Thermal Performance Improvement of a Cylindrical Thermosyphon with Modified Wettability on both Evaporator and Condenser Sections

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Abstract

This study investigated the thermal efficiency and thermal resistance of two-phase closed thermosyphons exhibiting surfaces with various wettabilities in the condenser and evaporator sections. Nano silica particles were coated to vary the wettability of the surfaces. The experimental results revealed that, in the surface of the evaporator section, thermal efficiency increased with an increasingly wettable surface; however, in the condenser section, thermal efficiency decreased with an increasingly wettable surface. The highest thermal performance of the two-phase closed thermosyphon was achieved when the evaporator section was superhydrophilic and the condenser section was superhydrophobic.

Keywords: Hydrophilic; Hydrophobic; Thermosyphon; Nanoparticle

1. Introduction

Recently, computers, communication products, and consumer electronics (3C) have become increasingly small and light, indicating that the space available for the cooling systems in these products is decreasing. Therefore, designing and implementing heat removal for these products is challenging. Although water micro channel cooling systems are effective at dissipating heat, the reliability of pumps and liquid leakage are substantial problems (Tuckerman and Pease, 1981). Two-phase closed thermosyphons (TPCTs) are another cooling solution because of their simplicity, compactness, and no need for electricity. In a TPCT, the internal fluid circulates through convection and gravity, thus transferring heat naturally, efficiently, and reliably. Therefore, TPCTs have been used in many devices including electronic components, heat exchangers, turbine blade coolers, and aerospace systems (Yarin et al, 2009; Vasiliev et al., 2008). Many studies have sought to improve the thermal performance of TPCTs. Improving the thermal performance of TPCTs can be separated into
two main approaches. The first improvement consists of using a nanofluid to substitute the working fluid for boosting thermal performance (Naphon et al., 2008). In recent years, studies have used nanofluids in TPCTs, determining that nanofluids can enhance the heat transfer coefficient and critical heat flux in the evaporator section (Kang et al., 2009; Noie et al., 2009). The reason for this is that nano particles in the working fluid deposit on the heating surface and change the surface wettability to hydrophilic or superhydrophilic (Liu et al. 2007; Shi et al., 2007). The second improvement involves surface characteristics, with surface wettability being a major subject for the heat transfer of TPCTs. Rahimi et al. (2010) reported changing surface wettability in the evaporator and condenser region of a TPCT. The internal surface of the evaporator was modified using micro silica particles, and the surface became superhydrophilic (CA=4°). By contrast, the condenser region was coated with (C₆H₅)₂SiO₂, and the surface became hydrophobic (CA=120°). The thermal performance increased by an average of 15%, and the average thermal resistance decreased 2.35 times in this example of surface modification.

Solomon et al. (2013) performed a series of experiments on a TPCT by using an aluminum tube. An anodizing process was conducted to attain a porous structure on the inner wall of the tube. The total thermal resistance of the anodized tube was lower than that of the non anodized tube. Although the thermal resistance in the condenser section was similar in these two cases, a large reduction in thermal resistance occurred in the evaporator section, decreasing the total thermal resistance.

Likewise, Solomon et al. (2012) built a pipe internally coated with nanoparticles, decreasing the wall temperature in both the evaporator and condenser sections of the heat pipe. The diminution of total thermal resistance was 14% (Qu et al., 2008). A gradient wettability was attained in the internal surface of the heat pipe, with the evaporator section, adiabatic section, and condenser section having different surface wettabilities. The surface with a gradient wettability exhibited smaller to larger contact angles from the evaporator section to the condenser section, thereby enhancing heat dissipation. The results revealed that the surface with a gradient wettability increased the maximum heat input of the heat pipe, compared with a surface with uniform wettability.

This study evaluated condenser and evaporator surfaces with various wettability characteristics affecting thermal performance. Nano silica particles and PFOCTs were coated on the evaporator and condenser surfaces, resulting in various levels of wettability. The results revealed that the effect of a superhydrophobic surface on the transfer of heat from the condenser was small. This study investigated the effects of changing the surface wettability from superhydrophilic to superhydrophobic on the evaporator section and condenser section of TPCTs.

2. Experimental Setup

2.1 Working Equipment
The copper tubes of the TPCTs consisted of three parts: the evaporator, adiabatic, and condenser sections (Fig. 1). The total length of the TPCTs was 150 mm, and the outer diameter was 6 mm. The evaporator section had a length of 30 mm at the bottom. The adiabatic section, having a length of 70 mm, was in the middle, and the remaining 50 mm corresponded to the condenser section, which was located at the top to dissipate heat through a water cooling system. The water cooling system consisted of a water jacket wrapping the condenser. Seven type-T thermocouples (with an accuracy of ±0.1 °C) were installed to record the temperature data from the inlet and outlet of the cooling
system by using a data logger (YOKOGAWA MX100 with an accuracy of ±0.1°C, 30 channel inputs, and a temperature measurement range of 0 to 400 °C). The power supply (Agilent Tech. E3646A, maximum output 60 W) was connected to the heating stick (Chung Shun Heater Co.), which was inserted in the copper block as the heating source. A vacuum pump (ULVAC G-100D) was fitted for removing the non-condensable gases from the TPCTs, maintaining a pressure of 20 Torr. The working fluid was pure water, and the filling volume was 72.5% (calculated according to the total length of the evaporator).

![Fig. 1. The experimental setup.](image)

2.2 Resurfaced Technology
To create various wettabilities in the evaporator and condenser section of the TPCTs, nano silica particles (40 nm) were coated to achieve a superhydrophilic effect on the internal surface of the copper tube, whereas the superhydrophobic effect was achieved by coating trichloro(1H, 1H, 2H, 2H-perfluorooctyl) silane (PFOCTs) on the internal surface after it became superhydrophilic.

The plain copper tube was cleaned in an ultrasonic bath with acetone for 10 min, and rinsed with ethanol and deionized (DI) water. Subsequently, the copper tube was dipped into a 2M hydrochloric acid solution for 10 min, and triple-rinsed with DI water. The contact angle (CA) of this plain copper surface after baking was approximately 90° (Fig. 2 a).
The proposed silica-based coating method can lead to different levels of surface wettability (superhydrophobicity to superhydrophilicity). A commonly used sol-gel method was applied to prepare nano silica particles. First, the precursor was prepared by mixing solution A with solution B (1.5/100, v/v). Solution A consisted of tetraethoxysilane (TEOS) and DI water at a molar ratio of 1:4. Solution B consisted of ethanol and DI water at a molar ratio of 1:3. Finally, 4 g of nano particles were mixed with the precursor solution, and magnetically stirred at room temperature for 8 h. The first step involved the nano particle-coating method, which consists of dipping the copper tube. The second step entailed preparing hydrophobic materials by using fluorocontaining mixtures. PFOCTs were mixed with methyl alcohol (1/100, v/v). The roughness caused by coating the surface with PFOCTs increased surface hydrophobicity. CA measurements were conducted using a CA meter (Sindatek Model 100SB), and a drop volume of 2 L. This procedure enabled achieving an internal surface angle of less than 10° or greater than 160° (Figs. 2b and 2c). Scanning electron microscope (SEM) images revealed that the nano silica particles were coated on the copper surface (Fig. 3a). The copper surface coated with nano silica particles and PFOCTs is shown in Fig. 3b.

Fig. 2. A view drops contact on the internal surface (a) un modified copper surface, (CA=90°) (b)Nano silica particles coated surface, superhydrophilic surface (CA<10°) (c) PFOCTs coated surface, superhydrophobic surface (CA>160°).

Fig. 3. (a)SEM image of nano particles coated at scale bars: 5µm. (b) SEM image of nano particles and PFOCTs coated are at scale bars: 5µm.
3. Results and Discussion

The formulae representing the thermal properties of the TPCTs, including thermal efficiency (\(\eta\)) and thermal resistance (\(R_{th}\)) are listed as follows.

The heat transfer rate of the heat input through the power supply was obtained as follows:

\[
Q_{in} = V \times I
\]

Where \(V\) and \(I\) are the input voltage and current of power supply, respectively. By contrast, the expression of input power was defined as follows:

\[
q_{in} = \frac{Q_{in}}{\pi d_i l_e}
\]

Where \(d_i\) is the inner diameter of the TPCT, and \(l_e\) is the length of the evaporator.

The rate of heat dissipation from the condenser section can be expressed as

\[
Q_{out} = \dot{m} \times c_p \times (T_{out} - T_{in})
\]

Where \(\dot{m}\) is the mass flow rate, and \(T_{out}\) and \(T_{in}\) represent the temperature of the water jacket. The uncertainty of the thermal efficiency and thermal resistance was calculated using the following equations. The average uncertainties in the thermal resistance and thermal efficiency measured at \(q=21\,\text{kW/m}^2\) to \(42\,\text{kW/m}^2\) are presented in Tables 1 and 2.

\[
\left(\frac{\Delta W}{W}\right)^2 = \left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta T_{in}}{T_{out} - T_{in}}\right)^2 + \left(\frac{\Delta T_{out}}{T_{out} - T_{in}}\right)^2
\]

\[
\left(\frac{\Delta R}{R}\right)^2 = \left(\frac{\Delta W}{W}\right)^2 + \left(\frac{\Delta T_e}{T_e - T_c}\right)^2 + \left(\frac{\Delta T_c}{T_e - T_c}\right)^2
\]

The thermal efficiency was defined as the output power over input power as follows:

\[
\eta = \frac{Q_{out}}{Q_{in}}
\]

In this study, thermal resistance (\(R_{th}\)) was used to compare the qualities of the TPCTs as follows:

\[
R_{th} = \frac{T_e - T_c}{Q_{out}}
\]

where \(T_e\) and \(T_c\) are the average temperature of the evaporator and condenser, respectively.

<table>
<thead>
<tr>
<th>Contact angle (Evap./Cond.)</th>
<th>Thermal efficiency uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat input (kW/m²)</td>
<td>10°/10°</td>
</tr>
<tr>
<td>21.2</td>
<td>6.38</td>
</tr>
<tr>
<td>28.6</td>
<td>5.97</td>
</tr>
<tr>
<td>32.5</td>
<td>5.42</td>
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<tr>
<td>36.8</td>
<td>4.20</td>
</tr>
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<td>41.3</td>
<td>-</td>
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The calculated thermal efficiency of the condensers and evaporators having different wettabilities shown in Fig. 4. The effect of the surface wettability of the evaporator sections on thermal efficiency was first investigated. A sample value of 10°/90° indicated a superhydrophilic (CA < 10°) evaporator section and a plain condenser section (CA = 90°). Initially, the study focused on changing the surface wettability of the evaporator sections. Sample values of 10°/90° and 90°/90° indicated a difference in the surface wettability of the evaporator sections. The thermal efficiency of sample 10°/90° was lower than that of sample 90°/90° when power input was low (< 25 kW/m²). By contrast, when power input was high (> 25 kW/m²), the thermal efficiency of sample 10°/90° was higher than that of sample 90°/90°. The thermal efficiency of sample 10°/90° increased by approximately 12% at 33 kW/m² of power input. The increase in thermal efficiency was greater when the evaporator section contained superhydrophilic nanoparticles on its surface. It increased nucleate boiling at a high power input. The SEM images (Fig. 3) display the structure of the nanosilica particles and reveal that these particles not only increased wetting but also created additional nucleation sites on the surface of the evaporator section. Similarly, a comparison of sample 10°/160° and sample 90°/160° showed that sample 10°/160° reached a higher thermal efficiency than sample 90°/160°. These results indicated that in the high-power heat-removal mode, a higher thermal efficiency of TPCT was achieved when the evaporator section had a wetting surface. Similarly, the results of the boiling heat transfer test indicated that critical heat-flux values increased with a decrease in the CA of the surface (Hsu and Chen 2012; Hsu et al. 2012). This study also investigated the changes in surface wettability because of the presence of superhydrophilic, hydrophobic, and superhydrophobic nanoparticles on condensation sections. The effect of surface wettability of the condenser section on thermal efficiency was studied in samples 10°/160°, 10°/10°, and 10°/90°. The lowest thermal performance was obtained when superhydrophilic condenser and evaporator sections were used (sample 10°/10°); this result was explained by the hydrophilic surface in the condenser causing a filmwise condensation. Usually, the heat transfer coefficient in dropwise condensation is 5–8 times higher than that in filmwise condensation. An increase in the wetness of the surface of the condenser leads to a decrease in the condensation heat transfer in the TCPT (Solomon et al. 2012). Filmwise condensation occurs on wetted materials, while dropwise condensation occurs on un-wetted materials. Therefore, the effects of non-wetting surfaces on the condensation heat transfer are significant. A superhydrophobic surface with a two-tier texture was explored to promote dropwise condensation (Chen et al., 2007), since dropwise condensation enhances heat transfer more
effectively than filmwise condensation does (Chen et al., 2007; Varanasi et al., 2009). When using a low-power input, the TPCT incorporated a superhydrophilic evaporator section and a superhydrophobic condenser section (sample 10°/160°) to achieve high thermal efficiency. However, when using a high-power input, the combination of a superhydrophilic evaporator section and a plain condenser section (sample 10°/90°) was incorporated to achieve high thermal efficiency. These results illustrated that a superhydrophobic surface does not enhance the condensation heat transfer at a high power input. Cheng et al. (2012) studied condensation heat transfer on two-tier superhydrophobic surfaces. Both dropwise condensation and filmwise condensation have been observed in the vapor chamber by using ESEM. Because of dropwise condensation, the condensation heat transfer coefficient of the superhydrophobic surface is lower than that of a flat hydrophobic surface, especially under high heat-flux situations.

![Fig. 4. Thermal efficiency which is plotted against the input power with different contact angle in the evaporator and condenser sections.](image)

In Fig. 4, thermal efficiency increased as heat input increased. By contrast, thermal resistance decreased as heat input increased (Fig. 5). In the cases of sample 10°/90° and 10°/160°, when a (super) hydrophobic (CA = 90° and 160°) condenser section and superhydrophilic (CA = 10°) evaporator section were used, the thermal resistance was lower than that of the conventional TPCT (sample 90°/90°). Samples 10°/90° and 10°/160° exhibited a thermal resistance up to 20% lower than that of samples 90°/90° and 90°/160°. This suggests that a superhydrophilic surface can increase the heat-transfer capacity of the evaporator by decreasing its thermal resistance. However, there are some rules in (super) hydrophobic surface can decrease thermal resistance. The results of this study showed that if the condensation surface is superhydrophilic, thermal resistance increases in comparison to the plain sample 90°/90°. This can be explained by the filmwise condensation that occurs because of the presence of superhydrophobic particles, which are detrimental for heat transfer. Thus, surface wettability of the condenser and evaporator sections substantially influenced heat transfer in TPCTs.
Fig. 5. Thermal resistance which is plotted against the input power with different contact angle in the evaporator and condenser sections.

4. Conclusion

The thermal performance of TPCTs with various surface wettabilities in both the evaporator and condenser sections was investigated. A low thermal performance was obtained when both the condenser and evaporator sections were superhydrophilic. By contrast, a high thermal performance was obtained when the copper surface of the evaporator section was coated with nano silica particles to achieve a superhydrophilic effect, which enhanced heat transfer during evaporation. Moreover, the condenser section maintained at hydrophobic and superhydrophobic to attain the dropwise condensation. By combining these two modified surfaces, thermal efficiency increased by 2.53% in the heat input from 21 KW/m² to 41 KW/m². Furthermore, using these modified surfaces decreased the thermal resistance of the TPCT by 26.1%, compared with that by using pure copper.

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References


