Research on droplets growth of Marangoni condensation during the time-series process

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Abstract. In this paper, the condensate droplets growth of Marangoni condensation during the time-series process was experimentally studied. The photographs taken in the experiments were handled by image processing method. The droplets coverage ratio was introduced to analyse the growth process. As the time-series process went on, the condensate droplets coverage ratio increased fast at first, and then increased slowly until reaching a stable state. The droplets coverage ratio increased with the increase in the vapor-to-surface temperature difference and decreased with the increase in the ethanol vapor concentration.

1. Introduction
Marangoni condensation is caused by the surface tension instability on the condensate film surface of binary mixtures in a positive system, where the surface tension of the mixtures has a negative gradient with the mass fraction of the more volatile component, such as ethanol-water mixtures. The Marangoni force, induced by the surface tension gradient, pulled the condensate with lower surface tension towards the higher part along the liquid surface, which tore the condensate film and resulted in the dropwise mode. It is a new way to achieve dropwise condensation and could maintain for a long time, which depends merely on the physical proprieties of the mixtures.

The heat transfer coefficient of Marangoni condensation was found to vary non-monotonously with the increase in the vapor-to-surface temperature difference and the ethanol vapor concentration, increase with the increase in the vapor velocity and pressure [1, 2]. Several condensation modes were observed during the experiments and variations of droplet size distribution and maximum diameter were analysed [3].

Previous studies on the Marangoni condensation were mainly on the vertical surfaces, horizontal tubes and vertical tubes, where the gravity effect acted on the condensate with the same direction of the surface tension gradient. However, the essential reason for dropwise modes in the Marangoni condensation was the surface tension gradient. When the gravity effect operated with the same direction of the surface tension gradient, the condensation modes were diversified under the effects of both surface tension gradient and the gravity effect. Thus, the condensation modes under the interference of the gravity effect were unrepresentative. Moreover, the interference of the gravity effect could make the condensate droplets leave the condensing surface early and the growth of the droplets was not complete. When the condensing surface was horizontal, the gravity effect was perpendicular with the direction of the surface tension gradient on the condensate. Then the interference of the gravity effect could be neglected and the condensate droplets could grow freely.
Then present Marangoni condensation modes were caused merely by the surface tension gradient, which could be regarded as the essential ones. Experimental study was conducted on the horizontal surface for Marangoni condensation of ethanol-water mixtures and droplets growth was analysed during the time-series process in this paper.

2. Experimental system
The experimental system consists of four closed loops, which are named as the main vapor loop, the impinging cooling loop, the condenser loop and the auxiliary condenser loop, respectively. The details could be found in the work by Li et al. [4]. As the experiments were conducted horizontally, the condensate film couldn’t be removed automatically. For the continuity of the condensation process, a wiper was designed and employed to remove the condensate film on the condensing surface, as shown in Fig. 1. Moreover, two pieces of magnets were adopted to transmit the driving power from a micro-motor for keeping the excellent vacuum condition. The test copper with a condensing surface area of 25.0 mm × 40.0 mm was horizontally installed and fixed with epoxy plates to ensure the heat flux inside transferred vertically.

3. Image processing method
The image processing method was also one focal point in this study. As the number of condensate droplets formed on the condensing surface was huge, it was difficult to figure out the numbers and sizes of the condensate droplets manually. So the image processing program was written by MATLAB herein and the flow chart was shown in Fig. 2. The ring-shape lighting source was equipped for improving the accuracy of the image processing. The result of the image processing method was also shown in Fig. 2. The white parts in the photo were the identified droplets and their numbers and sizes were obtained by the program automatically.
4. Results and discussions

The time-series process expressed the subsequent process after the wiper just brushed over the center of the condensing surface and the condensation process developed freely. The wiper didn’t work during this process. Figure 3 showed the visual figures during one time-series process. As the time-series process went on, huge number of small droplets appeared at the beginning and grew up fast mainly by direct condensation. As the time-series process went on, the droplets grew slowly mainly by coalescence.

As the primary heat transfer resistances came from the thermal resistances from the condensate droplets and the vapor diffusion layer, which were closely related to condensate droplets coverage ratio and ethanol vapor concentration, respectively. So the condensate droplets coverage ratio was introduced to evaluate the growth of the droplets, which expressed the areas ratio between all the droplets and the condensing surface. The definition equation of condensate droplets coverage ratio was shown in Eq. (1).

\[
C(t) = \frac{\sum_{i} A_i(t)}{A_s}
\]  

(1)

Where \( C(t) \) expressed the condensate droplets coverage ratio during the time-series process, \( A_i(t) \) expressed the occupied area on the condensing surface of one condensate droplet and \( A_s \) expressed the whole area of the condensing surface.

Figure 4 showed the variation of condensate droplets coverage ratio during the time-series process corresponding to the photos in Fig. 3. As the time-series process went on, the condensate droplets coverage ratio increased fast at first, and then increased slowly until reaching a stable state, with the growth of the condensate droplets.

Figure 4. Coverage ratio during the time-series process
Figure 5 showed the effects of vapor-to-surface temperature difference on the condensate droplets coverage ratio at the ethanol vapor concentrations of 2.0% and 5.0% respectively. The droplets coverage ratio increased obviously with the increase in the vapor-to-surface temperature difference, especially when the time-series reached the stable state. As the vapor-to-surface temperature was the dominant driving force for the Marangoni condensation, when the vapor-to-surface temperature difference increased, the condensate droplets grew up faster and the condensate droplets coverage ratio increased correspondingly.

![Figure 5. Effects of vapor-to-surface temperature difference](image)

Figure 6 showed the effects of ethanol vapor concentration on the condensate droplets coverage ratio at the impinging cooling water temperatures of 50 °C and 55 °C respectively. The condensate droplets coverage ratio decreased obviously with the increase in the ethanol vapor concentration. The effect of the ethanol vapor concentration mainly came from the thermal resistance in the vapor diffusion layer. As the ethanol vapor concentration increased, the thermal resistance from the vapor diffusion layer increased accordingly, which weakened the heat transfer process and slowed down the growth of the condensate droplets with the smaller droplets coverage ratio. The fluctuation in the data was mainly caused by the movement of condensate droplets.

![Figure 6. Effects of ethanol vapor concentration](image)

5. Conclusions
The condensate droplets growth process was experimentally studied on the horizontal surface during the Marangoni condensation for ethanol-water mixtures. The image processing program was written by MATLAB to identify the droplets in the photographs taken in the experiments. The condensate droplets coverage ratio, which expressed the areas ratio between all the condensate droplets and the condensing surface, was introduced to analyse the growth process. Results indicated that the condensate droplets coverage ratio increased fast at first, and then increased slowly until reaching a
stable state during the time-series process. And the condensate droplets coverage ratio increased with the increase in the vapor-to-surface temperature difference while decreased with the increase in the ethanol vapor concentration.

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