BUBBLE BEHAVIOR AND HEAT TRANSFER ON A HORIZONTAL FINE WIRE DURING POOL BOILING OF BINARY MIXTURES

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Abstract

Heat transfer coefficients were measured during pool boiling of mixtures of R22/R11 on a horizontal heated fine wire, and bubble behavior was simultaneously photographed with a high-speed video camera. An experiment was carried out at a pressure of 0.4 and 0.7 MPa all over range of fraction in the binary mixtures. We clarified the effect of mass fraction on the bubble behavior by measuring bubble departure diameter, frequency and growth rate on the basis of the video images photographed. As a result, the bubble departure diameter for the mixtures was smaller than that for the corresponding single component substances, and the bubble departure frequency was also shorter, except for the mixtures at the fraction of C = 0.1. The bubble growth rate was slower at any fraction than that for both the single component substances. Furthermore, we discussed a decrease in the boiling heat transfer of the mixtures, considering a relationship between the bubble behavior and the boiling heat transfer coefficients.

1. Introduction

Many studies have been conducted for bubble behavior in pure substances and the correlations [1-5] for the bubble departure size, the bubble departure frequency and the bubble growth rate were proposed. Fritz [1] proposed an empirical correlation for prediction of the bubble departure diameter by considering the buoyancy and the surface tension. Staniszewski [2] measured the bubble departure diameter in water and methanol and predicted the diameter by taking into consideration an effect of the bubble growth rate into the Fritz [1] equation. Zuber [3] proposed a correlation for the bubble departure diameter during pool boiling using the Jakob number. Zeng et al. [4] predicted the bubble departure diameter by introducing the buoyancy and growth force, \(m \frac{d^2r}{dt^2}\) (m is mass and r is the radius of a bubble). Cole and Shulman [5] measured the bubble departure diameter of a few kinds of hydrocarbon like acetone and methanol and proposed a correlation for them. Nishikawa et al. [6] measured a nucleation site density and the bubble departure frequency to predict the boiling heat transfer coefficient.

On the other hand, there are only a few studies on bubble behavior in binary mixtures. Van Wijk and Van Stralen [7] and Van Stralen [8] measured bubble growth rate in mixtures of methylethylketone/water and 1-buthanol/water on a horizontal heated wire and reported that the bubble growth rate becomes faster with an increase in the wall superheat and that the bubble growth rate in the mixtures is slower than that in pure substances. Scriven [9]
theoretically predicted the bubble growth rate in a superheated liquid.

In this study, we measured the nucleate pool boiling heat transfer coefficients in the mixtures of R22/R11 at a pressure of 0.4 and 0.7 MPa and simultaneously photographed the bubble behavior with the high-speed video camera. We clarified the effect of fraction on the bubble behavior by measuring the bubble departure diameter, the frequency and the growth rate on the basis of the movies filmed. Furthermore, we will discuss a relationship between the bubble behavior and the heat transfer coefficient in the binary mixtures.

We focused on mixtures of R22/R11 whose bubble behavior may dramatically differ from the pure substances of R22 and R11, since it was already clarified in Reference [10] that the heat transfer coefficients of R22/R11 is dramatically lower than those of each pure substance.

Nomenclature
C : Mass fraction of more volatile substance
D : Bubble departure diameter
f : Bubble departure frequency
f_{av} : Arithmetic average value of f
h : Heat transfer coefficient
H_{fg} : Latent heat of vaporization
P : Heat flux
Q : Heat transfer rate
t : Time
T : Temperature
V : Bubble departure volume
V_{av} : Arithmetic average value of V
\rho_v : Density of vapor

2. Experimental apparatus and procedure

2.1 Experimental apparatus

Figure 1 shows a schematic diagram of a present experimental apparatus. A platinum wire 2 (diameter d = 0.3 mm, length L = 88 mm) employed as a heated surface is horizontally blanketed in the center of a pressure vessel 1 and is heated by a direct electric current. Wall superheat is calculated using the temperature- electric resistance characteristic of the platinum wire, which is determined by a prior experiment. More details of the characteristics were described in Reference [11]. The pressure vessel 1 is immersed in a thermostat bath 8 to isolate it from the surroundings and the temperature of the vessel is kept constant with thermostat liquid through a thermostat with pump 9. The boiling feature can be observed and photographed with the high-speed video camera through a view window 3.

2.2 Experimental procedure

Heat flux to the heated wire 2 was increased stepwise up to 200 kW/m^2 and then was decreased stepwise, after a test liquid was maintained at a saturation temperature corresponding to a system pressure. The wall superheat and the heat flux were measured and then bubble growth and the departure process were photographed at a speed of 2250 frames per second with the high-speed video camera, after the mean temperature of the wire became steady at a given heat flux. There was a hysteresis in the measurements of wall superheat between the upward and downward process of the heat flux. Then the data in the downward process were adopted for the measurement of the heat transfer coefficients and the bubble behavior. The system pressure was kept constant by controlling the supply of cooling liquid to condenser 6 during the experiment. Additional details of the

![Fig 1 Schematic diagram of experimental apparatus](image-url)
experimental apparatus, the procedure and an accuracy of the heat transfer measurement are not explained here, as those were already indicated in Reference [11].

2.3 Observation of boiling feature

Measurement of the growth and departure process of bubbles was very difficult in moderate and high heat fluxes because the generated bubbles coalesce each other in these heat fluxes. So, we focused on isolate bubbles in low heat fluxes of 7 and 10 kW/m² just before the finish of boiling and on a few nucleation sites on the heated wire to measure the bubble growth and departure process. Video images of bubbles captured into a computer system were digitized. We measured the departure diameter, the departure frequency and the growth rate of bubbles on some nucleation sites. Figure 2 shows an example of a growth process from the growth to the departure of a bubble in the heat flux of q = 10 kW/m². The bubbles were grown spherically in the low heat fluxes as shown in Fig.2. The departure size is the diameter of a bubble just after departing from the heated wire, i.e. 38.2 msec in Fig.2 and the diameter was calculated using bubble area measured. The departure frequency is defined by the number of bubbles departing from the heated wire per second.

3. Experimental result and discussion

3.1 Effect of mass fraction on boiling heat transfer coefficient

Figure 3 shows the effect of the mass fraction on the boiling heat transfer coefficient in R22/R11 at a pressure of 0.7 MPa. The heat transfer coefficients in the mixtures are significantly lower than those of each single component substance and dramatically deteriorate in the vicinity of both the single component substances, reaching the lowest value at C = 0.3. The existing studies [10-13] also reported a similar character for heat transfer data obtained in different binary mixtures. The authors described the reason for deterioration in the heat transfer in Reference [10].

3.2 Visual observations of boiling phenomena

Figure 4 shows a boiling phenomena in mixtures of R22/R11 at P = 0.7 MPa and q = 10 kW/m², which corresponds to data in Fig.3. In mixture of C = 0.1, bubbles are generated at only a few locations on the heated wire. The bubble size at C = 0.1 almost coincides with that at C = 0 (R11) and the number of nucleation site at C = 0.1 is decreased in comparison with that at C = 0. Fine bubbles are generated all over the heated wire at a very short departure frequency, and the bubble size becomes larger with an increase in fraction in 0.3 ≤ C ≤ 0.9. The bubble size of the mixtures is smaller than that of single component substances except for C = 0.1. The bubble size becomes larger and the number of nucleation site increases with an
increase in heat flux, and bubbles coalesce in the range of middle and high heat flux in both the pure substances and the mixtures, though the pictures are omitted.

### 3.3 Bubble departure diameter, departure frequency and growth rate

Figure 5 shows the effect of the mass fraction on the bubble departure diameter at the same pressure and heat flux with Fig.4. The arithmetic average value in each fraction is indicated using a solid symbol in Fig.5 for reference. It shows that the bubble growth process is very complex, since the bubble size is widely distributed on the heated wire. Varieties of size and geometry of the nucleation site mainly cause the wide distribution of the bubble departure diameter. The bubble departure size in $C = 0.1$ is almost the same as that in $C = 0$. The bubble size of the mixtures is smaller than that of both the single component substances in $0.3 \leq C \leq 0.9$. The size is the smallest in the vicinity of $C = 0.5$ and becomes larger toward both the pure substances. Here, Sprow and Prausnitz [14] measured the surface tension for five kinds of binary mixtures and reported that it becomes smaller than that calculated by proportional allotment using each single component substance. According to their theory, the bubble size in $0.3 \leq C \leq 0.9$ becomes smaller than that in single component substances because the surface tension is depressed in the fraction range.

Figure 6 shows the effect of the mass fraction on the bubble departure frequency at

![Fig.4 Boiling feature in binary mixtures](image)

![Fig.5 Effect of fraction on departure diameter](image)

![Fig.6 Effect of fraction on departure frequency](image)

![Fig.7 Bubble growth rate](image)
the same pressure and heat flux given in Figs. 4 and 5. The frequency is the shortest in \( C = 0.3 \) and becomes longer as the mixture approaches both the pure substances, but surprisingly the frequency in \( C = 0.1 \) is longer than that in both pure substances.

Figure 7 shows the bubble growth process at 0.4 MPa and 10 kW/m². Bubbles grow abruptly just after growth and the growth rate becomes slower with time. The bubble growth rate is slower at any fraction than that for both the pure substances. Van Wijk and Van Stralen [7] and Van Stralen [8] also reported the same result with this. It can be considered that the tardiness of the bubble growth rate is one of a cause of deterioration of the heat transfer coefficients in the mixtures because the tardiness weakens agitation of the superheated liquid.

### 3.4 Bubble behavior and boiling heat transfer

Figure 8 shows the effect of the mass fraction on a vaporization rate and a heat transfer rate on the basis of Figs. 5 and 6. The signs of \( f_{av} \) and \( V_{av} \) in Fig.8 stand for the arithmetic average values of the bubble departure frequency and the bubble departure volume, respectively. Therefore, the value of \( f_{av}V_{av} \) in Fig.8 means the amount of vaporization at a nucleation site per second. The heat transfer rate, \( Q \), was calculated using \( f_{av}V_{av} \) and thermodynamic properties, which were predicted by the modified BWM method [15], as follows;

\[
Q = f_{av}V_{av}H_{fg} \tag{1}
\]

Vaporization rate and heat transfer rate in the mixtures decrease remarkably in comparison with those in the pure substances. Also from these results, we confirmed that the boiling heat transfer coefficients of the mixtures deteriorate as shown in Fig.3. However, the bubble behavior in \( C = 0.1 \), which is related to the decrease of vaporization rate, differs from that in \( 0.3 \leq C \leq 0.9 \). Namely, the bubble departure diameter in \( C = 0.1 \) is almost the same as that in R11 as shown in Figs. 4 and 5, whereas the bubble departure frequency in \( C = 0.1 \) is longest in the mixtures and the pure substances as shown in Fig.6, and the bubble growth rate is slowest as shown in Fig.7. The number of the nucleation site in \( C = 0.1 \) is scantest in the mixtures and both the pure substances as shown in Fig.4. These facts tell us that the heat transfer coefficient in \( C = 0.1 \) deteriorates in comparison with that in both the single component substances. In fact, Fig.3 shows that the coefficient in \( C = 0.1 \) is lower than that in the single component substances.

On the other hand, in \( 0.3 \leq C \leq 0.9 \), the boiling heat transfer coefficients of the mixtures deteriorate as shown in Fig.3, since the departure size becomes small as shown in Figs. 4 and 5, in spite of an increase in the nucleation site as shown in Fig.4. Although the bubble growth and the departure process vary with the fraction in the mixtures as mentioned above, the fact that the vaporization rate decreases is due to a rise of bubble point near the heated surface in the mixtures.
The decrease of the vaporization rate in the mixtures is attributed to that an available wall superheat for vaporization is deteriorated, since the bubble point temperature of liquid near the heated surface becomes higher because of preferential evaporation of volatile component liquid near the heated surface. The authors have already described in detail the rise of the bubble point temperature near the heated surface in Ref. [13].

Figure 9 shows the heat transfer coefficients normalized by the corresponding one for R22. The deterioration rate of the coefficient from R22 in the mixtures is almost the same in all heat fluxes at each fraction and has a trend similar to that of the vaporization rate estimated using the isolate bubbles as shown in Fig. 8. As a result, it can be thought that the trend in the change in vaporization rate with the fraction, which was measured using isolate bubbles in the low heat flux, is almost the same as that in 200 kW/m² in which the bubbles coalesce with each other.

4. Concluding Remarks

Nucleate pool boiling heat transfer coefficients were measured, and bubble behavior was simultaneously photographed using a high-speed video camera during pool boiling of the mixtures of R22/R11 on a horizontal heated wire. The bubble behavior and the heat transfer can be summarized as follows:

1. The bubble departure size of the mixtures is smaller than that of both single component substances, and the bubble departure frequency of the mixtures is shorter than that of both single component substances, except for the mixtures with a fraction of C = 0.1.
2. It was found from the bubble behavior that the nucleate boiling heat transfer is deteriorated by: (1) a decrease of the nucleation site in C = 0.1; (2) by an extreme diminution of the bubble departure size in 0.3 ≤ C ≤ 0.9; and (3) by the tardiness of the bubble growth rate in all mixtures of 0.1 ≤ C ≤ 0.9
3. The bubble growth rate in the mixtures is slower at any fraction than that in both the single component substances.

References