Experimental study on a loop thermosyphon with microencapsulated phase change material suspension

Zhenyu Tan\textsuperscript{1,2,3}, Xunfeng Li\textsuperscript{1,2,3,*}, Jingzhi Zhou\textsuperscript{1,2,3} and Xiulan Huai\textsuperscript{1,2,3*}

1 Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China

2 School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China

3 Nanjing Institute of Future Energy System, Nanjing 211135, China

* Corresponding author: lixunfeng@iet.cn (Xunfeng Li).

Abstract. Microencapsulated phase change material suspension (MPCMS) represents an innovative category of functional thermal fluids. This novel working fluid not only preserves the substantial energy density and high latent heat of phase change materials (PCM), but also mitigates the issues related to PCM, including susceptibility to aggregation and low thermal conductivity. This article selects phase change microcapsules with a phase change temperature of 70 °C, and uses pure water as the base liquid to prepare MPCMS as the working fluid for the loop thermosyphon. A series of heat transfer experiments are conducted, and the results are compared with those of pure water experiments. A 135mm*650mm copper loop thermosyphon, is designed and constructed to investigate the effect of various input power on the heat transfer performance. The results show that the addition of MPCMS can reduce the wall temperature by up to 2.9°C and the loop thermal resistance by 6.3%. Compared with water, the loop thermosyphon with MPCMS has better start-up characteristics. The performance of the MPCMS is affected by various parameters, which are interconnected. Particles in close proximity to the wall display erratic movement, fluctuating across different temperature zones, thereby undergoing a continuous cycle of melting and solidification. This study establishes a basis for further investigation into the practical implementation of MPCMS in industries.

1. Introduction

In recent years, there has been a notable rise in the peak power consumption of diverse electrical equipment, presenting a formidable obstacle to conventional cooling techniques [1]. Loop thermosyphon, being a passive cooling device, holds considerable promise in addressing the escalating cooling requirements while concurrently mitigating direct interaction between the equipment and the primary cooling medium (such as ambient air or water), thereby facilitating equipment protection and maintenance [2]. Scholars have proposed the concept of phase change capsules to enhance the heat transfer efficiency of the loop thermosyphon. These capsules consist of phase change materials enclosed within a thin film that exhibits stable characteristics [3]. Currently, the diameter of commercialized micro-scale phase change capsules typically ranges from 1 to 500 microns, and their shells remain solid when the PCM inside undergoes phase change, thus preventing the phase state of the material from
affecting the external environment. Additionally, since the shell is thin (usually 0.5 to 150 microns), it does not create significant thermal resistance [4][5]. This new type of latent heat thermal material is called microencapsulated phase change material (MPCM). Mixing MPCM with commonly used thermal fluid creates a suspension that can achieve both heat storage and transfer functions, reducing one heat transfer process and significantly improving heat transfer efficiency [6][7]. This new type of latent heat thermal fluid is called microencapsulated phase change material suspension (MPCMS).

Researchers have conducted numerous studies on the enhanced heat transfer of MPCMS, but current research focuses mainly on convective heat transfer. Wang et al. [8][9] experimentally investigated the heat transfer characteristics of MPCMS in circular tubes. The findings demonstrated that the utilization of phase change microcapsule suspension, as compared to water, can augment convective heat transfer efficacy, diminish non-dimensional inner wall temperature, and the heat transfer enhancement ratio escalates with higher suspension concentration, albeit the increment is not pronounced. Zhang et al. [10] performed an experimental investigation into the heat transfer behavior of a phase change microcapsule suspension when flowing in a circular tube under a constant heat flux. The findings indicated that, in comparison with water, the Nusselt number of the suspension experienced respective increases of 23.9%, 20.5%, and 9.1% during the solid, solid-liquid, and liquid states of the phase change material.

In summary, MPCMS exhibits remarkable enhancement in convective heat transfer within the tube. Nonetheless, scarce investigations have been carried out on the impact of MPCMS in loop thermosyphons, and few experimental studies have presented the bubble dynamics in two-phase oscillation. Thus, additional experimental studies are necessary to comprehend the boiling heat transfer mechanism of MPCMS. This article conducted tests on an integrated loop thermosyphon made for MPCMS and compared it with pure water. The starting characteristics, thermal resistance, and wall temperature of MPCMS and pure water were tested under different heating power, cooling water temperature, and filling rates, and the enhanced heat transfer performance of MPCMS in the loop thermosyphon was evaluated.

2. Experimental details

2.1. Experimental facility

In this study, we have designed and fabricated a prototype of an MPCMS loop thermosyphon, and conducted a comprehensive performance evaluation. Figure 1 (a) provides the physical schematic of the experimental setup. The loop thermosyphon’s dimensions are 135mm × 650mm, with an inner pipeline diameter of 8mm and an outer diameter of 10mm. The evaporation section and condensation section of the loop are constructed using purple copper, while the adiabatic section is composed of stainless steel. The evaporation chamber is a rectangular copper block housing a tubular cavity with an 8mm inner diameter. On one side of the evaporation chamber, there is a copper heating block with a heating area of 10mm×30mm, which is securely attached to the evaporation chamber using bolts. The condensation section is 400mm long and has a finned structure inside, which can fully cool the high heat flux density of the evaporation section. In order to prevent heat leakage of the pipeline, the adiabatic section and the heating block are wrapped with a layer of insulation cotton, and the outer side is wrapped with aluminum foil tape.
Eleven type-T thermocouples, each with a 1 mm diameter, are employed for temperature measurement, as depicted in Figure 1 (b). T₁ and T₂ are assigned for measuring the temperature at the inlet and outlet of the evaporation section respectively, while T₃ and T₄ are designated for recording the gas phase section temperature. T₅ and T₆ utilized for monitoring the fluid temperature at the inlet and outlet of the condensation section, and T₇ is specifically used for temperature measurement in the liquid phase section. T₈ and T₉ are employed to gauge the temperature of the cooling water entering and exiting the condensing casing. Wall temperature T₉ is the average temperature of the two thermocouples placed in the heated wall. In each test, the heating power starts at 30W/cm² and increases by 5W/cm². At each heat flux, the data is recorded after the evaporation chamber wall temperature has stabilized. All thermocouple signals were acquired through the utilization of the YOKOGAWA GP20 paperless recorder, and subsequently analyzed employing a computer for data analysis. The heating power was incrementally modulated from a low to high setting in each test, and the electrical power of the heating block was precisely measured by employing the KYORITSU KEW-6310 power quality analyzer.

2.2. Preparation of working fluid
In the experiment, the base liquid of MPCMS was ultra-pure water made by pure water mechanism. The core material of MCPM was a composite organic resin with phase change temperature of 70°C, the average diameter of the microcapsules was 6 microns, and the material making up the outer wall was polymethyl methacrylate (PMMA). The electron microscopic photos of MPCMS were shown in the Figure 2.
A stable suspension can be obtained by fully stirring MPCM with water and ultrasonic dispersion for one hour [11]. When injecting liquid, use the molecular pump to pump the ring tube to vacuum (the absolute pressure in the tube is less than $1 \times 10^{-3}$ Pa), and the working fluid is injected into the tube through the injection pipe on the evaporation chamber. According to the different injection rate, the pressure in the tube is 8-10kPa.

2.3. Uncertainty analysis

Holman’s method [12] was employed to analyze the uncertainty associated with each parameter. This approach relies on a comprehensive depiction of uncertainties pertaining to diverse primary experimental measurements. Addressing temperature measurements, the calibration of thermocouples and the adjustment of temperature based on thermocouple readings were taken into account. The greatest uncertainty in both wall and fluid temperature (using type-T thermocouple) is approximately $\pm 0.5 ^\circ C$.

The calculation of heat flux in the evaporation section has been conducted as:

$$q'' = \frac{VI}{S}$$

where $V$ is the voltage, $I$ is the current, $S$ is the effective heating area.

The loop thermal resistance has been estimated as:

$$R_{\text{loop}} = \frac{(T_{\text{evap.outlet}} - T_{\text{cond.outlet}})}{P}$$

where, $T_{\text{evap.outlet}}$ and $T_{\text{cond.outlet}}$ are the temperature at the outlet of the evaporation section and the condensing section respectively, corresponding to $T_2$ and $T_6$, and $P$ is the heating power of the loop thermosyphon.

The uncertainty of heat flux was estimated by taking into account the uncertainties associated with voltage, current, and the surface area being heated:

$$\frac{\delta q''}{q''} = \sqrt{\left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta I}{I}\right)^2 + \left(\frac{\delta S}{S}\right)^2}$$

The maximum uncertainty in heat flux was determined to be less than 1.03%. The loop thermal resistance uncertainty was calculated as:

$$\left(\Delta R_{\text{loop}}\right)^2 = \left(\frac{\partial R_{\text{loop}}}{\partial V}\right)^2 (\Delta V)^2 + \left(\frac{\partial R_{\text{loop}}}{\partial I}\right)^2 (\Delta I)^2 + \left(\frac{\partial R_{\text{loop}}}{\partial T_2}\right)^2 (\Delta T_2)^2 + \left(\frac{\partial R_{\text{loop}}}{\partial T_6}\right)^2 (\Delta T_6)^2 \quad (4a)$$
\[
\frac{\Delta R_{\text{loop}}}{R_{\text{loop}}} = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta T_2}{T_2 - T_6}\right)^2 + \left(\frac{\Delta T_6}{T_2 - T_6}\right)^2}
\] (4b)

In this experiment, the temperature varies between 15℃ and 65℃, and the uncertainty range of the loop thermal resistance is calculated to be between 1.47% and 4.81%. **Table 1** presents the uncertainties associated with each measured parameter.

**Table 1.** The uncertainties of various parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>±0.5℃</td>
</tr>
<tr>
<td>Voltage</td>
<td>±0.4%</td>
</tr>
<tr>
<td>Current</td>
<td>±0.9%</td>
</tr>
<tr>
<td>Length</td>
<td>±0.02mm</td>
</tr>
<tr>
<td>Data signal</td>
<td>±0.02%</td>
</tr>
</tbody>
</table>

3. Results and discussions

The experimental results show that MPCMS can significantly enhance the heat transfer capacity of loop thermosyphon compared with pure water, which is manifested in faster start-up speed, lower wall temperature and higher critical heat flux.

3.1. Start-up characteristics

The start-up of the thermosyphon refers to the process in which the internal working fluid begins to boil after it is heated. The curve of the temperature change of the heating wall surface over time in this process is called the start-up characteristic curve, and the start-up characteristic is an important index to measure the performance of the thermosyphon. **Figure 3** shows the start-up characteristic curves of loop thermosyphon under four different working conditions.

![Figure 3. Start-up characteristic curves of loop thermosyphon under four different working conditions](image)

Before the loop thermosyphon starts, the wall temperature increases approximately linearly, and the loop thermosyphon starts to work after the wall temperature reaches the phase change temperature of the base liquid. Before the heat flux reaches the starting heat flux, the temperature of the wall will
decrease rapidly after the thermosyphon is started, resulting in the working fluid cannot continue to boil and repeatedly switch between working and non-working states. When the heat flux is higher than the starting heat flux, the wall temperature of the thermosyphon will appear a sudden drop after starting, followed by a slow rise to a stable level. However, when the heat flux is particularly high, the wall temperature does not show a sudden drop when the loop thermosyphon starts, but shows a sudden decrease in the temperature growth rate and gradually decreases to zero.

Compared with pure water, MPCMS requires higher startup heat flow, because the microcapsule phase change improves the latent heat of evaporation of working medium, which also enables the thermosyphon to have stronger heat exchange performance after startup. As shown in the figure, MPCMS has temperature fluctuation under the heat flux of pure water, which indicates that MPCMS loop thermosyphon is in the cycle of startup, cooling and startup failure. Unstable boiling will occur inside the pure water loop thermosyphon during normal operation, which is manifested by small amplitude fluctuation of wall temperature. While the MPCMS thermosyphon operates normally, the temperature oscillation phenomenon is significantly inhibited, because the phase change of phase change microcapsules in the base liquid plays a thermal buffer role, and the movement of phase change microcapsules in the base liquid also inhibits the occurrence of unstable boiling.

### 3.2. Heat transfer characteristics

The main performance evaluation indexes of loop thermosyphon in operation are wall temperature and loop thermal resistance. Figure 4 shows the variation curve of wall temperature with heat flux when the loop thermosyphon of two working fluids reaches stability. MPCMS can significantly reduce the wall temperature of the loop thermosyphon. When the loop thermosyphon works at a medium heat flux, the wall temperature will be stable at 70°C to 90°C, which is the safe use temperature in most application scenarios of electronic devices [13]. The selected MPCMS core phase transition temperature is 70°C, and phase transition will be carried out near the wall to promote the heat transfer of working fluid. Under the action of gravity and bubbles, the particles will oscillate violently in the liquid phase in the ring tube, which greatly promotes the heat transfer inside the thermosyphon.

![Figure 4](image)

**Figure 4.** Curves of stable wall temperature with heat flux of two working fluids

When the heat flux continues to increase and reaches the heat transfer limit of the loop thermosyphon, continuous dry burning will occur on the heating wall, resulting in a sharp rise in the wall temperature, and the heat flux at this time is the critical heat flux. In the experiment, the critical heat flux is taken as the heat flux when the wall temperature loses stability and rises sharply.
Figure 5 shows the curve of the loop thermal resistance of the loop thermosyphon with the heat flux of the two working fluids. The thermal resistance of the MPCMS thermosyphon is lower than that of the pure water thermosyphon. With the increase of heat flux, the loop thermal resistance is greatly reduced, because the sensible heat transfer ratio is high, and the heat transfer efficiency is proportional to the circulation flow rate of the loop, and the circulation flow rate is proportional to the heat flux. The microcapsules in MPCMS will phase change repeatedly when flowing inside the thermosyphon, and the heat absorption and release during the phase transition process can transport more heat per unit volume of the working medium, which improves the heat transfer efficiency of the working medium on a macro level. In the experiment, MPCMS thermosyphon can reduce the loop thermal resistance by up to 6.3%. When the heat flux is about 100W/cm², MPCMS shows the best strengthening performance, because the heating wall surface temperature at this time is about 80°C to 90°C, slightly higher than the phase transition temperature of microcapsules, which is most conducive to the phase transition of microcapsules in the base fluid. In summary, the loop thermosyphon applied to various heat flux densities can be strengthened by selecting microcapsules with appropriate phase transition temperatures.

Figure 5. Curves of loop thermal resistance with heat flux of two working fluids

Loop thermal homogeneity is an important index to measure the heat transfer capacity of a thermosyphon. The non-homogeneous temperature coefficient is used to judge the loop temperature equalization of a thermosyphon, and its definition is shown in equation (5). The smaller the value, the better the temperature equalization of a thermosyphon. Improving the temperature equalization can ensure the safe operation of the equipment and extend the service life of the thermosyphon.

\[ \eta = \frac{(\Delta T)_{max}}{\bar{T}} \]  

(5)

where \((\Delta T)_{max} = T_{max} - T_{min}\) represents the largest temperature difference throughout the loop thermosyphon. \(\bar{T} = \frac{1}{7} \sum_{i=1}^{7} T_i\) is the average temperature of the 7 temperature measuring points on the loop thermosyphon, representing the average temperature of the entire loop thermosyphon.

The variation curve of non-homogeneous temperature coefficient of the loop thermosyphon is shown in Figure 6. During the operation of the loop thermosyphon, MPCMS will change phase repeatedly between the evaporation section and the condensation section. The disturbed flow field strengthens the heat transfer, makes the temperature distribution in the loop more uniform, and inhibits the unstable...
boiling in the loop thermosyphon. On the one hand, MPCMS can promote the liquid evaporation in the evaporation chamber, leading to the expansion of the two-phase region; On the other hand, the circulating heat flow is increased and the convective thermal resistance in the condensing section is reduced, so the thermal homogeneity of the loop thermosyphon is significantly improved.

![Figure 6. Non-homogeneous temperature coefficient of the loop thermosyphon](image)

4. Conclusions
In this paper, the MPCMS loop thermosyphon is designed and manufactured and its heat transfer capability is tested under various operating conditions. Experimental analysis is performed to compare the enhanced heat transfer capacity of the loop thermosyphon with that of water, and its effect on the start-up characteristics, heating surface temperature, and critical heat flux of the loop thermostat was quantitatively studied. The following conclusions can be drawn:

(1) MPCMS can enhance the heat transfer capacity of loop thermosyphon under various conditions, which is manifested in accelerating the start-up of loop thermosyphon, reducing the wall temperature and reducing the thermal resistance of loop. At low heat flux, before the start-up of the loop thermosyphon, the wall temperature of the evaporation chamber increases approximately linearly, reaching the phase change temperature of the microcapsule rapidly. The microcapsule in the MPCMS will absorb heat for phase change, which increases the phase change latent heat of the working fluid, and has higher requirements for starting heat flux than pure water. However, after reaching the starting heat flux, the wall stability temperature of MPCMS thermosyphon is reduced by 2.5 °C compared with that of pure water under the same heat flux.

(2) When the loop thermosyphon is running, the movement and phase transition of MPCMS in the liquid phase of the thermosyphon will promote heat transfer, improve temperature uniformity, reduce metal thermal fatigue, and extend service life. In the experiment, compared with the pure water thermosyphon, the wall temperature of MPCMS thermosyphon is reduced by 2.3 °C on average, and the maximum is reduced by 2.9 °C. The loop thermal resistance is reduced by 6.3% at the maximum, which significantly improves the performance of the loop thermosyphon.

(3) When the heat flux is about to reach the critical heat flux, the inside of the thermosyphon is boiling violently, the MPCM particles move rapidly in the liquid phase under the influence of gravity and bubbles, and some particles enter the gas phase, delaying the process of nucleate boiling to film boiling, and improving the heat transfer limit of the thermosyphon. In the
experiment, the critical heat flux of MPCMS loop thermosyphon was increased by 7.7% compared with pure water.

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References