thermal conditions. A flow regime may exist in which the latent heat absorption/release of the PCM suspension can effectively serve as the heat transfer enhancement mechanism, which must be defined through more extensive parametric simulations.

While there are still many outstanding challenges to the use of PCM suspensions in improving natural convection heat transfer, the application potential of PCM suspensions is of great interest. Therefore, this study investigated the thermal performance of a vertical U-shaped closed (single-phase) thermosyphon containing pure water and a water-based PCM suspension as working fluids as well as the application effect of the PCM via experimentation.

2. Materials and Methods

2.1. The Experimental Loop and the Measurement Instrument

The experimental model used in this study was a vertical U-shaped thermosyphon loop (Figure 1). The experimental loop had an overall height of 290 mm. The heating and cooling sections were located at the bottom and top of the loop, respectively. Each of the heating and cooling sections had a length of 58 mm, accounting for approximately one fifth of the height of the loop. The adiabatic section had a length of 174 mm, accounting for approximately three fifths of the height of the loop. The loop was composed of a copper pipe with an outer diameter of 6.35 mm and an inner diameter of 4.35 mm. The loop was filled with pure water and a PCM (octadecane) suspension fluid to compare the thermal performance of the thermosyphon when filled with different working fluids.

The outside of the copper pipe was wrapped with electric heating wires to simulate the heating section with a uniform heat flux condition. The heating section consisted of two subsections, each of which was heated by a power supply unit. An 8-mm-thick Centurylon insulating material (AP701, k = 0.036 W/mK) was applied onto the outside of the heating section to reduce heat loss. The heat exchanger in the cooling section was made of an aluminum alloy and contained a labyrinth path through which the cooling water from a constant temperature bath (Lauda RC20) passed. The outside of the heat exchanger and the adiabatic section were also wrapped with Centurylon insulating materials. The ambient temperature was controlled by the air-conditioning in the laboratory. Omega T-type (PR-t-24) thermocouples with Yokogawa HR 1300 and Yokogawa DA 100 data loggers were used to measure and record the temperature of the working fluid in the loop and the loop pipe wall, as shown in Figure 1.



Figure 1. Schematic of the experimental setup.

2.2. Preparation and Properties Measurement of PCM Suspensions

Octadecane (melting point: 27.4 °C) was used in this study as the PCM. To enable octadecane to homogeneously disperse in water in the form of particles, two emulsifiers, Sinopol 968 and Newcol, were used to reduce the surface tension between the oil and water and emulsified octadecane and water into a PCM suspension fluid containing PCM particles. The stability of a suspension fluid is closely related to its fabrication process. Various factors such as the mixing time and environmental temperature during the formulation process can affect the stability and properties of the formulated suspension fluid; an optimal suspension formula and fabrication process was determined after multiple experiments. The suspension formula was determined as follows: emulsifier/PCM ratio = 1/4 and Sinopol 968/Newcol = 1/4. The hydrophilic-lipophilic balance value of the suspension was 8.

- 1. A small amount of distilled water was added into a circular beaker; the required emulsifiers were then added into the beaker.
- 2. Octadecane was added into the beaker.
- 3. A magnetic stir bar was placed in the beaker and the beaker was placed on an electromagnetic stirrer to allow the mixture in the beaker to be mixed for 60 min to emulsify the octadecane and water. During the mixing process, the temperature of the mixture was maintained above the melting point of octadecane. The concentration of the mixed solution was higher than the concentration of the emulsion that we were planning to formulate.
- 4. Subsequently, a suitable amount of distilled water was added into the beaker to dilute the suspension fluid to the desired concentration. The mixture was then mixed for 20 min on the electromagnetic stirrer, after which the formulation of the suspension fluid was completed.
- 5. The suspension fluid was transferred from the beaker to a glass tube. The glass tube was allowed to stand still for 2 h, during which time observations were made to determine whether the octadecane particles were homogeneously dispersed and whether separation and agglutination phenomena had occurred.

- 6. The glass tube was then placed and allowed to cool down for 20 min in a refrigerator. Once the temperature of the emulsion decreased below the melting point of octadecane, the glass tube was removed from the refrigerator and the suspension fluid in the tube was observed to determine if the octadecane particles were homogeneously dispersed in water.
- 7. After the suspension fluid was repeatedly heated, dissolved, allowed to stand still, and cooled down to determine whether the octadecane particles continued to be homogeneously dispersed in water, the obtained suspension fluid was then used for subsequent experiments.

A digital viscometer (Brookfield, Model DV-II+) and a laser particle size analyzer (Malvern, MAF5000) were used to determine the viscosity and particle distribution of suspension fluids with different concentrations. Each property measurement was repeated at least three times to confirm repeatability.

2.3. UncertaintyAnalysis

Uncertainties in the measured quantities for this study, estimated based on the process described by Moffat [17], were ± 0.3 °C for the temperature measured by thermocouples and ± 0.05 W for the heat input measured by an electronic watt meter.

3. Results and Discussion

The parameters investigated in this study included the heat flux in the heating section (q_h) (1000, 2000, and 3000 W/m²), the pipe wall temperature in the cooling section (T_w) (10, 15, 20, 25, and 30 °C) and the PCM suspension concentration (f_p) (0.25%, 1%, 2%, and 3%). A steady state was reached in all the experiments under different parametric conditions.

3.1. Properties of PCM Suspensions

As shown in Figure 2, the specific gravity (the ratio of the density of the suspension fluid to the density of water) decreased with increasing temperature. This phenomenon occurred because the density of the octadecane in the liquid state was lower than that in the solid state. In addition, it can also be seen that the density of the suspension fluid decreased with increasing f_p , except very few data points (measurement uncertainty at 4%; 10 and 20 °C). This change occurred because the density of the octadecane was lower than that of water. When f_p increased, the proportion of the PCM also increased. As a result, the overall density of the suspension fluid decreased.



Figure 2. Relationship between the specific gravity and temperature of the suspension fluid.

Figure 3 shows the change in the viscosity of the suspension fluid with temperature. Figure 3b shows the comparison between the data obtained in this study and the Inaba model [18] and the Vand correlation [19]. The results show that the viscosity of the suspension fluid produced in this study fell between the Inaba model and the Vand correlation, except very few points (20%; below 20 °C). The relationship between the viscosity (μ) (N s/m²), concentration (*c*) (wt%), and temperature (*T*) (K) of the suspension fluid is as follows:

$$\mu = \left(2.0293 + 12.522c - 29.92c^2\right)e^{\frac{5.5}{T}}.$$
(1)



Figure 3. (a,b) Relationship between the viscosity and temperature of the suspension fluid.

The maximum error is 19% and the mean error is 11% (*C* = 0.25–20%; *T* = 283.15–323.25 K).

The size of suspension particles and toughness of the particle surface are primary factors that not only determine the stability of the suspension fluid but also affect the capability of the PCM to fully use its latent heat during thermal cycles. If the suspension particle size is excessively large, the scale of the solid-liquid phase change dispersion time is greater than that of the convection time. As a result, only a fraction of the PCM participates in the heat transfer reaction and the expected heat transfer effect will not be realized. However, if no strong protective membrane is formed on the surface of the suspension particles after they are formed, then the suspension particles will agglutinate after repeated heating and cooling. Figure 4 shows that the particle sizes of the suspension fluid used in this study exhibited a continuous distribution, and the main particle size in the distribution was approximately 150 µm.



Figure 4. Suspension particle size distributions.

Figure 5 shows the particle size distributions before the experiment and after the 10-h-long natural convection heat transfer experiment. Notably, the suspension particle distributions measured in this study were not the actual particle sizes because the laser particle size analyzer could only determine particle size distributions in the range of $0.3-300 \ \mu\text{m}$. However, after the heat transfer experiment, there were many particles with diameters greater than 300 µm. Therefore, we used a relatively high rotational speed (2000 rpm) during the measurement process. As a result, the measured particle sizes were far smaller than the actual particle sizes. Nonetheless, the measured particle size distributions can still help in investigating the thermal effect on the suspension particles. Based on Figure 5, we know that the suspension particle size distribution was less even after 10 h of thermal cycles (see "After experiment" in the figure legend) than after the suspension fluid stood still for 10 h (see "After 10 h"). The suspension particle size distribution after the suspension fluid stood for 10 h was approximately similar to that right after the suspension fluid was produced. The small change in the particle size distribution was caused by the instability of the suspension fluid. The suspension particle size distribution became significantly uneven after 10 h of thermal cycles because the PCM particles constantly underwent thermal expansion and contraction during the thermal cycles, resulting in the agglutination of PCM particles on whose surface a strong protective membrane was not formed, thus forming relatively large particles after the emulsifier-coated absorption membrane fractured.



Figure 5. Effect of thermal cycles on the suspension particle sizes.

Because the settling velocity of the particles is directly proportional to the square of the particle size, there was a chance for the agglutination and separation phenomena to occur once the suspension particle size distribution became uneven. As a result, the PCMs located between the agglutinated particles were unable to participate in the heat transfer process, and the heat transfer efficiency decreased.

3.2. Basic Observations

We initially observed the temperature distribution of the fluid in the thermosyphon loop when $q_h = 2000 \text{ W/m}^2$, $T_w = 20 \text{ °C}$, and pure water was used as the working fluid ($f_p = 0\%$). Based on Figure 6a, we know that, in the cooling subsection $l_{c,1}$, the temperature of the fluid was very close to the design T_w . In the adiabatic subsection $l_{a,2}$, the temperature of the fluid exhibited an increasing trend. At the end of the adiabatic subsection $l_{a,2}$ (prior to the heating subsection $l_{h,1}$), the temperature of the fluid exhibited a more significant increasing trend. At the end of the heating subsection $l_{h,1}$ (prior to the adiabatic subsection $l_{a,3}$), the fluid could not maintain its highest temperature and the temperature of the fluid decreased rapidly. At the cooling subsection $l_{c,2}$, the temperature of the fluid was once

again close to T_w . The subsequent change in the temperature of the fluid followed the same pattern. When the 3% PCM suspension fluid was used as the working fluid, the temperature distribution of the fluid was qualitatively similar to that of pure water as the working fluid (Figure 6b). Based on the change in the temperature of the fluid in the adiabatic section, we know that, due to the axial heat transfer along the copper pipe wall in the adiabatic section, the pipe wall temperature in the adiabatic section was affected by the adjacent heating and cooling sections; consequently, the temperature of the fluid in the adiabatic section.



Figure 6. Steady-state temperature distribution of the fluid in the thermosyphon loop when $q_h = 2000 \text{ W/m}^2$ and $T_w = 20 \text{ °C:}$ (a) Pure water as the working fluid ($f_p = 0\%$); (b) Pure water as the working fluid ($f_p = 3\%$); (c) The experimental loop.

3.3. Effect of T_w

This section discusses the effect of different T_w value in the cooling section on the steady-state temperature of the fluid when $q_h = 2000 \text{ W/m}^2$. Based on Figure 7a, we know that, when pure water was used as the working fluid, the steady-state temperature distributions of the fluid in the loop under different T_w value in the cooling section quantitatively exhibited very similar variation trends. The only difference lies in the temperature values: the difference in the temperature values between

the steady-state temperature distribution under one T_w and the steady-state temperature distribution under another T_w was directly proportional to the difference between the T_w value. When the PCM suspension fluid was used as the working fluid, the effect of T_w on the temperature of the fluid varied under different f_p s (Figure 7b,c).



Figure 7. Steady-state temperature distributions of the fluid under different T_w value ($q_h = 2000 \text{ W/m}^2$): (**a**) $f_p = 0\%$; (**b**) $f_p = 0.25\%$; (**c**) $f_p = 3\%$; (**d**) The experimental loop.

When $f_p = 0.25\%$ (Figure 6b) and $T_w = 30$ °C (higher than the melting point of the PCM), the steady-state temperatures of the fluid were all higher than the melting point of the PCM, and the PCM suspension fluid did not undergo any phase change. Consequently, the system could not take advantage of the PCM latent heat. However, the addition of the PCM suspension fluid resulted in an increase in the viscosity of the fluid and an increase in the resistance to the flow of the fluid. As a result, the temperature of the fluid in the two heating subsections was higher than that when pure water was used as the working fluid. When T_w was lower than the melting point of the PCM ($T_w = 10$, 15, 20, and 25 °C), the highest temperature of the fluid (occurring in subsection $l_{h,1}$) was lower than that when pure water was used as the working fluid, whereas the lowest temperature of the fluid remained the same (very close to T_w). In addition, the decreasing trend of the highest temperature of the fluid in subsection $l_{h,1}$ (with decreasing T_w) was different from the aforementioned temperature variation trend when pure water was used as the working fluid. This phenomenon was caused by the solid–liquid latent heat effect of the PCM suspension fluid.

When $f_p = 3\%$ (Figure 7c), the highest temperature of the fluid (occurring in subsection $l_{h,1}$) was lower than when pure water was used as the working fluid only when T_w was relatively low ($T_w = 10$)

and 15 °C). Therefore, we can conclude that the highest fluid temperature did not continuously decrease with increasing f_p .

3.4. Effect of q_h

As seen in Figure 8a, the steady-state temperature distributions of the fluid in the loop caused by different q_h values quantitatively exhibited similar trends but were different in temperature value and variation trend. The slopes of the temperature change in the two heating subsections when $q_h = 3000 \text{ W/m}^2$ were greater than those when $q_h = 1000 \text{ W/m}^2$ and $q_h = 2000 \text{ W/m}^2$. When the PCM suspension fluid was used as the working fluid, the trend was the same as when pure water was used as the working fluid (Figure 8b,c).



Figure 8. Steady-state temperature distributions of the fluid under different q_h value ($T_w = 20 \text{ °C}$): (a) $f_p = 0\%$; (b) $f_p = 0.25\%$; (c) $f_p = 3\%$; (d) The experimental loop.

3.5. Effect of fp

When the PCM suspension fluid is used as the working fluid, the added PCM particles will affect the physical properties of the fluid (viscosity, specific heat, etc.). The change in the viscosity and specific heat of the fluid affects the heat transfer characteristics of the loop. When more PCM particles are added, f_p increases. Consequently, the viscosity of the fluid increases and the specific heat of the fluid decreases. Under the natural convection mechanism, an increase in the viscosity of the working fluid will result in a decrease in the flow rate of the fluid, a decrease in the convection efficiency, and a possible increase in the highest temperature of the fluid in the loop. When the specific heat of the working fluid decreases, the temperature of the fluid can also easily increase. However, a solid–liquid phase change may occur in the fluid after the PCM is added, resulting in an increase in

the heat capacity of the fluid, which in turn results in a decrease in the highest temperature of the fluid. Therefore, the change in the viscosity and specific heat of the fluid that occurs after the addition of the PCM suspension will affect the eventual heat transfer phenomenon of the system.

As seen in Figure 9a,b (see the data around the 0% red lines), when f_p changed, there appeared to be a critical value at which the solid–liquid phase change effect and the viscosity and specific heat effects could reach a balance. When f_p was higher than this critical value, the addition of the PCM suspension had no positive effect on reducing the highest temperature of the fluid in the loop but instead resulted in an increase in the temperature of the fluid in the loop. More detailed experiments are needed to observe the phenomena and decide critical values under different experimental parameters. This is not what we are mainly exploring in this study, but is worth further consideration.



Figure 9. Steady-state temperature distributions of the fluid under different $f_p s$ ($q_h = 2000 \text{ W/m}^2$): (a) $T_w = 10 \degree$ C; (b) $T_w = 20 \degree$ C; (c) $T_w = 30 \degree$ C; (d) The experimental loop.

As seen in Figure 9c (also see the data around the 0% red line), the temperature of the entire loop was higher than the melting point of octadecane. Therefore, the PCM particles existed in the liquid state, and no solid–liquid phase change occurred. The addition of PCM particles only resulted in a change in other physical properties of the fluid. When the temperature of the fluid in the loop reached the steady state, the highest temperature of the fluid did not decrease but rather increased to some extent due to the change in the physical properties of the fluid.

4. Conclusions

This study experimentally investigated the thermal performance of a closed thermosyphon containing pure water and a PCM suspension fluid. The following conclusions can be summarized based on the obtained results:

- 1. When pure water was used as the working fluid, the steady-state temperature distributions of the fluid in the loop under different cooling temperature exhibited similar variation trends. When the PCM suspension fluid was used as the working fluid, the effect of cooling temperature on the temperature of the fluid varied under different PCM suspension concentration (f_p).
- 2. When f_p changed, there was a critical value at which the solid–liquid phase-change effect and the viscosity and specific heat effects could reach equilibrium. When f_p was higher than this critical value, the addition of the PCM suspension had no positive effect on reducing the highest temperature of the fluid in the loop but instead resulted in an increase in the temperature of the fluid in the loop. The critical f_p value varied under different experimental parameters. Further and more detailed experiments are needed to understand the phenomena.

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