Effect of vapor flow direction on spontaneous movement of drops during condensation of water-ethanol vapor mixture

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ABSTRACT

As a widely utilized phenomenon, condensation heat transfer is deeply related to the efficiency of energy utilization in industry. In recent decades, the condensation of vapor mixture attracted extensive attention, since the possibility to achieve high performance of heat transfer. During the condensation of some binary vapor Marangoni condensation), a special phenomenon was discovered that the spontaneous movement of condensate drop occurred. It was observed that condensate drops moved from the low temperature region to the high temperature region on a heat transfer surface. Therefore, the surface tension gradient induced by the temperature gradient was considered as the driving force. However, another affecting factor on the spontaneous movement of condensate drops, the direction of vapor flow, was also discovered. In this study, the experimental study was performed, and the results showed that the condensate drops tended to move towards the inlet direction of vapor flow.

Keywords: Marangoni condensation, Spontaneous drop movement, Water–ethanol vapor mixture, Surface tension

Nonmenclature

Symbols	
T	temperature, °C
T_S	surface temperature, °C
C	mass fraction of ethanol in vapor
h	heat transfer coefficient, W/m^2·K
q	heat flux, W/m^2
ΔT	surface subcooling, °C
ΔT_A	averaged surface subcooling in uniform temperature region, °C
U	vapor velocity, m/s
v	velocity of condensate drop movement, mm/s
x	distance from the left side of the condensing surface, mm
σ	surface tension coefficient, mN/m

1. INTRODUCTION

Improving the energy efficiency is one of the important ways to solve the current problem of energy shortage. Condensation heat transfer, as an efficient heat transfer way, widely exists in industry. Marangoni condensation is a special kind of condensation heat transfer, which occurs in the condensation process of some binary vapor, and this condensation can obviously enhance the heat transfer. So, it has extremely high value of research. During the condensation process of some vapors, the surface of the condensate is slightly disturbed, which causes a difference in surface tension, and the condensate can form bead-like drops. This phenomenon occurs during the condensation process of the vapor mixture conforming to the so-called "positive system". In this system, the surface tension of the high-boiling components in the mixture is greater than the surface tension of the low-boiling components (for example, water-ethanol mixtures) [1,2]. According to the gas-liquid equilibrium relationship, temperature gradients in different regions will cause concentration gradients, and the concentration gradients will cause surface tension gradients, driving the flow of condensate from thinner areas to thicker areas [3]. With the surface tension, the condensed liquid film become thinner, which can significantly enhance heat transfer. Under the previous experimental research, the condensation heat transfer coefficient is up to 8 times stronger than the pure water vapor condensation [4].In addition, Utaka, et al. [5-9] used the water-ethanol mixture as the working fluid and found that condensed drops would spontaneously move from the area of the low temperature to the high temperature on the horizontal heat transfer surface with the temperature gradient, and they pointed out the average velocity of the drop movement increases with the surface tension gradient, regardless of the size of the drop diameter.

This study discovers the direction of vapor flow is a new affecting factor on the spontaneous movement of condensate drops. Experiment shows that on the horizontal heat transfer surface with uniform temperature, the condensate drops move spontaneously towards the inlet direction of vapor flow. The average velocity of the drop movement is related to the surface subcooling. It is pointed out that the direction of vapor flow and the temperature gradient of the heat transfer surface are the two main factors that affect the direction of drops movement.

2. EXPERIMENTAL SYSTEM AND METHOD

2.1 Experimental system and method

Fig. 1 shows the schematic diagram of the experimental system, including the vapor cycle and the cooling water system. In the vapor cycle, the binary vapor of water-ethanol mixture was generated by electrical heating and then directed into the condensing chamber, in which a portion of the vapors condensed on the heat transfer surface. The uncondensed vapor flowed out of the chamber and condensed completely in the auxiliary condenser. The condensate flowedback to the vapor generator after passing the deaerator. In addition, the pressure in the condensing chamber was kept at barometric pressure, by opening the deaerator to the atmosphere. Fig. 2 shows the chematic diagram of the condensing chamber. Two heat transfer blocks were arranged in the chamber. One is for the observation of the drop movement during condensation, and the other is for dew point measurement. During the experiments, the heat transfer block for condensation was cooled by the jet of cooling water. As shown in Fig. 2, the jet section was divided into two small rooms, and the jet intensity was adjustable separately in each of the rooms. Therefore, the surface temperature distribution of the heat transfer block can be controlled by changing the jet intensity in the two jet rooms. In addition, dew point of the binary vapor was measure by the heat transfer block for dew point measurement. The temperature of the block was adjusted by the attached heater and the temperature of the block was record as the dew point temperature when the condensate initially appeared on its surface. Moreover, during the process of the experiment, vapor can be set to different flow directions to verify the influence of the flow direction.

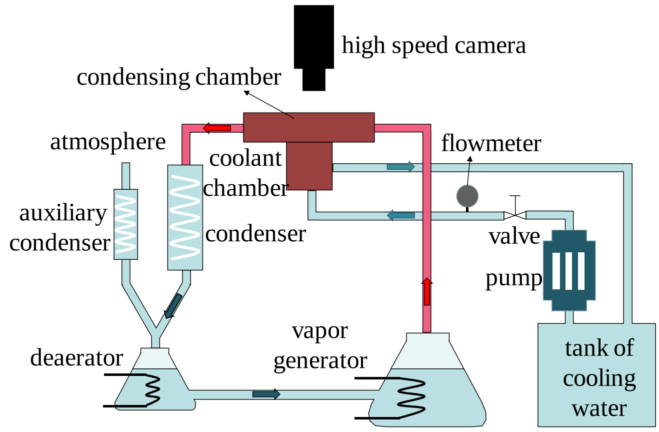

Fig. 1. Schematic diagram of the experimental apparatus

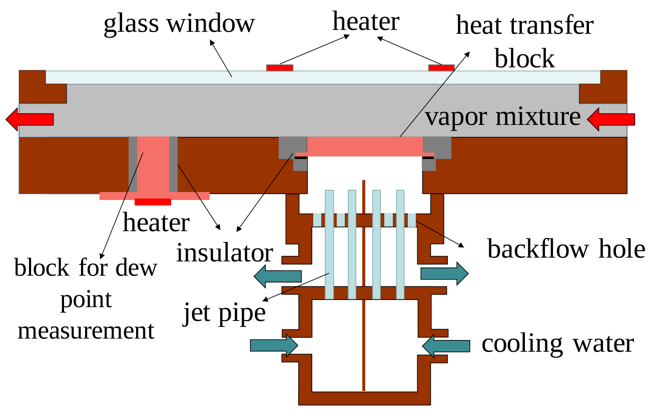

Fig. 2. Schematic diagram of condensing chamber

Fig. 3 shows the schematic diagram of the heat transfer block for the observation of the drop movement. It is a cuboid block that made of brass, its cross section and dimensions were shown in the figure. In the direction that vertical to the cross section, the size of the block is 20 mm. 9 sheathed K-type thermocouples with 0.5 mm diameter were inserted into different positions of the block (marked by the black dots in the Figure) to measure the temperature in the heat transfer block. The temperature distribution on the surface of the heat transfer block can be calculated based on the measure temperature

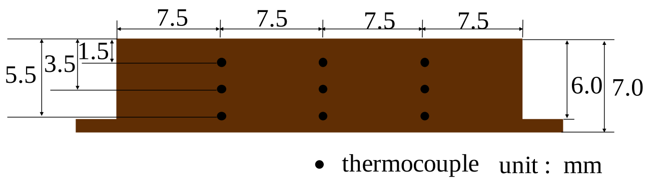

Fig. 3. Schematic diagram of heat transfer block

2.2 Data processing

The following describes the definition of direction (vapor flow direction, drop movement, and temperature gradient) and the method to calculate distribution of the heat transfer surface temperature and the velocity of condensation drop movement. First, the positive direction along the x-axis is defined as positive. So, the vapor flow direction is positive along the x-axis and the drop movement direction is positive along the x-axis. As shown in Fig. 3, temperature measurements were taken at three locations (x = 7.5, 15, 22.5 mm) along the direction of the heat transfer surface. In this experiment, when the temperature fluctuations of the three heat transfer surfaces were within the mean value ±0.3°C range, which is considered as the surface with the uniform temperature. In addition, the condensation drop movement process is recorded and saved in image format by a high-speed camera, and after image processing, the center position of the drop is extracted, and the movement distance of the center position in fixed time is calculated to obtain the velocity of the drop movement. The uncertainty of the thermocouple causes the uncertainty in the heat flux, heat transfer coefficient, and the vapor concentration. First, the thermocouples were calibrated and had the uncertainty within 0.1 °C. Then, the 2-dimensional heat conduction of the heat transfer block was performed, and the values of the surface temperature, the surface heat flux and the surface heat transfer coefficient were obtained and used as the true values. Compared with the true values, we can calculate the uncertainty of the the surface temperature for 0.2 °C, the surface heat flux for 18 kW/m^2 and the surface heat transfer coefficient for 3 kW/(m^2·K). The uncertainty of ethanol mass fraction was 0.01(1%), due to the uncertainty of dew temperature was 0.1 °C.

3. RESULTS AND DISCUSSION

3.1 Confirmation of the heat transfer characteristics

Because the heat transfer of Marangoni condensation is easily to be affected by several factors, such as mass fraction of ethanol in vapor, vapor velocity and the mixed noncondensable gas. Therefore, in order to confirm the reliability of the results obtained, it is necessary to compare the heat transfer characteristics in this study to the previous results[4].

Figs. 4 and 5 show the characteristics of heat flux and heat transfer coefficient with the variation of surface supercooling, respectively. The open symbols are the results obtained in the previous study [4] and solid symbols are those obtained in this study. It is clearly shown that the results obtained in this study were generally agreed with the previous results, despite the experimental conditions were not totally consistent. Therefore, it can be confirmed that the experiments were correctly conducted and the results were reliable.

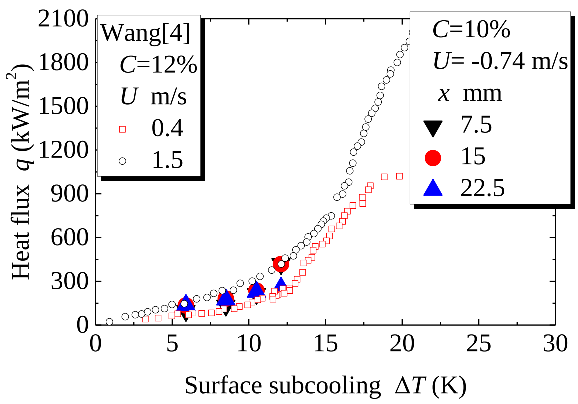

Fig. 4.Variation of heat flux with surface subcooling

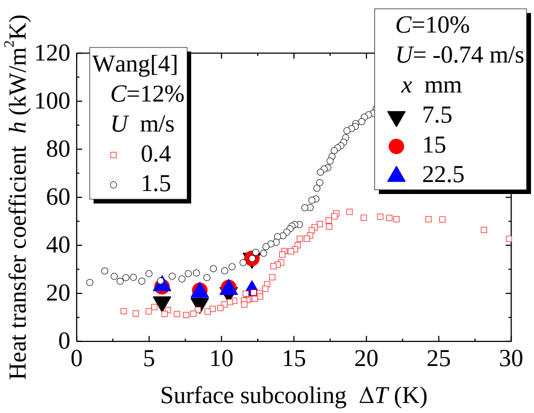

Fig. 5.Variation of heat transfer coefficient with surface subcooling

3.2 Spontaneous movement drops induced by vapor flow

As mentioned in the introduction, it was discovered by the authors that [9] the condensate drops moved spontaneously from the low to high temperature side on the heat transfer surface. The driving force was considered to be the surface tension gradient. The shearing force induced by the vapor flow was considered as another effect to influence the movement of condensate drops. In order to avoid such kind of the influence from vapor flow, the vapor direction was set reversely to direction the drop movement. Normally, it was considered that the only effect of the vapor flow was to prevent the condensate drops moving toward the direction of inflow. However, a surprising effect was recently discovered that the vapor flow helps the condensate drops move toward the direction of inflow.

In order to confirm such kind of effect from vapor side, the experiments were performed on a heat transfer surface with uniform temperature distribution (without bulk temperature gradient). The driving force was limited to confirm if the directional movement of condensate drops occur. The behaviors of one typical condensate drop on the surface were shown in Fig. 6(a), under the experimental conditions of C=10%, U=0.74m/s, ΔT_A=12.1K. The surface temperature distribution and the drop velocity during its moving process were shown in Fig. 6(b). It was shown that the average temperature of the heat transfer surface is 86.4°C, and the maximum deviation is ±0.3°C. Such temperature different is obviously smaller than the bulk temperature difference that induced the spontaneous movement of condensate drop in the previous studies [10]. Therefore, the effect of surface tension gradient induced by the temperature gradient can be ignored. However, it was still observed in Fig. 6(a) that the condensate drop still moved from the left side to right side. In the figure, the blue dots represent the center positions of a drop at different moments, and the yellow arrows represent the trails of the drop movement. It should be noticed that the vapor flowed from the right to left side of the surface, indicating the condensate drop moved towards the inflow direction of vapor. The drop velocity increased and almost kept at a constant velocity after crossing the center line of the heat transfer surface.

In addition to the characteristics of individual condensate drop, the general characteristics of the drop movement on different positions of the heat transfer surface was shown in Fig. 7. It was shown that the instantaneous velocity scattered widely and the averaged velocity was general constant along the heat transfer surface. A slight decrease on the average velocity at the right side could be seen, which should be induced by the accumulation of the condensate drops along the direction of drop movement.

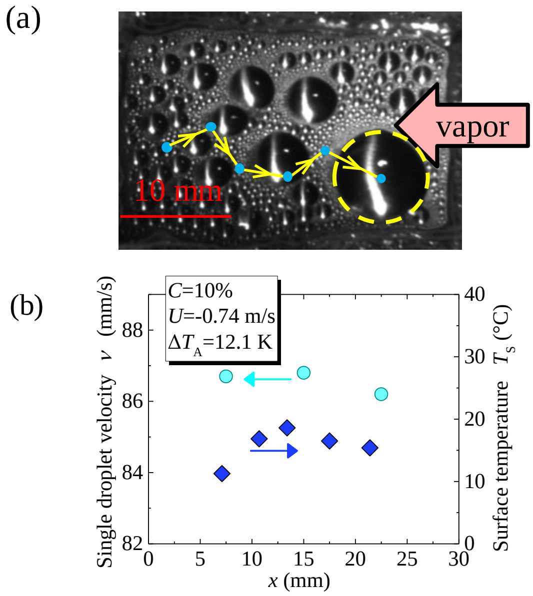

Fig. 6. Drop behavior(a) ,temperature distribution and single drop velocity(b) (C=10%, U=0.74m/s, ΔT_A=12.1K)

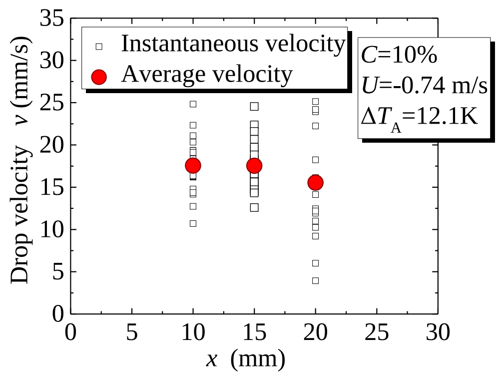

Fig. 7. Velocity of the drop movement

Here, the special phenomenon that condensates drops moved toward the inflow direction was observed. The further confirmation on such kind of effect of vapor flow was performed under different experimental conditions (different flow direction and wider range of surface subcooling). The results were summarized in Fig. 8. The positive value of vapor velocity U indicates the vapor flow from the left to right side, and the negative value indicate the opposite direction of vapor flow. The positive value of drop velocity indicates the drops move from the left to right side, and the negatives value indicates the opposite movement.

It can be obviously confirmed that the direction of drop velocity is opposite to that of the vapor flow, for both inflow directions. Besides, the average velocity of drop movement showed linear relation to the surface subcooling. Linear increase for the positive values of velocity and linear decrease for the negative values. The deep relation to the surface subcooling should be induced by the variation of Marangoni force as discussed in the previous study [10]. Furthermore, the positive and negative values of average velocity of drop movement showed good symmetrical characteristic for the same surface subcooling. On a condensing surface without obvious temperature gradient, such characteristic results mean that there were absolutely some effects that induced by the vapor flow can drive the spontaneous movement of condensate drops. Such kind of effect becomes significant with the increase of surface subcooling. The possible effects may be the microscopic gradient of concentration around the condensate drops induced by the condensation or microconvection along the flow direction. However, such microscopic effects are difficult to be evaluated by the experimental system in this study. It remains as the further work to elucidate the mechanism of spontaneous movement of condensate drop in Marangoni condensation.

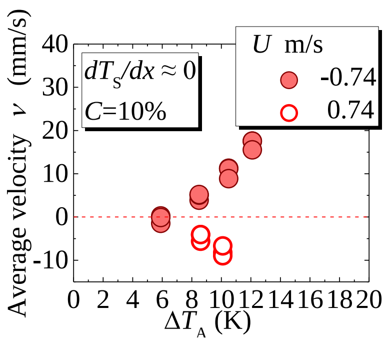

Fig. 8. Average velocity with the surface subcooling

3.3 *Drop behaviors influenced by the mixed effects of temperature gradient and vapor flow*

It was revealed in section 3.2 that the condensate drops tended to move toward the inflow direction of vapor. It was another effect that related to the spontaneous movement of condensate drop. Therefore, the relative strength of the two effects is to be examined in this section. Figs. 9 and 10 show the behaviors of condensate drops under the same conditions of C=10%, U=0.74 m/s, and the different conditions of ΔT_A=14.7 K, 7.1 K. It was shown that the condensate drops moved in the opposite direction, even though under the qualitatively consistent conditions. The inflow direction was from left to right and the right side was the high temperature side of the heat transfer surface. It was considered as the results of the mixed effects induced by temperature gradient and vapor flow. The effect induced by vapor flow drove the drop moved toward left, and the effect induce by temperature gradient drove the drop moved toward right. When the vapor flow effect won, the drop moved toward left, or it move to the right side. In the two conditions as shown, the condition under relative larger subcooling has the stronger effect induce by vapor flow (Fig. 9), which is agree with the analyzation in section 3.2. Anther condition with relative smaller subcooling has the stronger effect induce by surface tension gradient (Fig. 10).

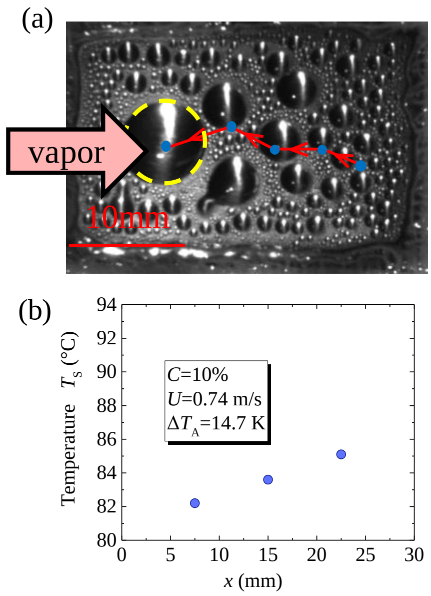

Fig. 9. Drop behavior(a) and temperature distribution (b) (C=10%, U=0.74m/s, ΔT_A=14.7K)

Furthermore, in addition to the results in Fig. 8, the average velocity for the condensate drops moving on the surface with temperature gradient were were summarized in Fig. 11. It was shown that the qualitatively similar tendencies were shown for the different condition with or without surface temperature gradient. That is, the average velocity has the linear relation with the surface subcooling and shows symmetry for different inflow direction of vapor. However, the obvious difference was also that the symmetric line (marked by the dashed lines) was at the different positions. For the conditions with surface temperature gradient of 100-300 K/m, the symmetric line was at a position significantly larger than 0 (about 17 mm/s as shown in the figure). It is an evidence that the temperature gradient drives the condensate drops to move toward the high temperature side.

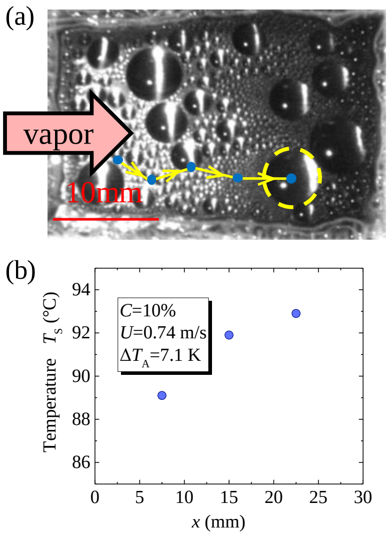

Fig. 10. Drop behavior(a) and temperature distribution (b) (C=10%, U=0.74m/s, ΔT_A=7.1K)

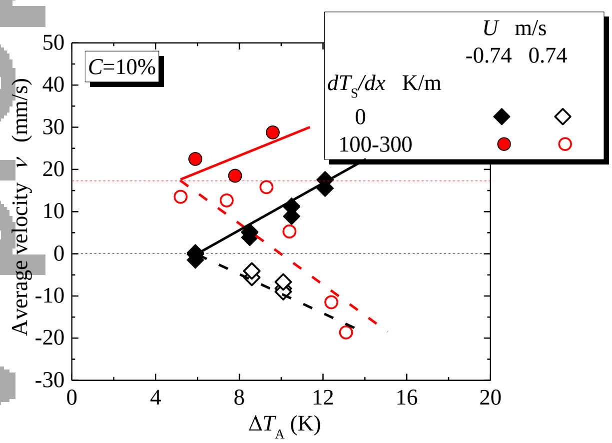

Fig.11.Average velocity of drop with surface subcooling

4. CONCLUSION

This study performed experimental study to confirm the effect of vapor flow direction on the spontaneous movement of condensation drops during Marangoni condensation of ethanol-water binary vapor. The major conclusions are summarized as follows:

(1) It was confirmed on the heat transfer surface without obvious temperature difference that, the condensate drops moved spontaneously toward the inflow direction of vapor. Such kind of special phenomenon became significant with the increase of surface subcooling.

(2) On a heat transfer surface with bulk temperature gradient, the direction of the condensate drop movement was determined by the mixed effect of vapor flow and bulk temperature gradient.

(3) The temperature gradient drove the condensate drops moved to the high temperature side and the vapor flow effect induced the movement of drops towards the inflow direction. The relative strength of the two effect determine the direction and velocity of condensate drop movement.

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