Microgravity Sci. Technol (2009) 21 (Suppl 1):S77–S85
DOI 10.1007/s12217-009-9131-y

Research on Marangoni Condensation Modes for Water–ethanol Mixture Vapors

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Received: 29 January 2009 / Accepted: 25 May 2009 / Published online: 4 June 2009

Abstract In this paper the condensation experiments for water–ethanol vapors were carried out at different vapor pressures over a wide range of ethanol concentration. The condensation modes were observed and quantitatively analyzed in order to clarify the condensation phenomenon and dropwise condensation mechanisms. The cycle time of dropwise condensation, affected by vapor-to-surface temperature difference, ethanol concentration and vapor pressure, was approximate 0.2 s to 2 s. The quantity proportion of drops with the diameter less than 1 mm was more than 70% in all drops for all mixture vapors. The peak values of the maximum departing diameters increased with the ethanol vapor concentration, and were weakly affected by the vapor pressure, and the values were about 1.5 mm to 5 mm. The rivulet condensation mode was usually observed as a transition state appeared when the drop mode changed to film mode. The maximum distance between rivulets was sensitive to the ethanol vapor concentrations and little dependent on the vapor-to-surface temperature difference.

Keywords Water–ethanol · Condensation · Heat transfer coefficient · Condensation mode

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Introduction

When a certain binary mixture condenses on a surface, one observes that the liquid condensate rises locally and eventually forms many droplets on the film. Mirkovich and Missen (1961) firstly observed the non-filmwise condensation phenomenon for binary vapors. Ford and Missen (1968) demonstrated a criterion for film instability by an inequality, and established a sign convention $d\sigma/db$ by $d\sigma/db \leq 0$ for stable and $d\sigma/db > 0$ for unstable, where σ was the surface tension and b was film thickness. A positive system, where the surface tension of the highboiling-point component was larger than that of the lowboiling-point component, coagulated on a solid surface, the sign convention $d\sigma/db$ was positive and the condensation film would be unstable. The later research indicated that the non-filmwise modes were caused by the surface tension gradients on the condensate surface. For Marangoni effect was responsible for the non-filmwise modes, some researchers called it Marangoni or pseudo-dropwise condensation. For the non-filmwise modes, Marangoni condensation got several times heat transfer compared to the film condensation of pure vapors. Morrison et al. (1998) conducted experiments using water –methylamine mixture over a range of 0.03–4.3% and found that the heat transfer coefficient was increased by as much as 30%. Utaka et al. (Utaka and Terachi 1995; Utaka and Wang 2004) performed a series of experiments on Marangoni condensation for water–ethanol vapor mixtures on a small vertical plate, and firstly found the heat transfer coefficient revealed nonlinear characteristics with peak values with the increase of surface subcooling. They pointed out the condensation heat transfer was enhanced approximately two to eight times compared to pure steam. Murase et al. (2007) investigated the heat transfer characteristic for steam–ethanol mixtures on horizontal tubes. They got the similar heat transfer characteristic, just some values difference from the Utaka's result.

In addition, many researchers also investigated the Marangoni condensation modes. Fujii et al. (1993) reported five condensation modes of water and ethanol mixtures: drop, streak, ring, smooth film and wavy film, and they observed the maximum drop size on the top of the horizontal tube, the minimum drop sizes and the relation between the vapor concentration and the drop shape on an outer surface of cylinder tube. Hijikata et al. (1994) analyzed the instability of the condensate film and showed the qualitative agreement with the observation of the condensate modes. Utaka et al. (1998) investigated the processes of initial droplets formation from thin condensate film and drop departure using a high speed digital camera and measured the initial drop distance and departing drop diameter. Utaka and Kobayashi (2001) concluded that the maximum heat transfer coefficient was proportional to around −0.35th power of the departing drop diameter. Utaka and Nishikawa (2003) measured the condensate film thickness during Marangoni condensation using a laser absorption method and found the smallest thickness of the condensate film was less than 1 μm.

The researches above were mostly carried out on an atmospheric pressure. Moreover, the previous investigations about the condensation modes were not enough to clarify the condensation phenomenon and dropwise condensation mechanisms and further construct a calculation model, with the view of quantitatively calculating the Marangoni condensation heat transfer. Thus it is necessary to investigate the Marangoni condensation modes in detail. An experiment system that the vapor pressure can be adjusted was set up. By the system the Marangoni condensation heat transfer characteristic under different vapor pressures over a wide range of ethanol concentrations were systematically investigated (Yang et al. 2008; Li et al. 2008). The main objective of the present work is to get the preliminary quantitative rules of condensation modes for Marangoni condensation.

Experimental Apparatus and Method

The experimental apparatus is shown as Fig. 1. The mixture vapor generated in the electrically heated boiler partly condensed on the vertical surface of a copper plate and excess vapor passed to an auxiliary condenser from which the condensate returned to the boiler by gravity. The auxiliary cooling water loop was set not only to cool the excess vapor, but also to control the vapor pressure. By controlling the mass flow rate of cooling water through the condenser, the pressure in the test was adjusted. The experiment copper plate is shown as Fig. 2. Also shown in Fig. 2 is thermocouples distribution in test plate. During the experiment, the condensation modes were observed and recorded through the glass window of the condensing chamber using a CCD camera, as shown in Fig. 1. Full details of the apparatus and procedure and the measure methods are given by Yang et al. (2008).

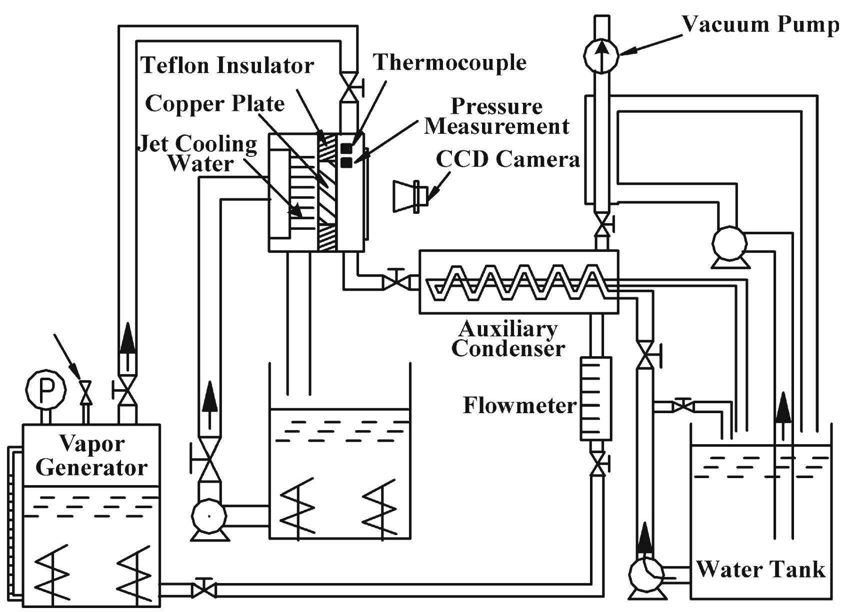
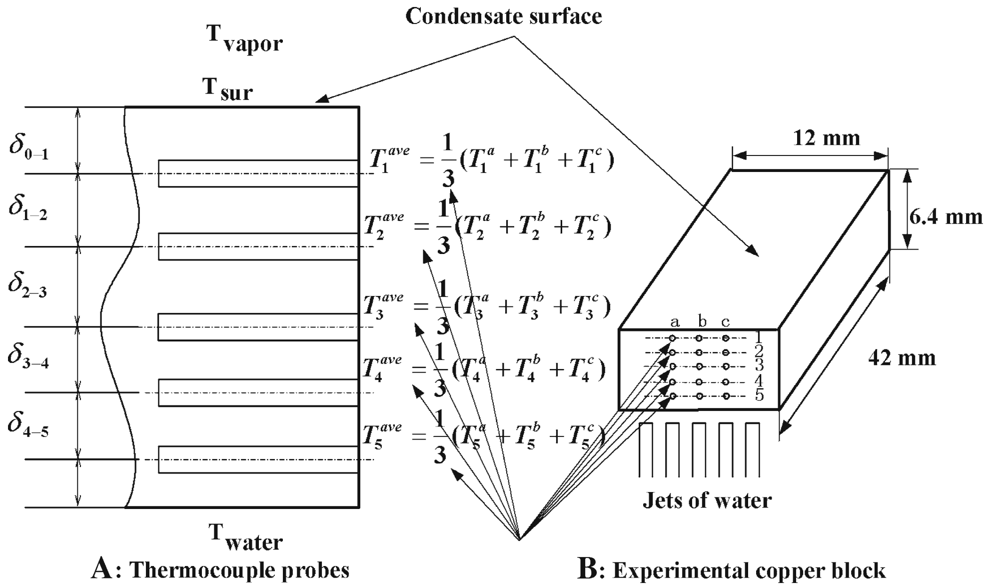


Fig. 1 Schematics of experimental apparatus

Fig. 2 Thermocouples distribution in test plate



$$T_1^{ave} = \frac{1}{3}(T_1^a + T_1^b + T_1^c)$$

$$T_2^{ave} = \frac{1}{3}(T_2^a + T_2^b + T_2^c)$$

$$T_3^{ave} = \frac{1}{3}(T_3^a + T_3^b + T_3^c)$$

$$T_4^{ave} = \frac{1}{3}(T_4^a + T_4^b + T_4^c)$$

$$T_5^{ave} = \frac{1}{3}(T_5^a + T_5^b + T_5^c)$$

The uncertainties associated with raw measurement and the derived data which were analyzed by the method of Moffat (1982). The uncertainty in the thermal conductivity was 2%, in temperature was 0.1 K, in distance was 2×10^{-5} m. The resultant uncertainties of heat flux (q) and heat transfer coefficient (h) were 4–18% and 4–19%, respectively. The uncertainty of drop diameter (D) and the distance between rivulets (S) was 1×10^{-5} m. The uncertainty of time (τ) was 1/24 s.

Results of Heat Transfer Coefficient

The present experiments were carried out at the vapor velocity of 1 m/s and two vapor pressures (84.53 and 47.36 kPa) over a wide range of ethanol concentration ($C = 0.5\%$, 1%, 2%, 5%, 10%, 20%, 50%, 100%). Figure 3 shows the heat transfer characteristic.

As same as the previous study carried out on an atmospheric pressure (Utaka and Wang 2004), the condensation curves of the heat transfer coefficient revealed nonlinear characteristics and had peak values with respect to the vapor-to-surface temperature difference for all vapor concentrations. In addition, for all ethanol concentrations, the heat transfer coefficient increased with increasing vapor pressure. It was found that the effect of vapor pressure on enhancing the condensation heat transfer coefficient was significantly greater for mixtures with low and middle ethanol concentrations of 0.5, 1, 2, 5, and 10%, than for mixtures

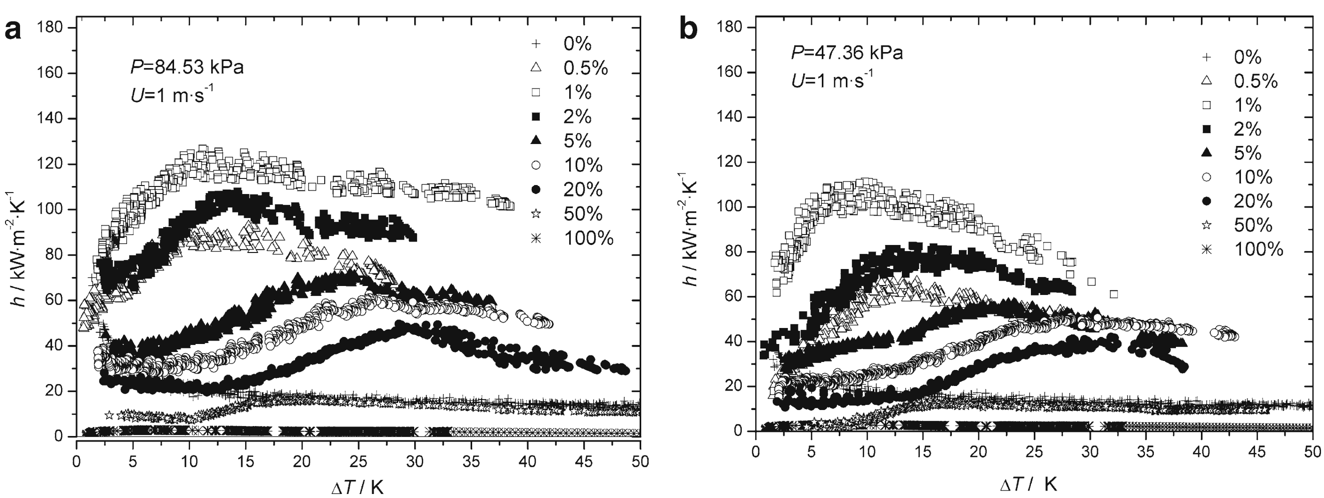


Fig. 3 Heat transfer coefficient versus vapor-to-surface temperature difference

with high ethanol concentrations of 20 and 50%. Full details of the experiment results and discussion of heat transfer characteristic are shown in our early literature (Yang et al. 2008).

Marangoni Condensation Modes Analysis

During the experiment, the condensation modes were recorded using a CCD camera. From the photographs, it was found that the present condensation mode was non-filmwise, and mostly was dropwise. Seven condensation modes were observed, such as smooth film, drop, film-drop, streak, drop-streak, wavy-streak, and drop with tail. The condensation modes were greatly depended on the ethanol vapor concentration and vapor-to-surface temperature difference. With the increase of vapor-to-surface temperature difference, the condensation modes changed from smooth film to wavy-rivulet or rivulet, then to drop-rivulet, to drop, and finally to smooth film. For the mixture vapors with different ethanol concentrations, the vapor-to-surface temperature region with dropwise mode appearance was different, and the size and distribution of drops was also different. Compared to the effect of the ethanol concentration and vapor-to-surface temperature difference, the effect of pressure on the condensation modes was weak.

The process of dropwise condensation was a periodic cycle, including drops formation, drops growth, drops coalescence and drops departure. The typical condensation cycle was shown as Fig. 4. It could be seen that, the small drops formed in certain positions, grew up and combined with other drops, then fell off. At the moment the new small drops formed at the same positions and a new cycle started again. From Fig. 4 it was found that the present cycle time was about 0.54 s (13/24 s) and 1.38 s (11/8 s). By observing many experiment conditions, the cycle time was found to be all affected by vapor-to-surface temperature difference, ethanol concentration and vapor pressure. The negative effect of the vapor pressure on the cycle time was much weaker than the effects of two other influencing factors. The cycle time was much short at the low ethanol concentration, and at the high ethanol concentration it needed more time to begin another new cycle. The effect of vapor-to-surface temperature difference was not linear and the shorter cycle time appeared

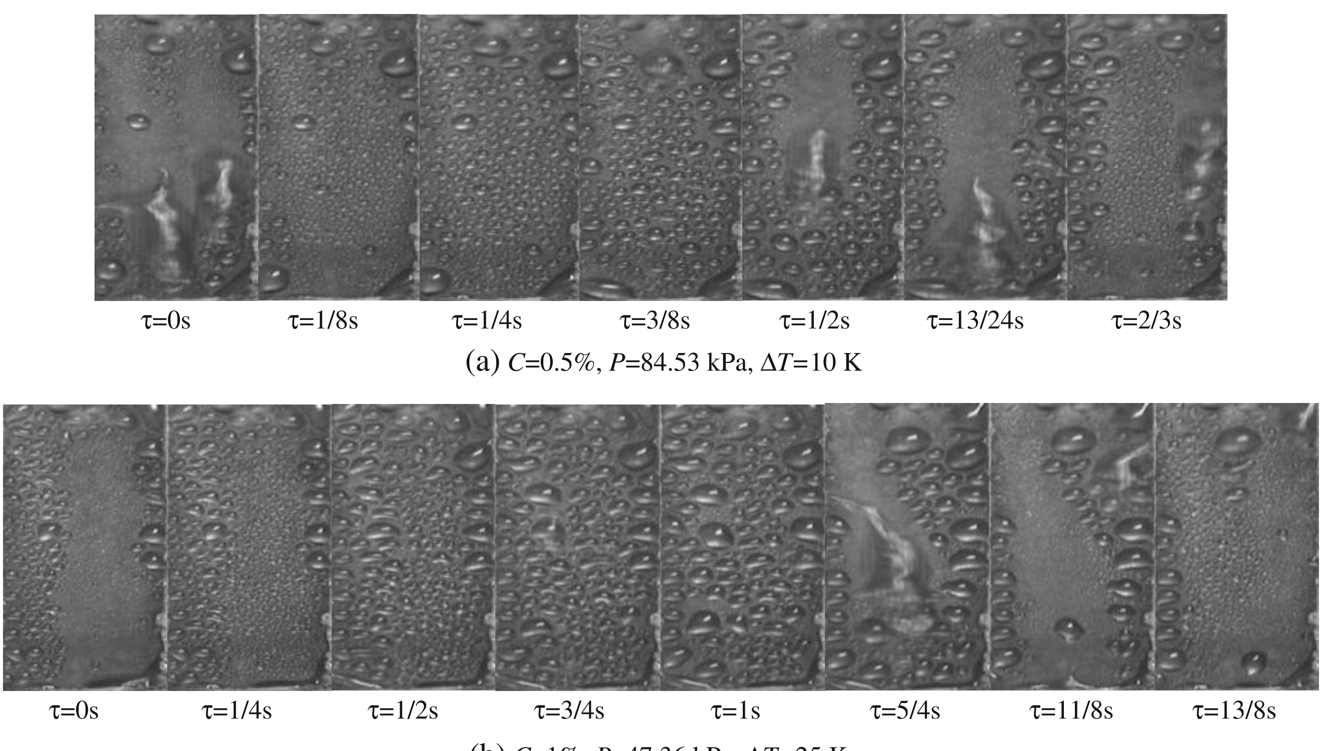


Fig. 4 Variation of condensation modes in a dropwise condensation cycle

at the middle vapor-to-surface temperature difference range. Generally, the circle time was approximate 0.2 s to 2 s.

In order to quantitatively describe condensation modes, it was necessary to introduce some parameters, such as drop size distribution and maximum drop diameter. The maximum drops were just the ones which would depart from the condensing surface during the condensation. So the maximum drop diameter was just the maximum departing drop diameter. The next work was to preliminarily investigate the parameters of Marangoni condensation modes.

1 Drop size distribution

In this paper the drop size distribution was counted at the moment appearing the maximum drops in a dropwise condensation cycle. The recorded photographs showed that, with the increase of the ethanol concentration, the diameter of maximum condensate drop increased and the quantity of the drops decreased. It indicated that, at the high ethanol concentration range the drops were sparse and the conclusion was opposite at the low ethanol concentration range. Figure 5 shows drop size distribution histograms for different ethanol concentrations. For a fixed ethanol concentration, the drop size distribution rate was variational with the drop size. The number of drops in Fig. 5a, b, c, d was 89, 72, 64 and 47, respectively. From Fig. 5 it could be seen that, at the ethanol vapor concentration of 2%, the drops with the diameter between 0 and 0.5 mm were most, and the ratio was about 39%. At the other higher vapor concentrations (10%, 20%, and 50%), the drops with the diameter between 0.5 and 1 mm were most, and the ratios were 46%, 48%, and 45%, respectively. The quantity proportion of drops with the diameter less than 1 mm was more than 70% in all drops for all ethanol concentrations. The rule indicated that, in the present Marangoni condensation, the drops with

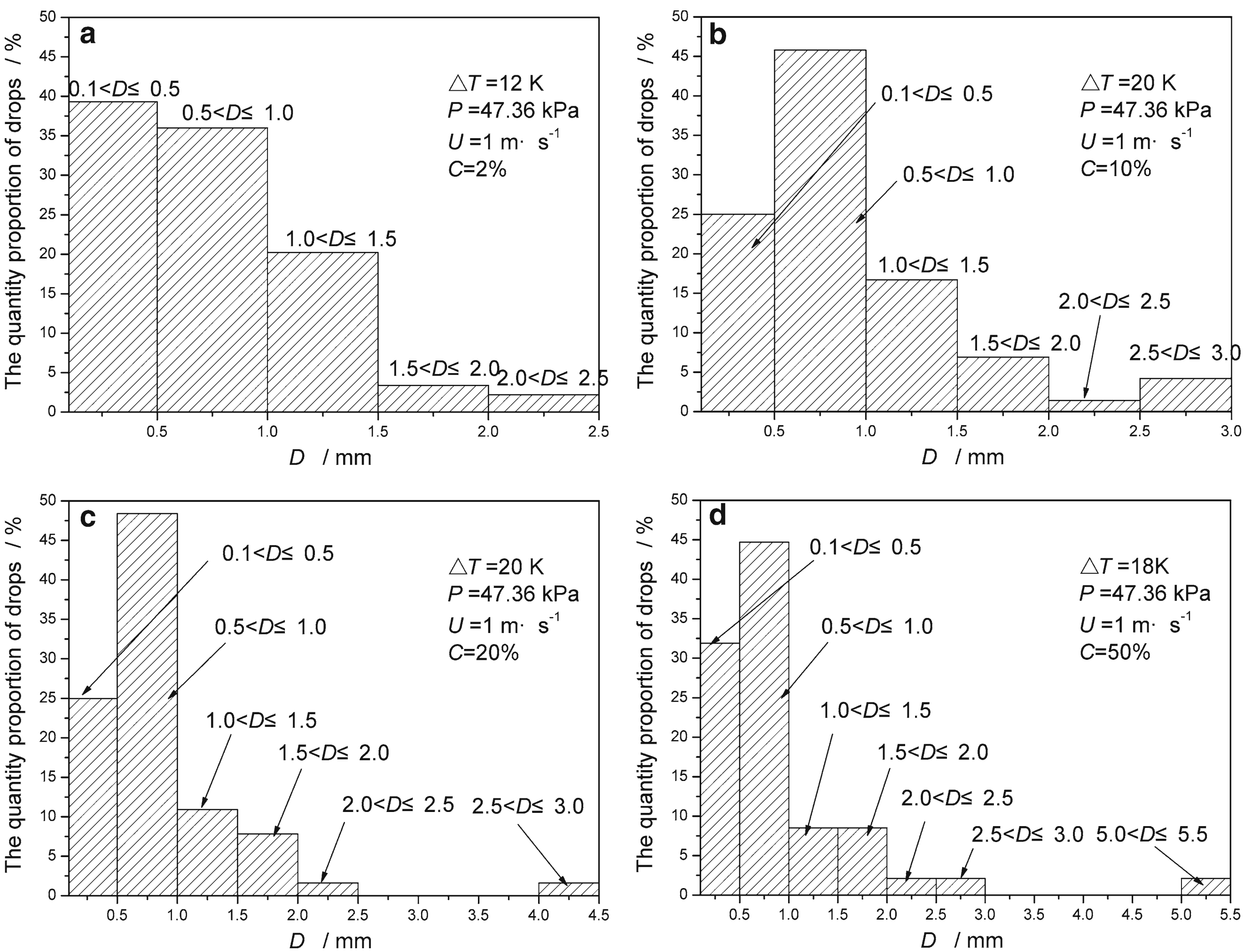


Fig. 5 Drop size distribution histograms for different ethanol concentrations

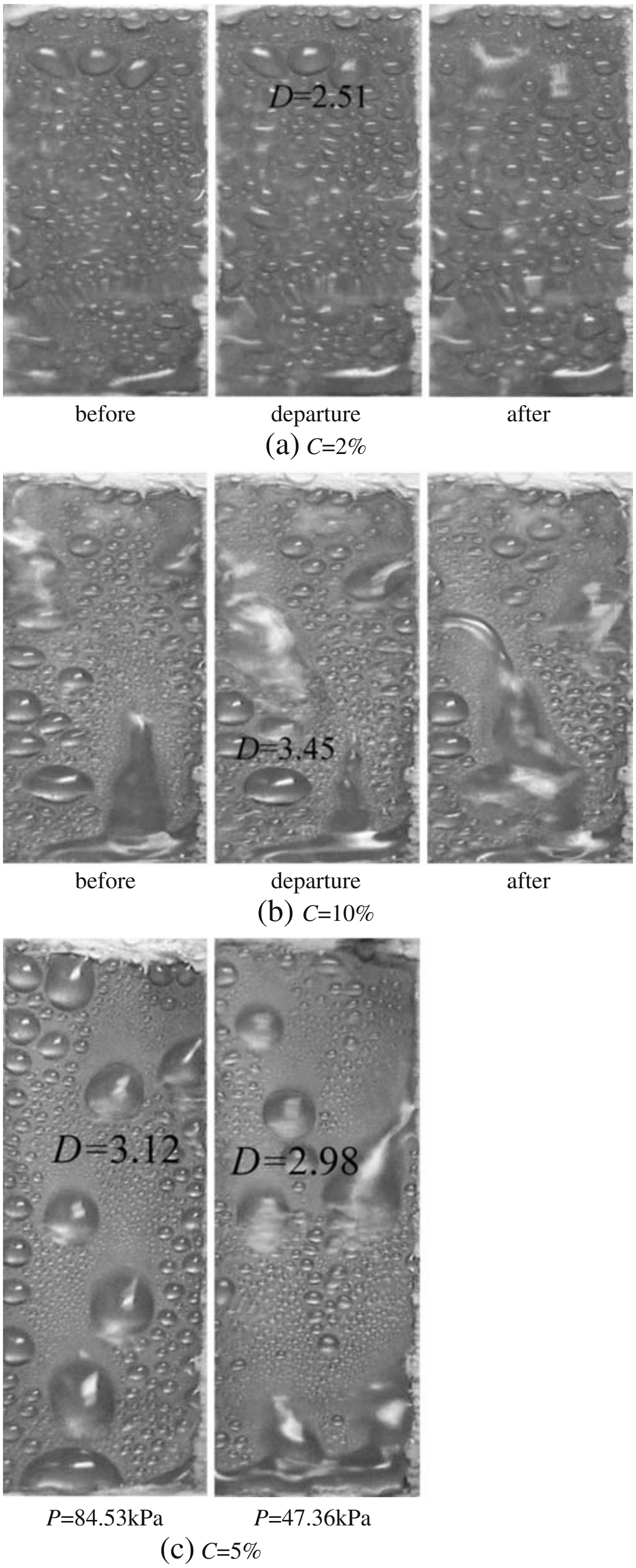


Fig. 6 Maximum departing diameter of drops for different experiment conditions

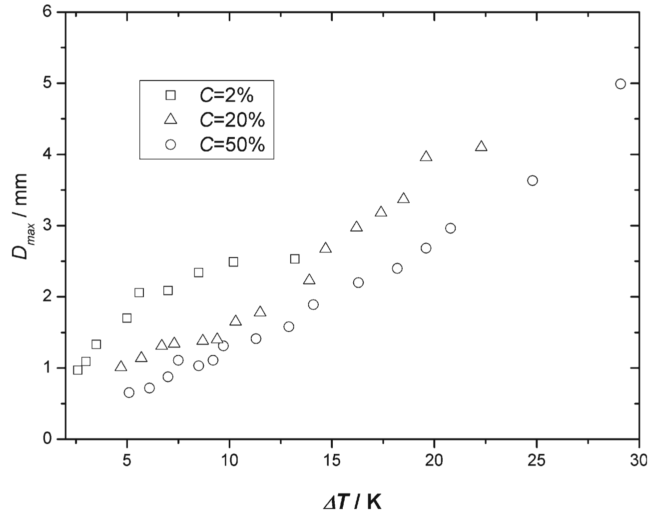


Fig. 7 Maximum departing drop diameter versus ΔT

the diameter less than 1 mm were the main transporting species of heat transfer.

2 Maximum departing drop diameter

The maximum departing drop diameter was a significant parameter to quantitatively analysis the condensation phenomenon. Fujii et al. (1993) observed the maximum drop size and found the maximum drop diameters were 1.5–2.5 mm on the top of the horizontal tube. Utaka et al. (1998) measured the departing drop diameters on a vertical surface. They found that the variations of the departing drop diameter exhibited U-shapes with the minimum values against the surface subcooling. The departing drop diameter was found to be little dependent on the ethanol concentration and

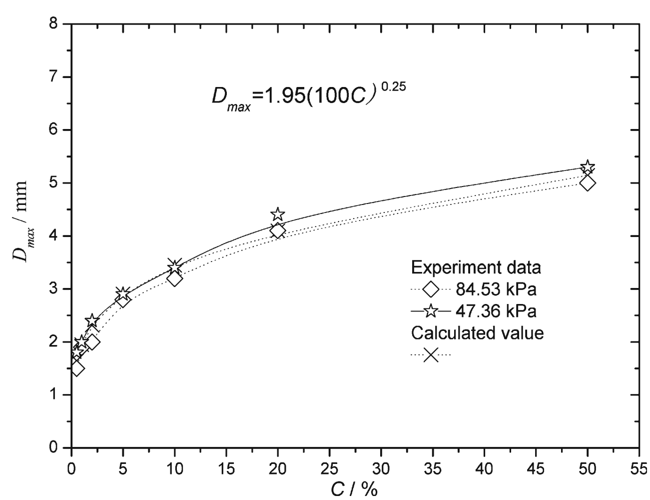


Fig. 8 Maximum departing drop diameter for different ethanol concentration

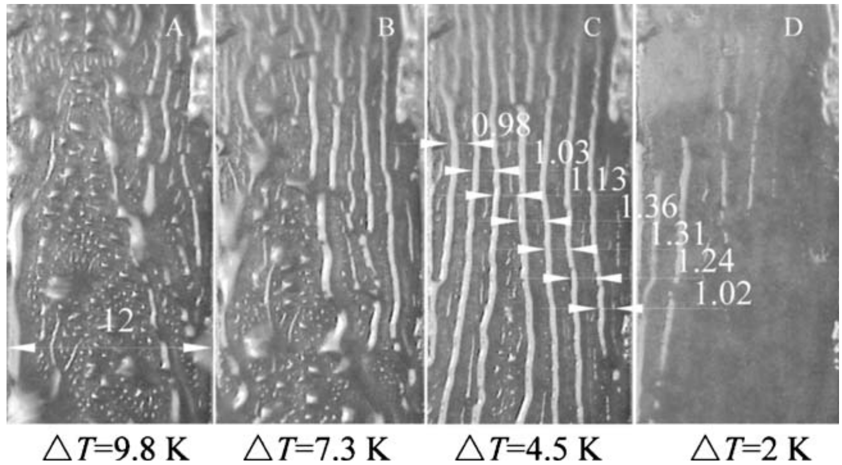


Fig. 9 The transition state between the drop mode and film mode ($C = 1\%$, $P = 84.53$ kPa)

those minima were about 1.5 mm. In present work the maximum departing drop diameter was measured directly. Figure 6 shows the maximum departing drops for different experimental conditions.

As the condensation modes always varied with the changing vapor-to-surface temperature difference, the drops might grow into a liquid block with an irregular border. When the condensation mode was a big liquid block with an irregular border, the diameter of the largest drop was replaced by an equivalent largest diameter. The equivalent diameter of liquid block is defined as:

$$D_{\max} = \frac{4A}{S} \tag{1}$$

Where A was the area of the condensate drops or block and S was the perimeter of the condensate drops or block.

The maximum departing drop diameter was found to increase nearly linearly with the vapor-to-surface temperature difference, as shown in Fig. 7. As the dropwise modes appeared at different vapor-to-surface temperature difference region at different ethanol concentrations, there was existed a peak value of maximum departing diameter for a fixed ethanol concentration.

Concluding from a number of photographs, the peak values of the maximum departing diameters were great dependent on the ethanol vapor concentration, and were weakly affected by the vapor pressure (as seen in Fig. 6c). The peak values were about 1.5 mm to 5 mm. A fitting formula for the peak values was obtained by measuring lots of diameters of drops as follows:

$$D_{\max} = 1.95(100C)^{0.25} \tag{2}$$

Figure 8 shows the comparison results of experimental data with calculated values. As the maximum departing drop diameter weakly affected by the vapor pressure, the fitting formula was obtained by the mean values of maximum departing drop diameter at different vapor pressures.

The present departing drop diameter was much higher than that in Utaka et al. (1998). The main reason might be the different definition of maximum departing

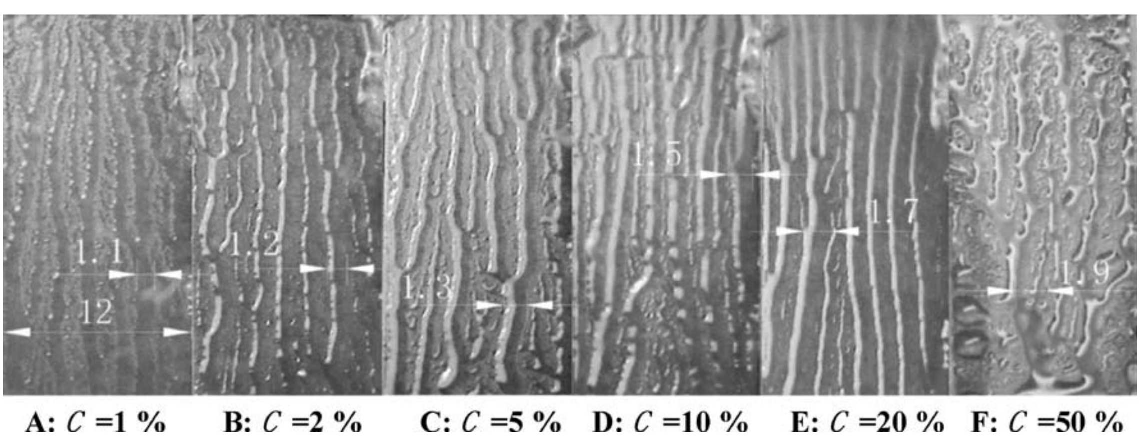


Fig. 10 Maximum distance between rivulets for different ethanol concentrations

drop diameter. In Utaka's research the maximum drop was strictly restricted as a sphere or spherical crown. In present research the definition of maximum drop was extended. Another assured reason was that the present experiment pressure was lower than that of Utaka. It had been confirmed that the departing drop diameter weakly decreased with the increase of pressure in the present experiment. Another difference between this work and Utaka's research was the variation of the departing drop diameter with the surface subcooling and ethanol concentration. The obvious difference between the two researches showed some more works should be done on the Marangoni condensation modes.

3 Quantitative analysis of rivulet condensation modes

The rivulet usually appeared in laminar falling liquid film. The rivulet was the result of the liquid film under the combination effect of gravity, surface tension and the shear stress caused by vapor velocity. Fujii et al. (1993) found the similar rivulet modes (so-called streak) in the condensation of water–ethanol mixture on a horizontal tube. During the present experiments the rivulet mode was usually observed as a transition state appeared when the drop mode changed to film mode. Figure 9 shows the transformation process during the experiment. The distances between the rivulets was some different. In the middle position the distance was wide. Figure 10 shows other rivulet modes for different ethanol vapor concentrations. Concluding from a number of experiment conditions, the maximum distance between rivulets was found to be sensitive to the ethanol vapor concentrations and little dependent on the vapor-to-surface temperature difference. A fitting formula was got to calculate the maximum distance between rivulets quantitatively as follows:

$$L_{\max} = 1.08(100C)^{0.14} \tag{3}$$

And the comparison of calculated values with experimental data is shown in Fig. 11. The calculated value was close to experimental values.

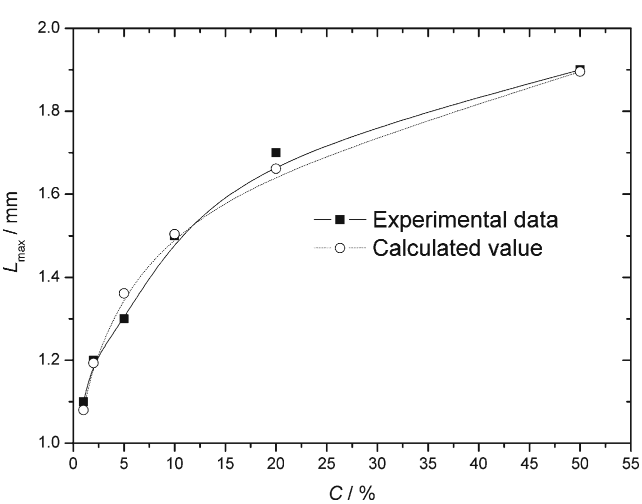


Fig. 11 Maximum distance between rivulets for different ethanol concentration

Conclusions

In this paper, a system that the vapor pressure could be adjusted was set up and the Marangoni condensation experiments were carried out under different vapor pressures over a wide range of ethanol concentrations. The condensation modes were recorded during the experiments and then were quantitatively analyzed in order to clarify the condensation phenomenon and dropwise condensation mechanisms. The analyzed results are summarized as follows:

1. The process of dropwise condensation was a periodic cycle, including drops formation, drops growth, drops coalescence and drops departure. The cycle time was all affected by vapor-to-surface temperature difference, ethanol concentration and vapor pressure, and it was approximate 0.2 s to 2 s.
2. The quantity of the drops decreased with increasing the ethanol concentration. For a fixed ethanol concentration, the drop size distribution rate was variational with the drop size. The quantity proportion of drops with the diameter less than 1 mm was more than 70% in all drops for all mixture vapors.
3. The peak values of the maximum departing diameters increased with the ethanol vapor concentration, and were weakly affected by the vapor pressure. The values were about 1.5 mm to 5 mm.
4. The rivulet condensation mode was usually observed as a transition state appeared when the drop mode changed to film mode. The maximum distance between rivulets was sensitive to the ethanol vapor concentrations and little dependent on the vapor-to-surface temperature difference.

Acknowledgements This project has been supported financially by National Natural Science Foundation of China through Grant Nos. 50476048 and 50521604. The authors also gratefully acknowledge Prof. Y. Utaka (Yokohama National University) for his helpful assistance.

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