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

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Introduction

Research Background

- Condensed heat transfer is a crucial phenomenon in the design and operation of nuclear power plants. In nuclear power plants, this process is particularly important for the removal of residual heat from the reactor core.
- 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.
- Using a **Self-Assembled Monolayers (SAM)** coating, droplets easily fall along the surface and recondense on the same spot, increasing the heat transfer coefficient.
- To improve nuclear power plants efficiency, condensation performance should be improved. Therefore, research was conducted to improve the condensation performance.

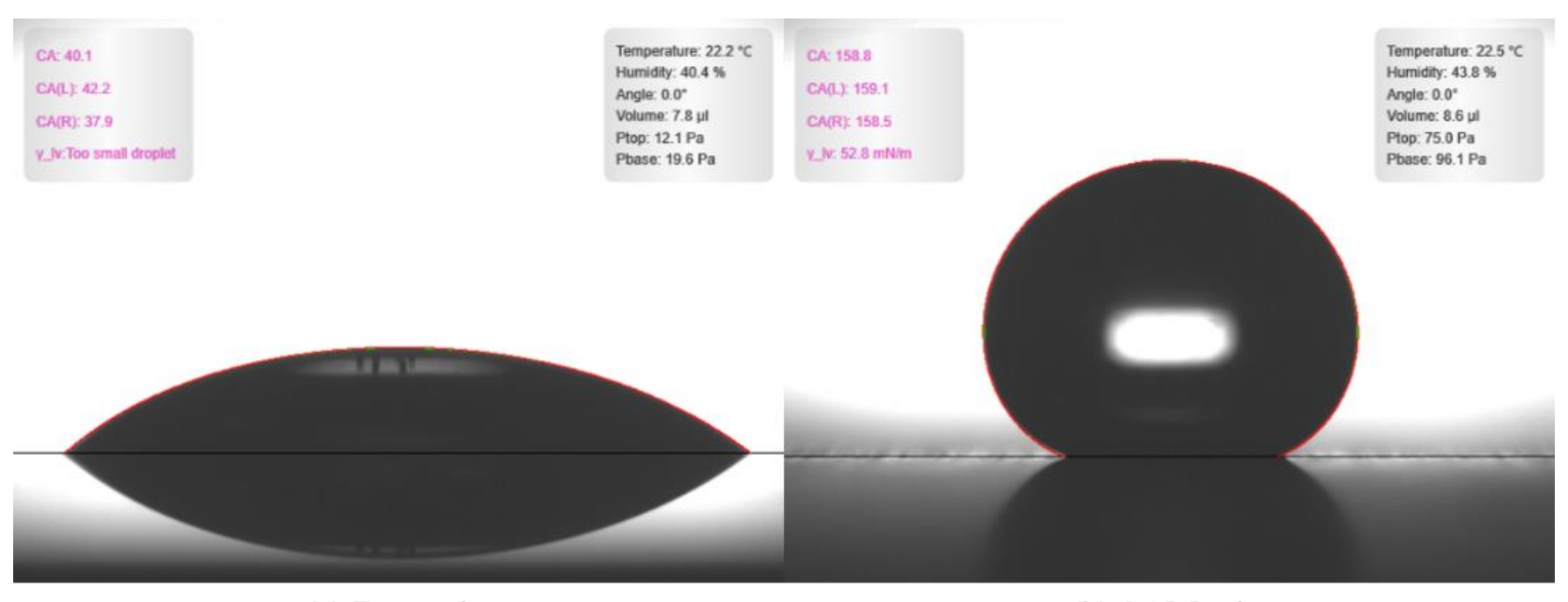
Purpose of Study

- Comparing 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.

Experiment Method

Surface Modification and Characterization

- Fabricating on super hydrophobic copper tubes based on SAM method.
- As shown in Fig. 1, the contact angle was measured with a contact angle analyzer to confirm the successful creation of a superhydrophobic surface



(a) Bare tube (b) SAM tube

Fig. 1. Superhydrophobic surface modification result

Experimental Facility

- The experimental facility for the multiple horizontal tube condensation experiment is shown in Fig. 2 and experimental facility setup parameters are shown in Table 1.

Table 1. Experimental facility setup parameter

Copper tube outer diameter	25.4 [mm]
Copper tube thickness	1 [mm]
Copper tube length	150 [mm]
Distance between each tube	31.25 [mm]

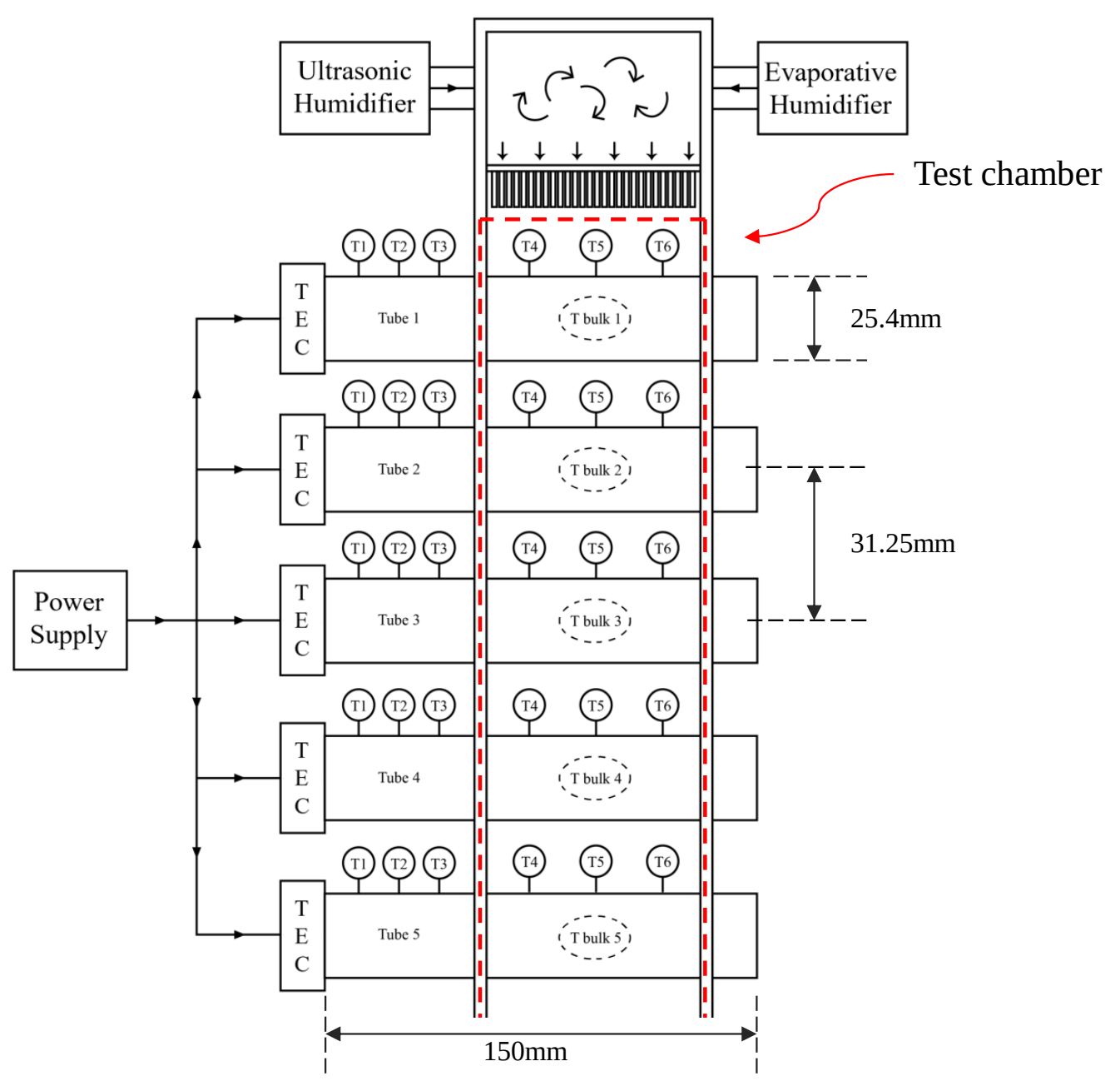


Fig. 2. Schematic diagram of experimental facility

Data Reduction

- The heat transfer coefficient and heat transfer rate were calculated using the conduction and convection heat transfer equations.
- The induced heat transfer rate can be equated to the heat conduction problem at the surface of the inner tube inside the chamber.
- By calculating the average surface temperature of the inner tube within the chamber, we can obtain the condensation heat transfer coefficient

Table 2. Used equation for data reduction

Conduction heat transfer	$Q_o = k \cdot \frac{T_3 - T_1}{\Delta L} \cdot A_{sec}$
Convection heat transfer	$Q_i = h \cdot (\overline{T}_C - \overline{T}_{surf})$
Conduction heat transfer at the surface of the inner tube	$Q_{total} = \frac{2\pi Lk(\overline{T}_C - \overline{T}_{surf})}{\ln(R_o/R_i)}$
Energy balance	$Q_{total} = Q_o = Q_i$

Results and discussion

Heat Transfer Results

- Fig. 3 and Table 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.

Table 3. Ratio of improved heat transfer rate

Tube number	Ratio of improved heat transfer rate
1	66%
2	26%
3	22%
4	25%

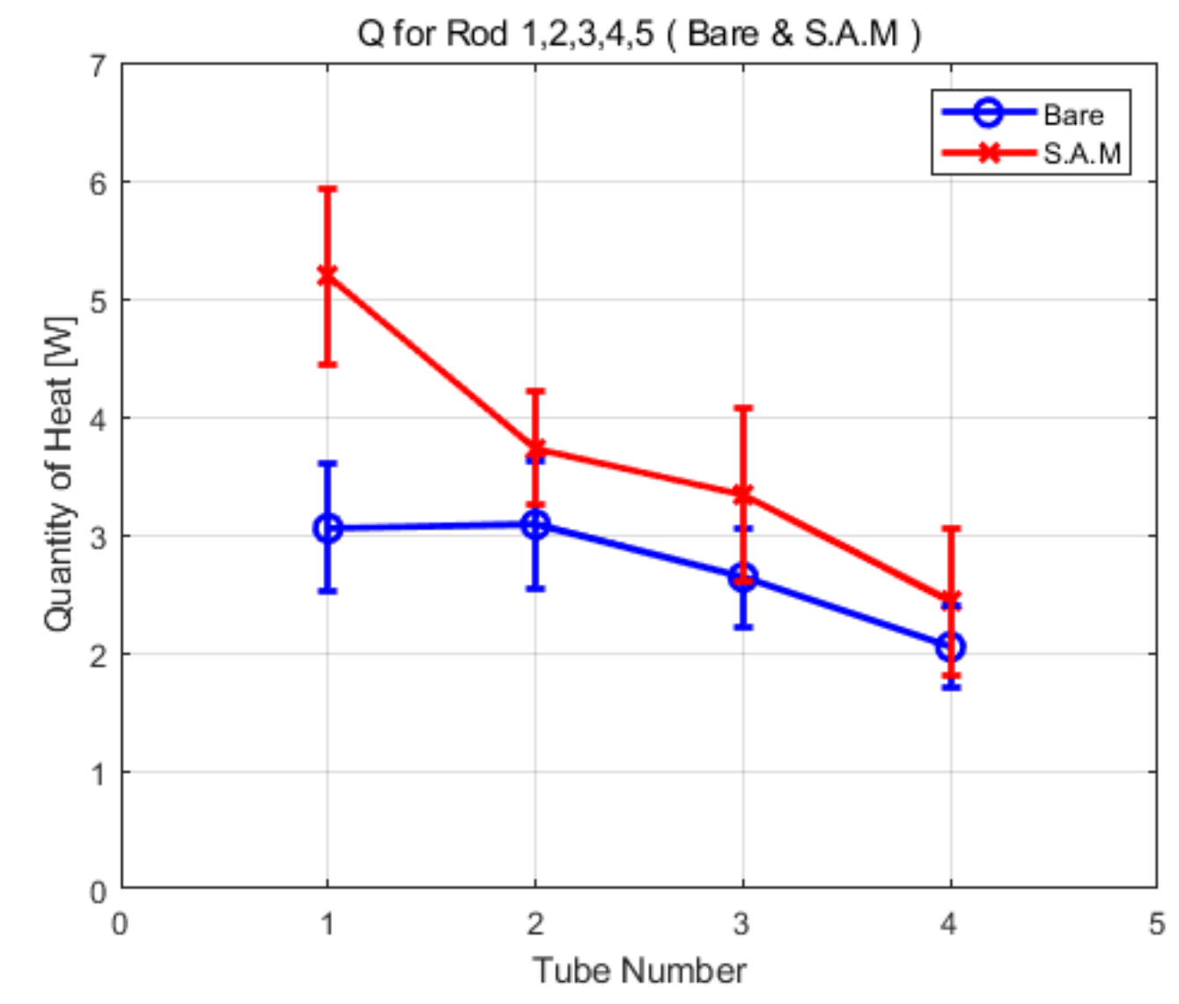


Fig. 3. Bare, SAM tube heat transfer rate comparison

- To provide a more intuitive comparison of the heat transfer coefficients shown in Fig. 4 and Table 4.

Table 4. Ratio of improved heat transfer coefficient

Max/Min	Ratio of improved heat transfer coefficient
Minimum	9.5%
Maximum	44.9%

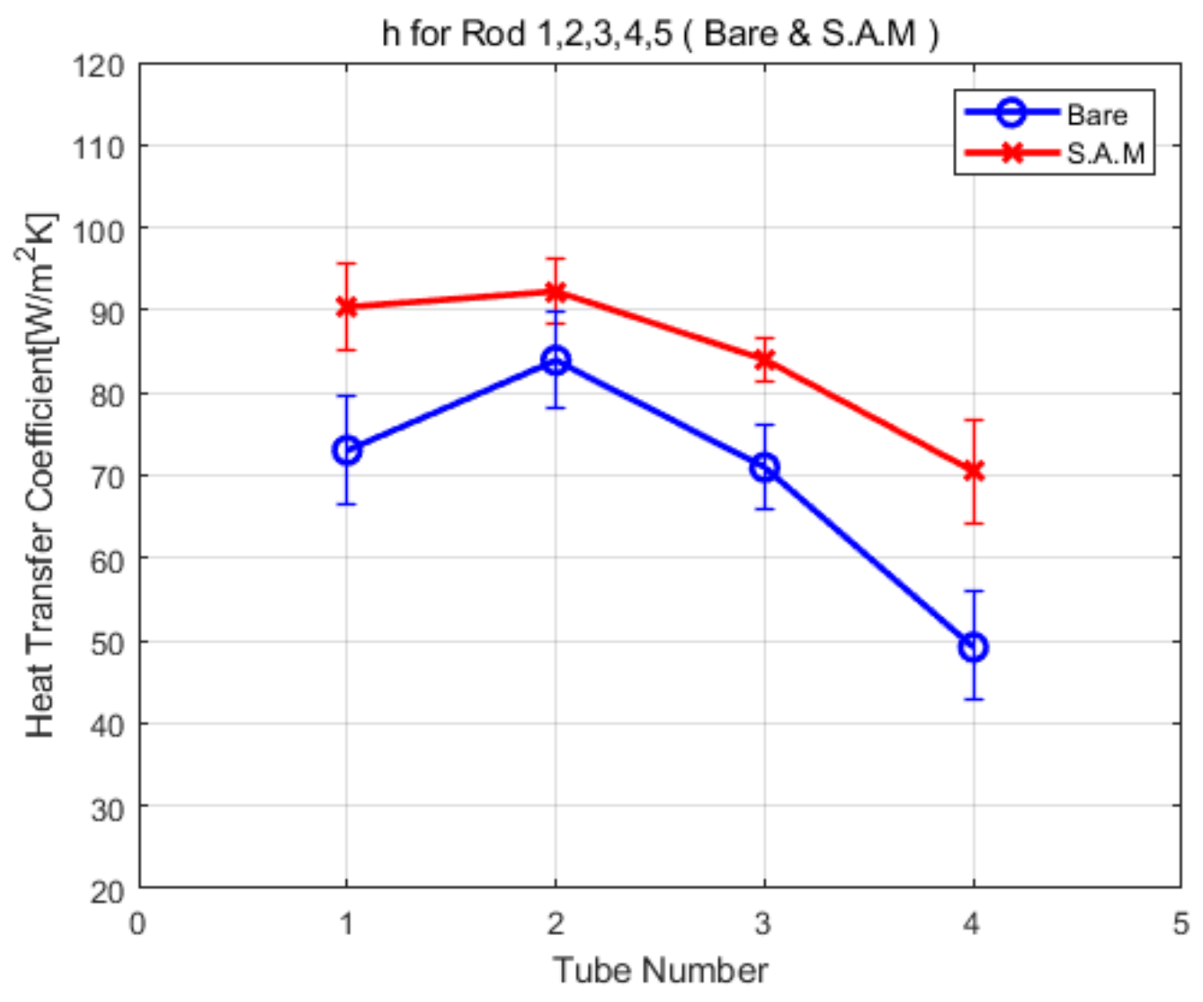


Fig. 4. Bare, SAM tube heat transfer coefficient comparison

Droplet Dynamics

- Fig. 5 shows a moment when a detached droplet from tube 1 of the bare tube influences the droplet on tube 2

Water streams are formed on the surface of the tube

The droplets spread smoothly, resembling a bell shape

Increasing the thickness of the water streams

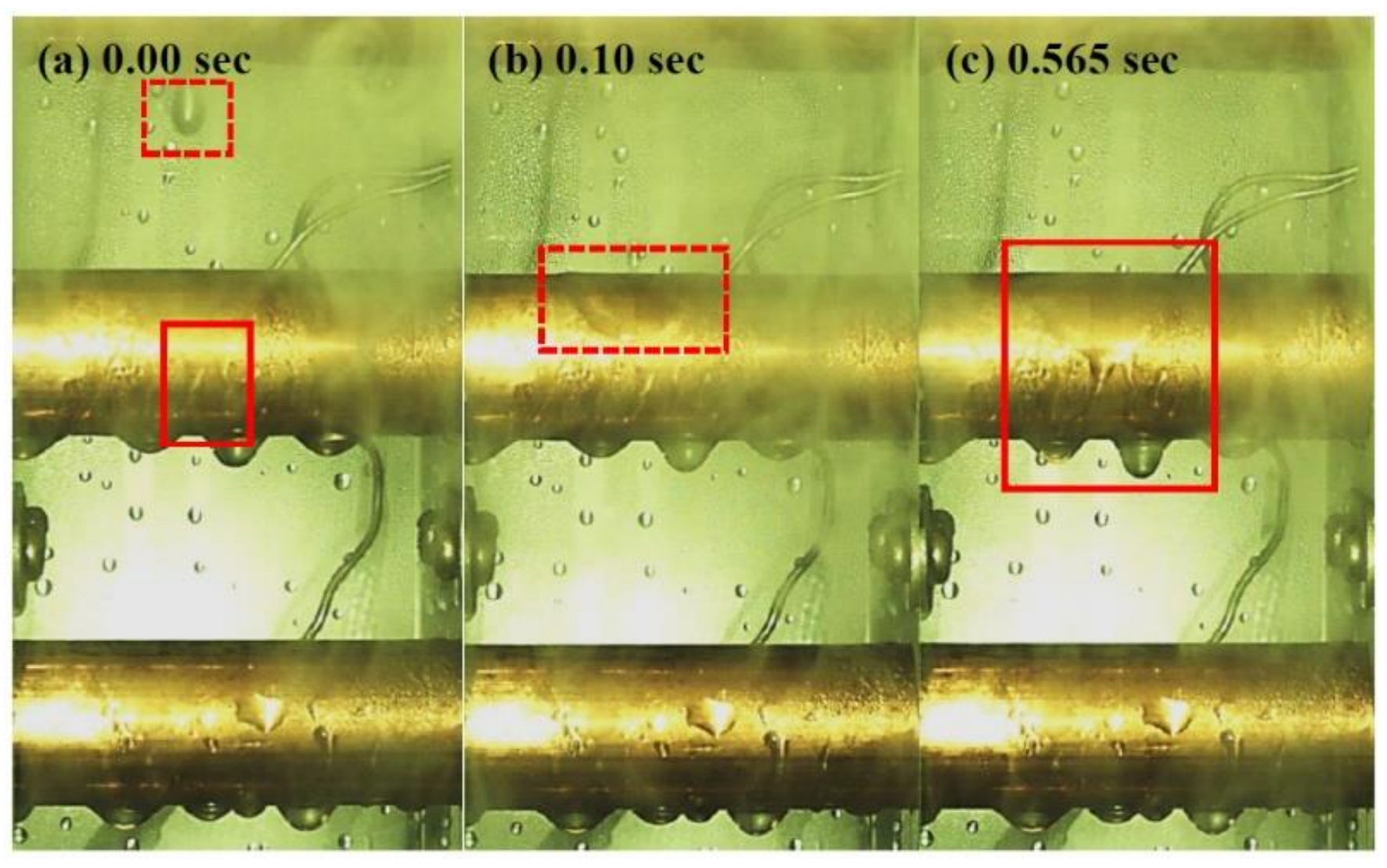


Fig. 5. Droplet dynamic of flowing previous water path shown with bare copper tubes (tube 1 to tube 3)

- Fig. 6 is a picture capturing the moment when a detached droplet from tube 2 of the SAM tube affects the droplet in tube 3.

Droplets only leave a slight water streams

Slight residue of droplets due to surface renewal.

Reducing the thickness of the water streams

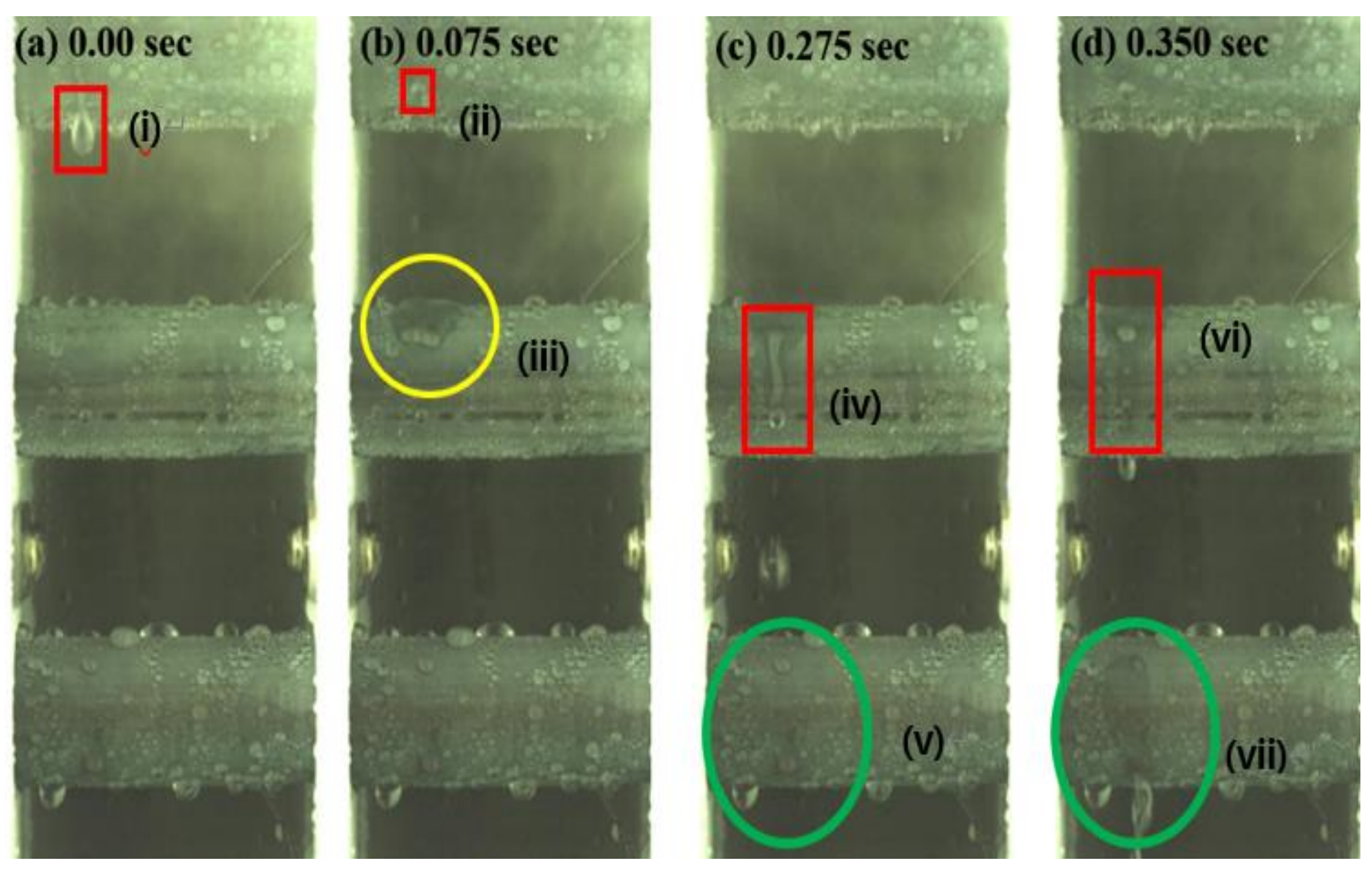


Fig. 6. Droplet dynamics shown with super-hydrophobic copper tubes (tube 2 to tube 4)

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.
- 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, 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.