Effect of Non-Condensable Gas Mass Fraction on Condensation Heat Transfer for Water-Ethanol Vapor Mixture

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The condensation heat transfer characteristic curves for a ternary vapor mixture of water, ethanol and air (or nitrogen) under several ethanol concentrations and relatively low concentrations of air (or nitrogen) were measured. The effect of non-condensable gas on several different domains in the condensation curves was discussed. The effect of non-condensable gas in the domains controlled by the diffusion resistance and the filmwise condensation was not notable; whereas that in the domain dominated by the condensate resistance of dropwise mode was remarkable. Moreover, variations due to changes in non-condensable gas concentration of several characteristic points representing the curves were discussed.

Key Words: Condensation, Heat Transfer, Non-Condensable Gas, Vapor Mixture, Water-Ethanol

1. Introduction

The condenser is one of the important equipment of the steam cycle power system. In order to improve the thermal efficiency of power cycles, the use of multi-component mixtures as working fluids is considered to be one of the most promising alternatives for the conventional single component working fluid\(^1\), especially, in the case that the geothermal energy and the industry residual heat be used to generate power. In general, the condensation heat transfer coefficient of vapor mixtures is smaller than that of a single pure component and especially, degradation of condensation heat transfer coefficient is considerable resulting in increase in size of heat exchangers.

Based on this background, studies on condensation heat transfer of vapor mixtures are quite numerous\(^2\). For the condensate aspect and condensation heat transfer characteristics of water-ethanol vapor mixture, Fujii et al.\(^3\),\(^4\) reported their experimental results for natural convection condensation on the outer surface of a horizontal tube and a vertical plate surface. In addition, Hijikata et al.\(^5\) reported the experimental result of natural convection condensation on a horizontal plate. These experiments were carried out at various ethanol vapor concentrations and the ethanol concentration was found to be a dominant factor that determines the condensate mode and the heat transfer characteristics. However, an experimental result for the condensation of water-ethanol vapor mixture on a vertical plate reported by one of authors\(^6\) shows that surface subcooling (cooling strength) is also a dominant factor in determining condensation characteristics. As shown in Fig. 1, the dependences of the heat flux and the heat transfer coefficient on the surface subcooling (condensation characteristic curves) revealed a remarkably nonlinear nature. Such pseudo-dropwise condensation phenomena caused by the surface tension difference on the condensate surface due to the concentration distribution of the condensate surface is called solutal Marangoni condensation.

The solutal Marangoni condensation characteristic curve can be divided into several domains, as shown in Fig. 1. These include the domain controlled by the diffu-
sion resistance in the vapor side (from point A to point B), the domain in which the diffusion resistance decreases steeply (from point B to point C), the domain controlled by the pseudo-dropwise condensation (from point C to point E) and the domain controlled by filmwise condensation (from point E). Points B, D, and D’ are referred to respectively as the commencement point of steep increase in heat transfer, the point of peak heat transfer coefficient, and the point of peak heat flux.

For the solutal Marangoni condensation, the effect of a non-condensable gas must be considered because both the heat flux and the heat transfer coefficient are high over a relatively wide range of surface subcooling. Therefore, clarifying the effect of non-condensable gas is important. Based on a previous study\(^{(1)}\), we know that the effect of non-condensable gas on solutal Marangoni condensation cannot be ignored, even in the case in which the non-condensable gas content is very small. However, detailed research concerning the effect of non-condensable gas on solutal Marangoni condensation has not yet been reported.

The objective of the present study is to investigate experimentally the effect of non-condensable gas on solutal Marangoni condensation. In particular, the characteristics of the variation of the commencement point of steep increase and the peak points of heat transfer, which represent the nature of the condensation heat transfer characteristic curve, are clarified.

**Nomenclature**

\( a_1, a_2 \): coefficients of Eq. (1)
\( b_1, b_2 \): coefficients of Eq. (4)
\( C \): mass fraction
\( P \): vapor pressure (kPa)
\( q \): heat flux (kW/m\(^2\))
\( \Delta T \): surface subcooling (K)
\( V \): vapor velocity (m/s)

**Greek symbols**

\( \alpha \): heat transfer coefficient (kW/m\(^2\)K)

**Subscripts**

\( e \): ethanol  
\( g \): non-condensable gas
\( \text{peak} \): peak points of condensation curves

**2. Experimental Apparatus and Method**

A heat transfer block having a trapezoidal cross section with notches was used in order to realize sufficient uniformity of surface temperature and solutal Marangoni condensation over a large range of surface subcooling (See Ref. (8) for details).

The vapor loop is shown in Fig. 2. In order to realize the lowest non-condensable gas concentration, the leak-tight vapor loop was first sealed off from the atmosphere. The vapor from the vapor generator was condensed almost entirely in the auxiliary condenser after passing through the condensing chamber (cross section: 80 mm \( \times \) 20 mm), in which the heat transfer block was positioned. The condensate was fed back into the vapor generator by a plunger pump connected to flow measurement equipment. Both the vapor flow and gravitational acceleration are in the same direction. Non-condensing gas is continuously extracted by the vacuum pump near the outlet of the auxiliary condenser. An electronic cooler was used to cool the inlet of a vacuum pump in order to maintain constant the concentration of the vapor mixture in the loop by maintaining the vapor pressure of the suction as low as possible. The loop was divided into high- and low-pressure areas bounded by a pressure adjustment valve and the plunger pump. The vapor pressure of the high-pressure side is maintained approximately 1 kPa above atmospheric pressure by adjusting the pressure adjustment valve. In order to transport the condensate from the near-vacuum low-pressure area to the vapor generator at approximately atmospheric pressure, the plunger pump of low-inhalation-pressure and high-precision flow control was used.

Next, in order to change the non-condensable gas concentration, as shown in Fig. 3, a structure in which ni-
Table 1  Experimental condition

<table>
<thead>
<tr>
<th>$C_e$</th>
<th>$C_r$</th>
<th>$10^8$</th>
<th>$C_p$</th>
<th>$10^8$</th>
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<tr>
<td>0.01</td>
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<td>0.25</td>
<td>9</td>
<td>46</td>
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<td>287</td>
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<td>494</td>
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<tr>
<td>0.07</td>
<td>16</td>
<td>0.45</td>
<td>11</td>
<td>35</td>
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<td>498</td>
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<td>457</td>
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$\nu = 0.5 \text{ m/s, } P = 103 \sim 104 \text{ kPa}$

Fig. 3  Condensation characteristics curve for $C_e = 0.01$.  

Fig. 4  Heat transfer coefficient $\alpha [\text{W/(Km)}]$ as a function of surface subcooling $\Delta T [\text{K}]$.

The error of multiple measurement results for the non-condensable gas concentration under each experiment condition was within $\pm 6 \times 10^{-6}$.

3. Results and Discussion

### 3.1 Determination of experimental conditions

As reported in a previous study(10), the velocity of the vapor mixture was the dominant factor in solutal Marangoni condensation, but its effect on the qualitative change in the condensation characteristic curve was small. Hence, in order to measure the peak values of heat flux and heat transfer coefficient over a wide range of the ethanol concentrations in the vapor mixture(11), the velocity of the vapor mixture was set to be relatively low at 0.5 m/s.

From Ref. (11), both of the variations in the peak value in heat flux and heat transfer coefficient with respect to the ethanol concentration of the vapor mixture exhibit a maximum, which appeared at ethanol concentrations of approximately 0.06 and 0.01, respectively. In order to investigate the effect of non-condensable gas on solutal Marangoni condensation over a wide range of vapor concentrations, vapor mixtures of four ethanol concentrations of 0.01, 0.07, 0.25 and 0.45 were used.

When determining the concentration of non-condensable gas for the experimental condition, the lowest possible concentration of non-condensable gas was first selected. In order to realize measurement under this condition, the vapor loop was sealed off from the atmosphere and the non-condensable gas in the vapor loop was continuously extracted using the vacuum pump. In this case, the mass fraction of non-condensable gas in the vapor mixture was approximately $12 \times 10^{-6}$. Next, the vapor loop was open to the atmosphere, and the mass fraction of the non-condensable gas in the vapor mixture was approximately $38 \times 10^{-6}$. In order to investigate the variation of heat transfer characteristics with respect to the non-condensable gas concentration, the nitrogenous gas was added to the vapor loop as the non-condensable gas. The error of multiple measurement results for the non-condensable gas concentration under each experiment condition was within $\pm 6 \times 10^{-6}$.

The experimental conditions are shown in Table 1.

### 3.2 Measurement of condensation curves

Figures 3 and 4 show the condensation characteristic curves of the heat flux and the heat transfer coefficient under ethanol mass fractions of the vapor mixture of 0.01 and 0.45. The condensation heat transfer performance improves with the decrease in the concentration of the non-condensable gas for vapor mixtures of all ethanol concentrations. In particular, the condensation heat transfer performance of the vapor mixture can be improved by further reducing the concentration of the non-condensable gas, even in cases of very small non-condensable gas concentration (For example, in the case in which the mass fraction of the non-condensable gas is $40\times10^{-6}$ and $C_e = 0.01$).

As mentioned above, solutal Marangoni condensation characteristic curves can be divided to four domains. For each domain, since the main factor governing the heat transfer is different, the degree of the effect of the non-condensable gas on the condensation heat transfer should

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trogenous gas could be added to the vapor mixture as non-condensable gas was adopted. The amount and the stability of the added non-condensable gas were observed by measuring the flow of nitrogenous gas using a flow meter. The amount of non-condensable gas was adjusted using the valve at the outlet of the gas cylinder and that behind the nitrogenous gas flow meter. Before and after the measurement of the condensation characteristic curves, the concentration of non-condensable gas contained in the vapor mixture was measured using a measurement apparatus (See Ref. (9) for the details of the apparatus and measurement method). The ethanol mass fraction of the vapor mixture was measured using two methods(7).

After the vapor condition reached the steady state, the condensation characteristic curves were measured continuously via a quasi-steady measurement method, in which the temperature of the cooling water was changed very slowly at fixed concentration and velocity of vapor(5).
also be different.

First, in the domain controlled by the diffusion resistance of the vapor-side (domain A–B in Fig. 1), the diffusion resistance of the vapor-side is large and the amount of condensate is comparatively small due to the small heat flux. Therefore, the effect of the non-condensable gas is thought to be comparatively small. This tendency is particularly clear, for the case of high vapor ethanol concentration (Fig. 4). Next, in the rapid decrease domain of the diffusion resistance (domain B–C in Fig. 1), as the diffusion resistance of the vapor-side decreases rapidly while the condensate is maintained dropwise, the condensation heat flux increases suddenly. Corresponding to this change, the effect of the non-condensable gas increases suddenly, as seen in the figures. Moreover, in the domain controlled by the dropwise condensation (domain C–E in Fig. 1), since the condensate maintains the dropwise aspect and the diffusion resistance on the vapor-side is small, the heat transfer coefficient showed was high. Hence, the domain is thought to be a domain in which the effect of non-condensable gas on solutal Marangoni condensation appears easily. These figures show that the decrease in the heat transfer coefficient or heat flux due to the existence of the non-condensable gas becomes remarkable around the peak value of the condensation characteristic curve and is comparatively large. For example, in the case of $C_e=0.01$, when the non-condensable gas concentration was increased from $15\times10^{-6}$ to $494\times10^{-6}$, the peak value of the heat transfer coefficient was reduced by about 35% and the peak value of the heat flux was reduced by about 40%. Even at other vapor ethanol concentrations, the decrease in the peak heat transfer coefficient or peak heat flux due to the increase in the non-condensable gas concentration to the abovementioned degree is approximately 30%–50%. The reasons for this are thought to be as follows. 1) In this domain, since the condensation heat flux is comparatively high, the non-condensable gas accumulates easily, so the diffusion resistance layer of the non-condensable gas is thought to form easily. 2) In this domain, both the heat transfer resistance in the condensate and the diffusion resistance due to the low-boiling-point component in the vapor mixture are small. In other words, the diffusion resistance caused by the non-condensable gas is thought to become relatively large compared to other heat transfer resistance in the condensation process. Finally, in the domain controlled by the filmwise condensation (the area to the right of point E in Fig. 1), since the condensate becomes filmwise, the diffusion resistance formed by the non-condensable gas and the low-boiling-point component in the vapor mixture is relatively small in the condensation process, the effect of the non-condensable gas is not readily apparent.

These figures also indicate that the effect of the non-condensable gas in the condensation process is different under different ethanol concentrations of vapor mixture. Specifically, in the case of the low ethanol concentration of vapor mixture, the heat flux characteristic curve of which is supposed to have a strongly nonlinear shape, the non-linearity became weak and the heat flux peak becomes indistinct with the increase in non-condensable gas concentration. The effect of the non-condensable gas is thought to become stronger because the diffusion resistance of the low-boiling-point component in the condensation process is small when the ethanol concentration of the vapor mixture is low.

### 3.3 Examination of characteristic points of condensation curves

In order to clarify the effect of the non-condensable gas on solutal Marangoni condensation of the binary vapor mixture, we examined variations in the characteristic points on the condensation characteristic curve due to the existence of the non-condensable gas.

Figure 5 shows the variation of the commencement point of the steep increase in heat transfer with respect to the concentration of the non-condensable gas. The straight lines in the figure are obtained by applying the least squares method to each experimental result. It is confirmed that, the surface subcooling at the commencement point of the steep increase coincided probably with the temperature difference between boiling point line and dew point line. For all ethanol concentrations of the vapor mixture, the variation of the surface subcooling due to the increase in the non-condensable gas concentration in the vapor mixture was slight. Therefore, the effect of the increase in the diffusion resistance due to the existence of non-condensable gas is relatively small compared to the effect of the inherent diffusion resistance in the vapor layer at the commencement point of the steep increase.
Fig. 5 Variation of steep increase point of heat flux with respect to non-condensable gas concentration

Fig. 6 Variation of peak heat flux

Figures 6 and 7 show the variations of the heat flux and the surface subcooling in the peak heat flux point with respect to the concentration of non-condensable gas in the ethanol mass fraction of the vapor mixture as the parameter, respectively. Since the peak point could not be defined for the case of $C_e = 0.07$, $C_e \geq 240 \times 10^{-6}$ because the nonlinearity of the heat flux characteristic curve became weak, and thus the ethanol concentration in the vapor mixture is reduced. As shown in Fig. 6, the larger the peak heat flux the larger the effect of non-condensable gas. Specifically, in cases of low ethanol concentration $C_e = 0.01$ and low non-condensable gas concentration, the decrease in the peak heat flux due to the increase in the concentration of non-condensable gas is remarkable. This corresponds to the general characteristics of the effect of the non-condensable gas on the condensation. Moreover, applying the least squares method to the experimental result shown in Fig. 6, the correlations, which represent the variation in the peak heat flux in the solutal Marangoni condensation characteristic curve due to the concentration of non-condensable gas under the present experimental conditions, can be given as follows:

$$q_{\text{max}} = a_1 + a_2 \ln(C_e \times 10^3)$$

$$a_1 = 1872.2 + 6452.5C_e - 58634.9C_e^2 + 120699.1C_e^3 - 78304.1C_e^4$$

$$a_2 = -168.4 - 445.5C_e + 3960.3C_e^2 - 5175.5C_e^3$$

The calculation results obtained via Eq. (1), represented by the solid line in Fig. 6, corresponds well to the experimental results, and the maximum difference is approximately 6%.

Figure 7 indicates that the variation of the peak heat flux point has a tendency to shift to the side of the larger subcooling with the increase in the concentration of non-condensable gas. As mentioned above, since the effect of non-condensable gas becomes large with the rise in the heat transfer coefficient, the decrease in the heat flux should be greatest in the smaller subcooling side from the point of the peak heat flux. Thus, the point of the peak heat flux shifts to the side of the larger subcooling with the increase in concentration of non-condensable gas.

Figures 8 and 9 show the variations of the heat transfer coefficient and the surface subcooling in the peak heat transfer coefficient point with respect to the concentration of non-condensable gas. The larger the heat transfer coefficient, the larger the rate of decrease in the peak heat transfer coefficient due to the existence of the non-condensable gas, as shown by the ethanol concentrations of 0.01 and 0.45. The tendency to decrease is greatest at low non-condensable gas concentration, as is the case in Fig. 6. The straight lines in the figure are obtained using the least squares method for the experimental results. Under the present experimental conditions, the relationship between the peak heat transfer coefficient and the ethanol concentration of vapor mixture and the non-condensable gas concentration can be expressed as follows:

$$a_{\text{max}} = b_1 + b_2 \ln(C_e \times 10^3)$$

$$b_1 = 227.2 - 1107.5C_e + 4023.8C_e^2 - 7262.3C_e^3 + 4961.7C_e^4$$

$$b_2 = -13.4 + 44.8C_e - 41.0C_e^2$$

The result obtained by Eq. (4) differs from the experimental value by less than about 9%.

Figure 9 shows that the point of the peak heat transfer coefficient shifts to the smaller subcooling side with the increase in concentration of non-condensable gas for all the ethanol concentrations of the vapor mixture except...
Fig. 8 Variation of peak heat transfer coefficient

C_e = 0.45. In the vicinity of the point of the peak heat transfer coefficient, since the heat flux in the smaller subcooling side is smaller than that in the larger subcooling side, the rate of decrease of the heat transfer coefficient due to the existence of non-condensable gas is larger on the larger subcooling side, and the peak heat transfer coefficient shifts to the smaller subcooling side with the increase in concentration of non-condensable gas.

Moreover, in the case of the higher ethanol concentration of vapor mixture, such as C_e = 0.45, since the diffusion resistance in the vapor layer is large and the slope of the heat flux characteristic curve around the point of the peak heat transfer coefficient is small, the above-described effect does not appear easily.

4. Conclusions

Present paper examined the effect of non-condensable gas on the solutal Marangoni condensation of water-ethanol mixture that as the strong candidate of the working fluid to generate power by using a middle-low temperature heat source. The results are summarized as follows:

(1) The effect of the non-condensable gas on the solutal Marangoni condensation heat transfer had different characteristics in different domains of the condensation characteristic curve. That is, the effect of the non-condensable gas was slight in the domains controlled by the diffusion resistance of the vapor side and the filmwise condensation, but was remarkable in the domain controlled by the dropwise condensation.

(2) The peak heat flux and the peak heat transfer coefficient decreased greatly with the increase in concentration of the non-condensable gas. In particular, the decrease is most remarkable at low ethanol concentration and low non-condensable gas concentration, which provide good heat transfer performance.

References