

Experimental study of droplet characteristics in dropwise condensation along the axial length of a long vertical tube

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1. Introduction

The dropwise condensation has been a considerable interest to many researchers due to higher heat transfer performance than filmwise condensation. Several studies have investigated the heat transfer mechanism of dropwise condensation [1-3] and droplet growth behavior on the micro/nano modified surface [4-6]. These studies observed the detailed mechanism by using experimental facilities adopting mostly horizontal tubes or short vertical plates. However, many industrial facilities adopting condensation heat transfer such as passive containment cooling system (PCCS) and emergency core-makeup tank (ECT) applicable for the nuclear power plant systems employ long vertical tubes [7]. In the long vertical tube, the condensate flows down along the surface and it sweeps out other residual droplets. Thus, it may cause unique condensation characteristics between upside and downside of the vertical surface. Surprisingly, however, no studies so far identified the characteristic transition of droplet behavior with distance from the beginning of condensation in a vertical tube. Therefore, the goal of this study is to observe condensate droplet on the upside and downside of the vertical tube.

2. Experimental method

2.1. Test loop and test conditions

A schematic of the condensation heat transfer experimental system is illustrated in Fig. 1. The test section consists of a single vertical tube made of stainless-steel grade 316, whose length and diameter are 1,180 mm and 19.05 mm, respectively. Inside the vertical tube, the coolant flowed upward, and the saturated steam is condensed on the outside vertical tube. The upper and lower sides were set to 15 cm apart from the top and bottom of vertical tube. The saturated steam supplied from a steam generator to the test section after passing through a steam/water separator. When the steam is condensed, the condensed water is flowed into a heat exchanger and recirculated to the steam generator. As a coolant, de-ionized water was used at atmospheric pressure. The coolant temperature and flow rate were controlled by proportional-integral-derivative (PID) control and coolant pump, respectively. In this study, the pure saturated steam under atmospheric pressure was supplied to the test section. The wall subcooling which is calculated by log mean temperature difference method was 10 K.

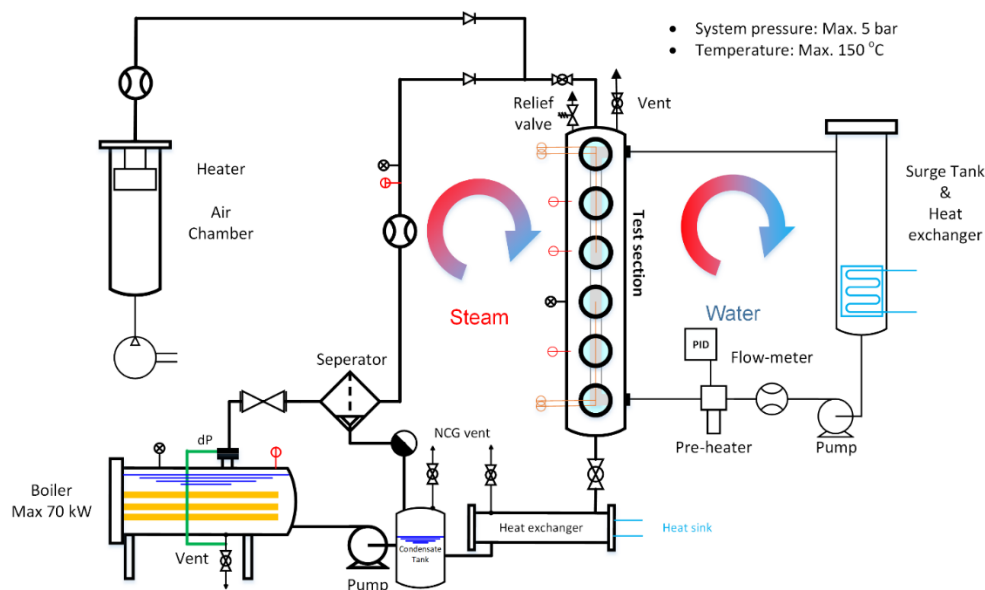


Fig. 1. A schematic of condensation heat transfers experimental system

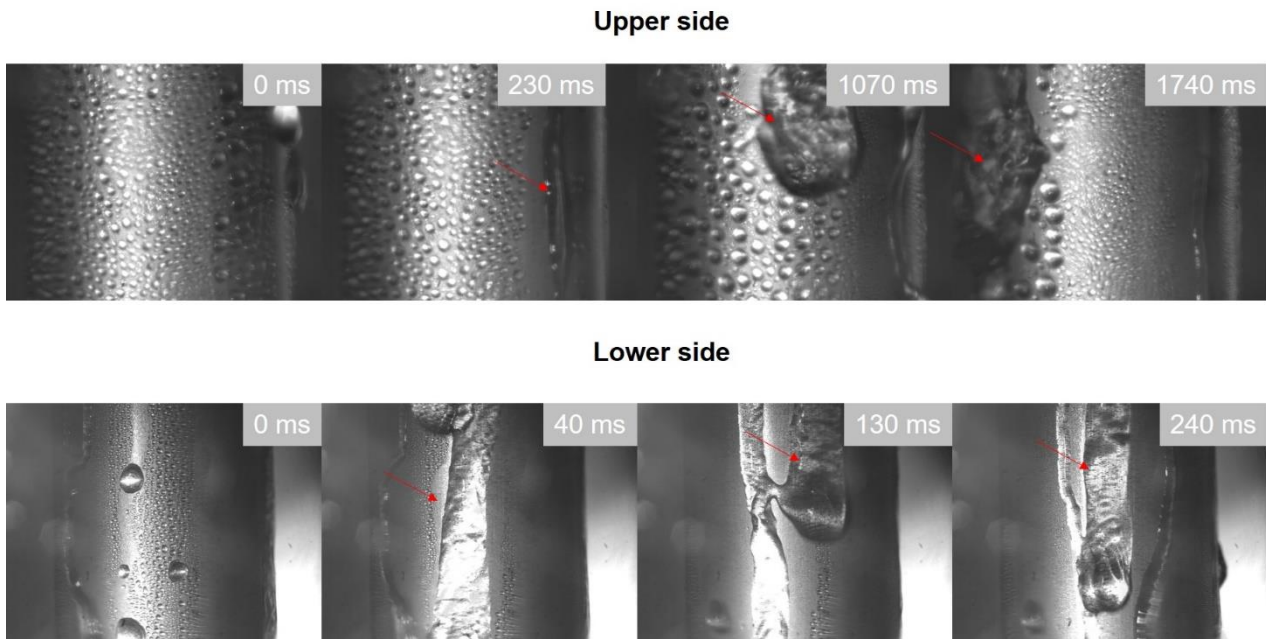


Fig. 3. Visualization of the dropwise condensation characteristic on upper and lower side surface (subcooling is 10 K)

2.2. Droplet visualization

To compare the condensate droplet between upside and downside of the test section, visualization of dropwise condensation phenomenon was conducted by using a high-speed video system (Phantom V7.3 high speed camera). Fig. 2 shows the measurement of droplet diameter using Phantom Camera Control (PCC) software.

As far as the condensate region, it was measured by ImageJ program, which is a graphical software facilitating the quantitative analysis through the pixel form. Once a liquid film region is selected, the number of pixels in the region can be calculated automatically. Finally, the average droplet diameter and the condensate film region ratio were measured.

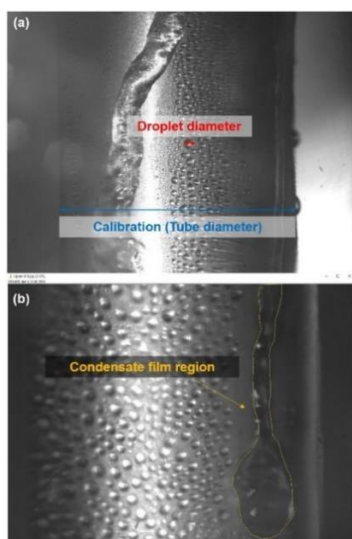


Fig. 2. Droplet measurement image by using a PCC software

3. Results and Discussion

3.1. Droplet characteristics along the axial length

Under subcooling condition, the vapor atoms form clusters on the surface, and droplet nucleation occurs [8]. If the droplet diameter exceeds a critical size, with which the gravitational force is larger than the capillary force on contact area, the droplet flows down along the vertical surface [3]. If the surface is long enough, the generated droplet in the upper side sweeps out other residual droplets in the lower side. After sweeping out other droplets, it may cause new nucleation on the lower side surface. High sweeping frequency on the lower side due to the condensate generated in the upper side disturbs the droplet growth, so the lower side includes the smaller droplet size than the upper side.

Fig. 3 shows the visualization images of the condensation droplets on the upper and lower sides. The upper side includes the larger average droplet size than in the lower side because the droplets can grow up to the critical size and flow down along the surface. Moreover, the droplet departure frequency in the upper side becomes low because the droplet growth time is longer than in the lower side. On the other hand, the droplet in the lower side was swept by condensate escaped from the upper side, so the growth of the droplet is limited and may not reach to the critical size. Therefore, the average droplet size in the lower side was smaller than in the upper side. However, the condensate from the upper side forms the liquid film (colored in red in Fig. 4) on the lower side surface. Although it just passed away through surface, it still covered a large area on the surface because of a large amount of condensate and very frequent falling.

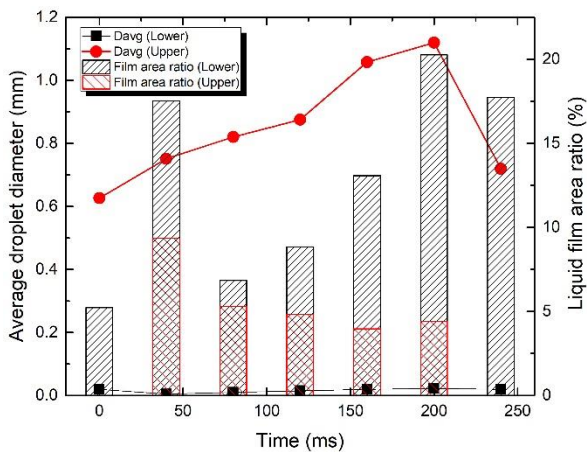


Fig. 4. The average droplet diameter and the condensate liquid film area ratio in the upper and lower sides

The average droplet diameter and the condensate liquid film area ratio (ratio between the tube area and liquid film area) were measured as shown in Fig. 4. The droplet behavior in dropwise condensation is irregular, so no specific tendency was observed for the average droplet diameter and the condensate liquid film area ratio. Nevertheless, the average droplet diameter in the upper side was higher than in the lower side because the condensate swept out the still growing droplet of in the lower side. On the other hand, the condensate liquid film area ratio in the lower side was larger than in the upper side as mentioned. These droplet characteristics can affect condensation heat transfer significantly.

3.2. Effect on heat transfer

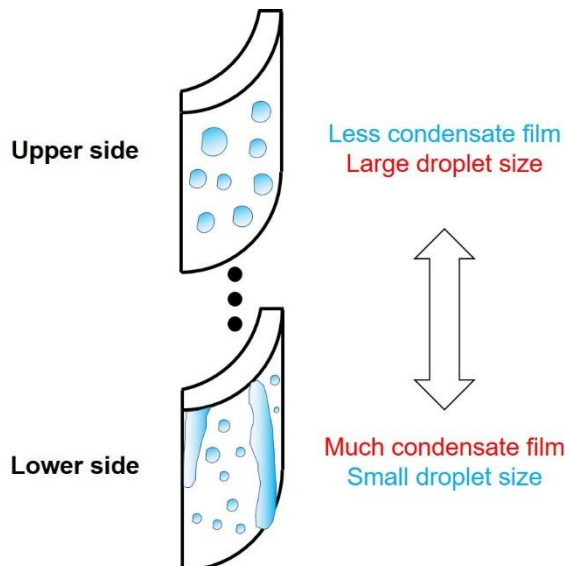


Fig. 5. Comparison of the effect on condensation heat transfer between the upper and lower sides of the vertical tube

In this situation, the lower side includes the smaller droplet size than in the upper side. In general, smaller droplet size enhances heat transfer performance because of low conduction resistance of droplet.

However, the condensate liquid film area is similar with filmwise condensation which has lower heat transfer performance than dropwise condensation. In short, higher nucleation frequency is encountered with condensate film in condensation heat transfer performance in the lower side. As shown in Fig. 5, the droplet behavior in the lower side has the positive (colored in sky blue) and negative (colored in red) effect on the condensation heat transfer. Meanwhile, the upper side also imposes the positive and negative effect on the condensation heat transfer. Therefore, to confirm the advantage of the dropwise condensation with quantitative measure, it is necessary to investigate the condensation heat transfer between the upper side and lower side in more detail. This is left for a future study.

4. Conclusion

In this work, the droplet characteristics in dropwise condensation on the vertical tube was investigated. The condensation heat transfer experiment was conducted, and the droplet parameter along the length was measured by high speed camera visualization. Major findings in this study and future work can be summarized as follows:

- In the vertical tubes, the condensate generated in the upper side was slid down and formed liquid film similar to filmwise condensation in the lower side.
- The droplet in the upper side could grow up to the critical size, but its growth was limited in the lower side due to the downward condensate film flow.
- The upper side includes less condensate film but the larger droplet size than in the lower side due to the condensate film.
- More detailed comparison of the condensation heat transfer performance between the upper and lower regions should be investigated to confirm the advantage of the dropwise condensation in the long vertical tube.

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