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Experimental Study on Super Hydrophobic Surface Modification of Multiple Horizontal Copper Tubes

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1. Introduction

Condensed heat transfer is a crucial phenomenon in the design and operation of nuclear power plants. It refers to the process of heat transfer from a vapor phase to a condensed phase, typically involving the condensation of steam or other vapors on heat transfer surfaces. In nuclear power plants, this process is particularly important for the removal of residual heat from the reactor core. Condensation is classified into two types based on droplet contact angle: film condensation and dropwise condensation [1]. To prevent dropwise condensation from turning into film condensation, it is necessary to create a micro/nano structure that allows droplets to fall off the surface easily [2-3]. Using a Self-Assembled Monolayers (SAM) coating, droplets easily fall along the surface and recondense on the same spot, increasing the heat transfer coefficient. The micro/nanostructure of the surface can be artificially fabricated using recently developed manufacturing/ design technology to control surface energy. A new experimental facility has been designed that can easily observe droplet dynamic in multiple tube condensation situations and calculate the condensation heat transfer coefficients of each tube to analyze heat transfer performance. In this research, we compare the condensation performance of super hydrophobic copper tubes with nano-sized surface structures and bare copper tubes in multiple horizontal tubes using humid air and observe droplet dynamics.

Nomenclature

A	area [m^2]
h	heat transfer coefficient [W/m^2·K]
k	thermal conductivity [W/m·K]
L	length [m]
Q	heat transfer rate [W]
T	temperature [℃]
$\bar{T}$	average temperature [℃]
U	overall heat transfer coefficient [W/m^2·K]
x	distance between T1 and T3 [m]
R	radius [m]
t	thickness of tube[m]

Subscripts

bulk	bulk
c	center
i	inner
o	outer
sec	cross-section of area
surf	surface
total	total
tube	curved area of tube

2. Experiment

2.1 Surface Modification and Characterization

To enhance the condensation heat transfer coefficient, it is necessary to obtain the hydrophobic properties by reducing the surface wettability of bare tubes. Surface wettability can be evaluated by the contact angle of water droplets, and super hydrophobicity refers to surfaces with a contact angle of greater than 150 degrees [4]. We fabricated super hydrophobic copper tubes based on SAM method. As shown in Figure 1, the contact angle was measured with a contact angle analyzer to confirm the successful creation of a superhydrophobic surface, with a contact angle of approximately 159 degrees, which is greater than 150 degrees.

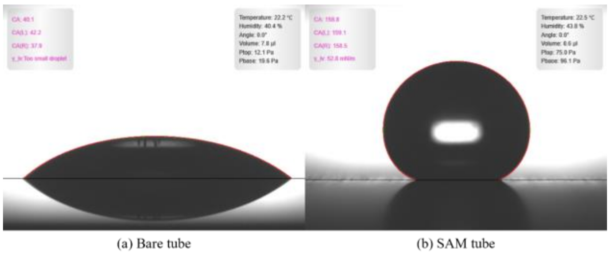

Fig. 1. Superhydrophobic surface modification result:

2.2 Experimental Facility

The experimental facility for the multiple horizontal tube condensation experiment is shown in Figure 2. The design goal was to create a facility that takes up minimal space and allows for easy observation of droplet dynamics during condensation. To set the temperature of the tubes, a TEC(Thermal Electric Cooler) cooling device was used. The model is TEC1-12712, with a maximum operating current of 12A and dimensions of 40mm x 40mm x 3.6mm. Each tube used in the experiment is made of copper with an outer diameter of 25.4mm, thickness of 1mm, and length of 150mm. The TEC allowed for downsizing of the experimental setup as it has the advantage of being easier to control and smaller in size compared to the previously used cooling jacket. The inside of each tube is insulated with glass wool and five tubes are arranged vertically with a distance between each tube set to 31.25mm, which is 1.25 times the diameter of the tube.

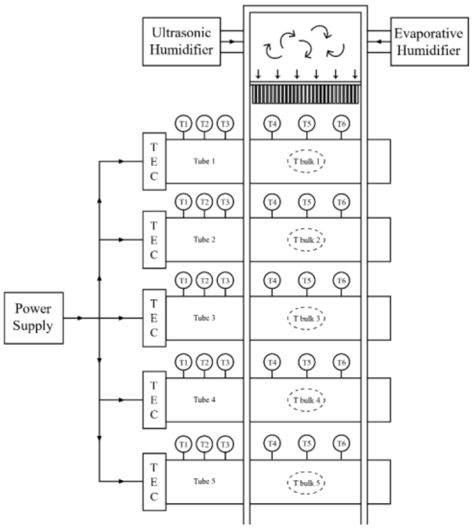

Fig. 2. Schematic diagram of experimental facility

2.3 Data Reduction

The heat transfer coefficient and heat transfer rate were calculated using the conduction and convection heat transfer equations. The equations (1) and (2) about conduction heat transfer are as follows:

$$Q_o = k \cdot \frac{T_3 - T_1}{\Delta L} \cdot A_{sec} \quad (1)$$

$$A_{sec} = \pi(R_o^2 - R_i^2) \quad (2)$$

Using equation (3), the induced heat transfer rate can be equated to the heat conduction problem at the surface of the inner tube inside the chamber.

$$Q_{total} = \frac{2\pi Lk(\bar{T}_c - \bar{T}_{surf})}{ln(R_o/R_i)} \quad (3)$$

$$\bar{T}_{surf} = \bar{T}_c - Q_{total} * \frac{ln(R_o/R_i)}{2\pi Lk} \quad (4)$$

According to energy balance, the following equation (5) is valid.

$$Q_{total} = Q_o = Q_i \quad (5)$$

This enables us to determine the average surface temperature, and by calculating the average surface temperature of the inner tube within the chamber, we can obtain the condensation heat transfer coefficient using equations (1), (4) and (5). The equations (6) and (7) about convection heat transfer are as follows:

$$Q_i = h \cdot (\bar{T}_c - \bar{T}_{surf}) \cdot A_{tube} \quad (6)$$

$$A_{tube} = 2\pi R_o L_{chamber} \quad (7)$$

The convective heat transfer coefficient can be obtained through Equation (6).

3. Results and discussion

3.1 Heat transfer results

Figure 3 shows the heat transfer rates, where the heat transfer rate of the SAM tube is higher than that of the bare tube in all tubes. Additionally, it can be observed that the heat transfer rate decreases from the top tube to the bottom tube. The heat transfer rate has effectively improved in the SAM tube compared to the bare tube. In Tube 1, the heat transfer rate of the SAM tube increased the most by about 66[%] compared to the bare tube, and in Tube 2, the heat transfer rate of the SAM tube increased by about 26[%]. In addition, it increased by about 22[%] in tube 3 and about 25[%] in Tube 4. This confirms that heat transfer performance improvement through the SAM tube has been achieved in all tubes.

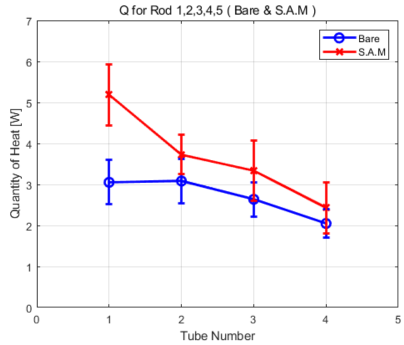

Figure 3. Bare, SAM tube heat transfer rate comparison

To provide a more intuitive comparison of the heat transfer coefficients shown in Figure 4, the experiments were repeated and the average heat transfer coefficients were plotted as two curves. It can be observed that the heat transfer coefficient of the SAM coated tube is always higher than that of the bare tube in all cases, indicating that the SAM coating is effective in multiple tube systems.

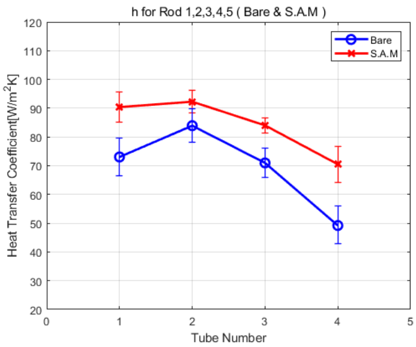

Figure 4. Bare, SAM tube heat transfer coefficient comparison

3.2 Droplet dynamics

Figure 5 shows a moment when a detached droplet from tube 1 of the bare tube influences the droplet on tube 2 under normal operating conditions. As shown in Figure 5(a), when the droplet falls from the top tube, two thin water streams are formed on the surface of the tube. In Figure 5(b), since a thin film has already formed on the intermediate tube, the droplet spreads smoothly, resembling a saddle shape. In Figure 5(c), as the saddle shaped droplet flows down due to gravity, it merges with the water stream formed earlier, increasing the thickness of the water stream. It can be observed that the size of the droplets collected at the bottom of the tube also increases due to the influence of the droplet flowing on top of the intermediate tube. During condensation, the droplets spread widely and the water stream continue to remain.

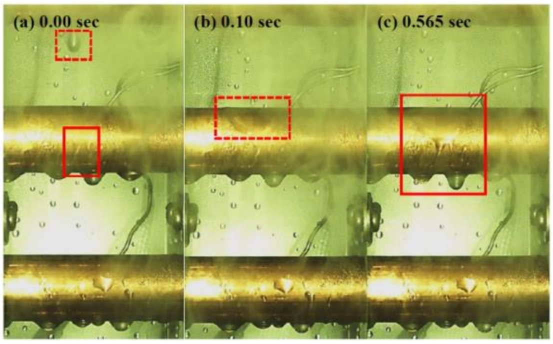

Figure 5. Droplet dynamic of flowing previous water path shown with bare copper tubes (tube 1 to tube 3)

Figure 6 is a picture capturing the moment when a detached droplet from tube 2 of the SAM tube affects the droplet in tube 3 under normal conditions. Unlike the bare tube described earlier, the droplets in the SAM tube show a different dynamic. In Figure 6(a)(i), we observe a droplet trying to fall from the upper tube. This droplet is smaller than the droplet in the bare tube, and it leaves a thin and distinct water stream. Figure 6(b)(ii) shows a droplet that leaves no water stream and only leaves a slight trace. Figure 6(b)(iii) shows the moment when the detached droplet merges with the pre-existing droplet. Such droplet dynamic is observed in all five SAM tubes, so it is expected that droplet condensation will continue under normal conditions.

Figure 6(c)(iv) shows the formation of a droplet as small droplets are absorbed during the merging of droplets flowing down the tube. When the droplet reaches the bottom of the tube, small water droplets remain as traces of the passing droplet, as seen in Figure 6(d)(vi). Unlike in bare tubes, where the thickness of the remaining water film increases after droplets flow down the tube and leave, the SAM coated tubes show a slight residue of droplets due to surface renewal.

Figure 6(c)(v) and Figure 6(d)(vii) show that as the droplets fall and sweep along the wider surface of the tube, surface renewal occurs, leading to improved heat transfer efficiency in the tube.

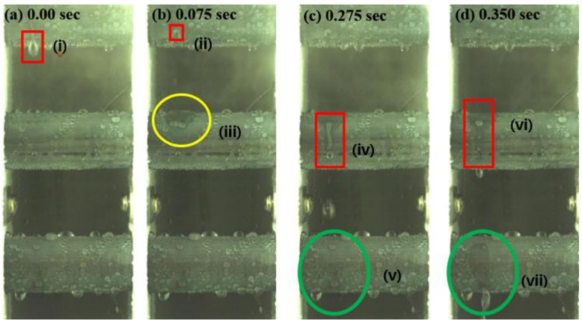

Figure 6. Droplet dynamics shown with super-hydrophobic copper tubes (tube 2 to tube 4)

5. Conclusion

The condensation heat transfer performance was measured for each of the five copper tubes, and droplet dynamics and evolutions of the condensate droplet were observed for optical analysis using a TEC as a cooling device. The heat transfer rate was found to be improved by 22% to 66% on the SAM tube compared to the bare tube. Furthermore, the heat transfer coefficient was observed to be higher on the SAM tube than the bare tube for all sections, with an improvement of 9.5% to 44.9%. As a result, it was discovered that dropwise condensation, leading to frequent droplet sweeping, was successfully implemented on super hydrophobic coated copper tubes, and the condensation heat transfer rate and coefficient was enhanced for all tubes. Although this research mainly deals with normal atmospheric conditions with humid air, the observation of the expected condensation process with the superhydrophobic surface is highly efficient and cost-effective with great potential for real-world condensation applications on nuclear power plant.

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