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Experimental investigation of local nucleate boiling heat transfer and mixing ratio on copper surface about mixture R 32 / R 1234ze(E)

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Abstract

In this study, the heat transfer coefficients of R 32 and R 1234ze(E) were measured, respectively. In order to mixing affect, the heat transfer coefficient and mass ratio were measured and analyzed by changing the mixture mass ratio of the R 32 / R 1234ze(E) from 3 to 100 kW/m^2 heat flux. By attaching a thermocouple directly to the copper boiling surface, raw data were successfully measured without obtaining the surface temperature by a calculation formula. The mass fraction on the heating surface were also analyzed by gas chromatography. The above methods have made it possible to acquire data with high accuracy. The heat transfer coefficient was decreased for the zeotropic refrigerant mixtures compared to the pure refrigerants, specifically, the data of refrigerant mixture R 32 / R 1234ze(E) with a mass ratio of 0.2/0.8 showed the minimum value. The variation of the mass ratio near the heating surface that was not observed for the near-azeotropic refrigerant mixture occurred for the zeotropic refrigerant. In zeotropic mixtures, it was clear that the change in properties occurred in the boiling region.

Keywords: Nucleate Pool boiling, Local heat transfer coefficients, Mixture, Refrigerant, HFO

Introduction

1. Introduction

Currently, one of the measures to cope with global warming is the development of a refrigerant with a low GWP for use in refrigeration air conditioner. In addition, the Kigali amendment to the Montreal Protocol, agreed upon in 2016 and issued in 2019, restricted the production and consumption of HFC-based refrigerants. Therefore, development and use of natural refrigerants such as olefin-based low-GWP refrigerants and natural refrigerants using CO_2 and NH_3 as new alternative refrigerants have been promoted. However, due to flammability, toxicity, and reduced efficiency, some proposed new alternative refrigerants for use in refrigeration air conditioner units have not been determined at this stage[1]. New refrigerant mixtures of HFCs and olefin-based refrigerants are expected to be developed to solve this problem.

On the other hand, the phase change heat transfer equation is necessary for the optimal design of the heat exchanger of a refrigeration and air-conditioning equipment. There are various correlations, but they are limited due to their dependence on the diameter, the shape of the pipe and the type of refrigerant used. In actual phase change flow studies of existing refrigerant mixtures, boiling and condensation heat transfer and pressure drop in the tubes are obtained by changing the mixing ratio[2-9]. Pool boiling of refrigerant mixture has also

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been studied from various viewpoints[10-13]. However, even if the mixing ratio of the system is known, the local properties where pressure drop and heat transfer occur remain unknown.

The purpose of this study is to measure the local physical properties by using an experimental apparatus of nucleate pool boiling heat transfer and to enable the calculation of local physical properties from the mixing ratios of the location where thermal physical phenomena occur. Ultimately, this method will enable us to treat complex refrigerant mixtures, which are not dependent on tube size or refrigerant, as a single refrigerant by simply using a conversion formula from system properties to local physical properties. In this study, as an initial step, the nucleate pool boiling heat transfer and phase of zeotropic mixture R 32 / R 1234ze(E) on a circular copper block were investigated and observed. Moreover, Gas chromatography was used to analyze the mass ratios of the boiling area of the refrigerant.

2. Experiment

2.1. Experimental apparatus and methods

A schematic diagram of the experimental apparatus used in this experiment is shown in Fig. 1. Refrigerants flowed through the port valves of System 2, passing through a solenoid valve, a check valve, a Coriolis flowmeter, and a needle valve, in that order, to the tank beyond valve 4. The Coriolis mass flowmeter, control system, and solenoid valve were synchronized, and the Coriolis mass flowmeter measured the mass flow rate, and when the mass flow rate reached the mass flow rate set by the control system, the solenoid valve automatically stopped the flow. Two thermostatic baths, one in the tank and the other in the test section, were used to transport the refrigerant using pressure fluctuations caused by temperature differences. The tanks were removable and weighed using digital measurements as the refrigerant was transported or recovered. Pressure sensors are installed in two locations to measure both in vapor and liquid. The mass flow rate of the lost refrigerant could be measured and confirmed by assembling a circuit to allow the refrigerant that was spilled when using gas chromatography to flow to the port valve in System 1. A vacuum pump was used to draw a vacuum throughout the entire apparatus before and after the experiment, and when the mixing mass ratio was changed, it was done outside the test section. After the experiment, refrigerants were disposed of in the refrigerant collection unit beyond valve 5.

Figures 2 and 3 show the test section of copper surface (diameter of 30 mm) and Copper block. Thermocouples were placed at seven locations: three on the copper surface, three in the copper block, and one in the liquid. Thermocouples in the copper block with metal grease were installed to measure the heat flux, and thermocouples on the copper surface were installed to measure the raw data directly, so it was expected to be measured with greater accuracy. Incidentally, all of the thermocouples used in this study were tested and were able to be measured with an accuracy of ±0.05°C.

Figure 4 shows a visualization of the nucleate pool boiling. The long bar in the center is a probe, which sucks up refrigerant and makes it possible to analyze the local mass ratio where boiling occurs. The distance between the probe tip and the copper surface is 6 mm. The wall superheat can be calculated from the saturation temperature measured by thermocouples in the liquid refrigerant and the wall temperature measured by thermocouples attached to the copper surface.

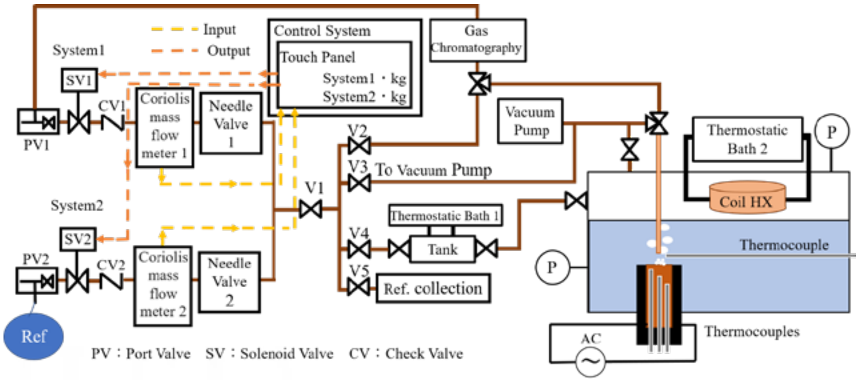

Fig. 1. Schematic diagram of experimental apparatus

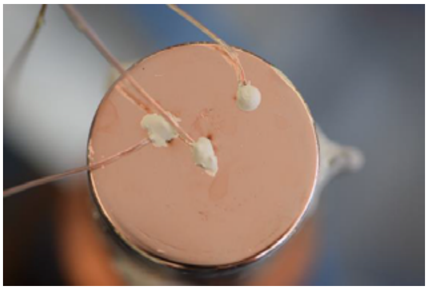

Fig. 2. Test section of copper surface

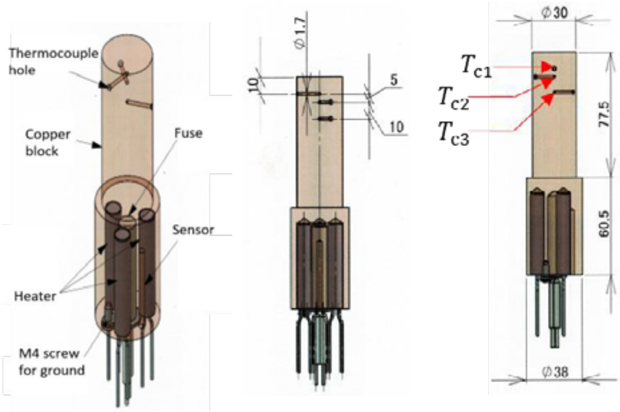

Fig. 3. Test section of copper block

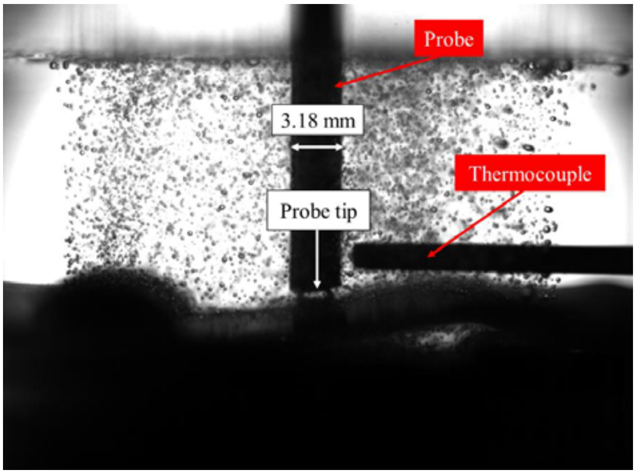

Fig. 4. Visualization of nucleate pool boiling (R 32 / R1234ze(E) (0.7/0.3), $q = 7$ kW/m^2)

2.2. Data reduction methods

The heat flux was calculated by Eq. (1).

$$q = \lambda \frac{dT}{dx} \tag{1}$$

where q and λ are the heat flux of the copper block [W/m^2] and the thermal conductivity of copper [W/mK], respectively. As for dT/dx, it is determined by the temperature gradient [K/m] calculated from the temperature T_{c1}, T_{c2} and T_{c3} measured by the first, second, and third thermocouples from the top inserted in the copper block and the displacement between each thermocouple, as shown in Fig. 5.

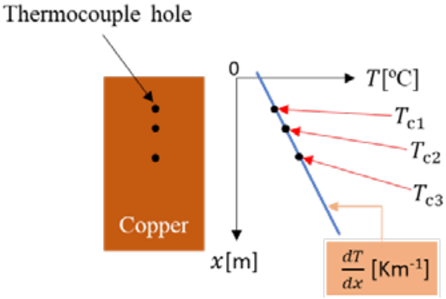

Fig. 5. How to determine heat flux

Using Equation (1), the local heat transfer coefficient is defined as follows:

$$\alpha = \frac{q}{(T_w - T_l)} \tag{2}$$

where α, T_w and T_l are local heat transfer coefficient of the copper surface [W/m^{2}K], the measured temperature of the thermocouple directly mounted on the copper surface [°C], and the temperature measured by the thermocouple in the liquid [°C], respectively. As described in section 2.1, raw data could be obtained by attaching the thermocouple directly to the copper surface, and therefore, more accurate measurements were expected.

When analyzing the local properties of a boiling region using gas chromatography, the mass ratio is calculated as follows:

$$W_{R\,32} = \frac{\frac{w_{R\,32}}{S_{R\,32}} S'_{R\,32}}{\frac{w_{R\,32}}{S_{R\,32}} S'_{R\,32} + \frac{w_{R\,1234ze(E)}}{S_{R\,1234ze(E)}} S'_{R\,1234ze(E)}} \tag{3}$$

$$W_{R\,1234ze(E)} = \frac{\frac{w_{R\,1234ze(E)}}{S_{R\,1234ze(E)}} S'_{R\,1234ze(E)}}{\frac{w_{R\,32}}{S_{R\,32}} S'_{R\,32} + \frac{w_{R\,1234ze(E)}}{S_{R\,1234ze(E)}} S'_{R\,1234ze(E)}} \tag{4}$$

where w and S are mass ratio and peak area determined by gas chromatography before boiling. W and S' are mass ratio and peak area determined by gas chromatography while boiling in optional heat flux. The peak area is automatically analyzed and shown by gas chromatography.

2.3. Investigation of soundness of the experimental equipment

In order to confirm the soundness of the experimental equipment used in this study, a comparison of the experimental data for refrigerant R 32 and R410A with the equation of Jung et al.[14] is shown in Fig. 6. The results were able to predict the experimental data within 8.2% mean deviation and 9.2% standard deviation. These results provide relatively accurate data that will enable reliable measurements of the heat transfer coefficients for any unknown refrigerant from now on. All properties were obtained from REFPROP 10.0 when using the Jung et al.'s correlation.

Figure 7 shows the results of measuring the mass ratio of the R 32 component of R 410A for each heat flux. Since R 410A is a near-azeotropic refrigerant mixture, it was confirmed that the physical properties near the heat transfer surface didn't change during boiling. On the contrary, different mass ratios were revealed to cause changes in local physical properties.

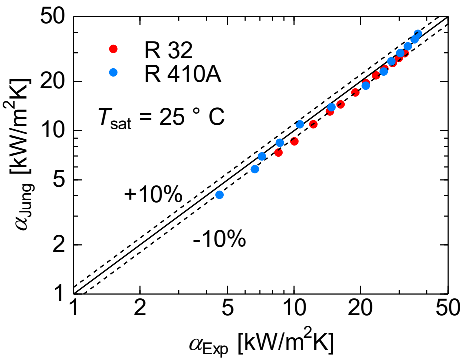

Fig. 6. Comparison of experimental values of R 32 and R 410A with Jung et al.'s correlation

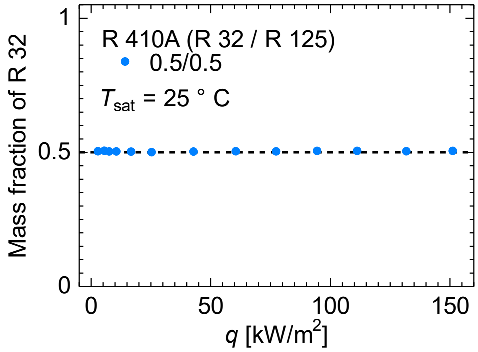

Fig. 7. Mass fraction of R 32 of R 410A

3. Results

In this study, local heat transfer coefficient measurements of pure refrigerants R 32 and R 1234ze(E) and local heat transfer coefficients and mass ratios of the refrigerant mixture R 32 / R 1234ze(E), varying the mixture mass ratio, were measured under the experimental conditions of saturation temperature of 25°C and heat flux of 3 to 100 kW/m^2.

3.1. Local heat transfer coefficients of each refrigerant

Figure 8 shows R 32, R 1234ze(E) and the refrigerant mixture R 32 / R1234ze(E) as heat flux on the horizontal axis and heat transfer coefficient on the vertical axis. As reported by other researchers, a feature of the zeotropic mixtures was found to be a decrease in the amount of increase in heat transfer coefficient decreased with increasing heat flux[10,11]. The reduction in heat transfer coefficient in this zeotropic mixture has been attributed to mass transfer resistance caused by interdiffusion due to the concentration gradient of the mixed refrigerant[2,3,6,7,8,12]. Moreover, the heat transfer coefficient of the nucleate pool boiling of R 32 /

R1234ze(E) was found to be the lowest at a mixing mass ratio of 0.2/0.8. The results are similar to the report that the evaporative heat transfer coefficient was at a minimum value for the mass ratios of refrigerant mixture R 32 / R 1234ze(E) of 0.15/0.85, 0.20/0.80, and 0.25/0.75 for quality 0.2, 0.5, and 0.8, respectively, as shown in the Kondo et al.'s flow experiments[3] and the evaporative heat transfer coefficient was at a minimum value for the mass ratios of refrigerant mixture R 32 / R 1234ze(E) of 0.25/0.75 as shown in the Lee et al.'s flow experiments[4]. The reason why the refrigerant mixture R 32 / R 1234ze(E) of 0.2/0.8 was the lowest heat transfer coefficient will be the subject of future research.

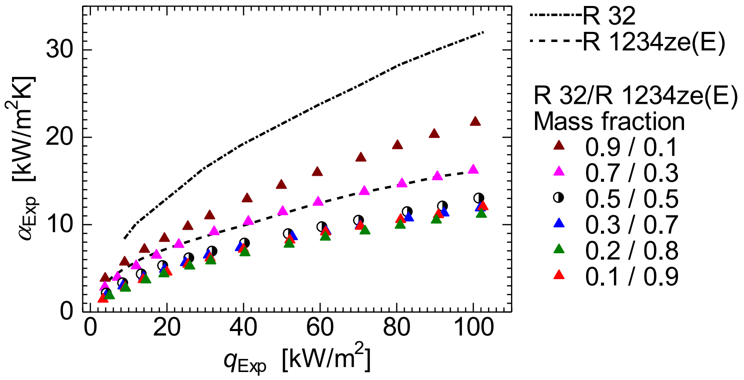

Fig. 8. Local heat transfer coefficients of R 32, R 1234ze(E) and R 32 / R 1234ze(E)

3.2. Mass fraction change of refrigerant mixture R 32 / R 1234ze(E)

Figure 9 shows the local mass fractions of nucleate pool boiling for R 32 and R 1234ze(E) during heat flux measurements for each mixture of R 32 / R 1234ze(E) with different mass ratios. The plot points represent the mean value of the mass ratio and the error bars indicate the range of concentrations that can be taken, i.e. the maximum and minimum values. When the mass ratio of the mixture was biased in favor of one of the refrigerants, there was relatively little variation, but when the mass ratio was close, significant variation was observed. In particular, for the refrigerant mixture R 32 / R1234ze(E) mass ratios of 0.5/0.5, there was an overall decrease in the mass ratio of R 32 and an increase in the mass ratio of R 1234ze(E). In addition, on the whole, in the case of a mass ratio of R 32 below 0.5, the local mass ratio of the boiling region tended to become decrease, and the mass ratio tended to become increase when the mass ratio was greater than 0.5. Comparing the results of Figs. 6 and 8, it was confirmed that the zeotropic refrigerant mixture caused a remarkable change in properties near the heat transfer surface. In addition to the mass transfer resistance, this change in physical properties may have a marked effect on the heat transfer coefficients of an azeotropic mixture.

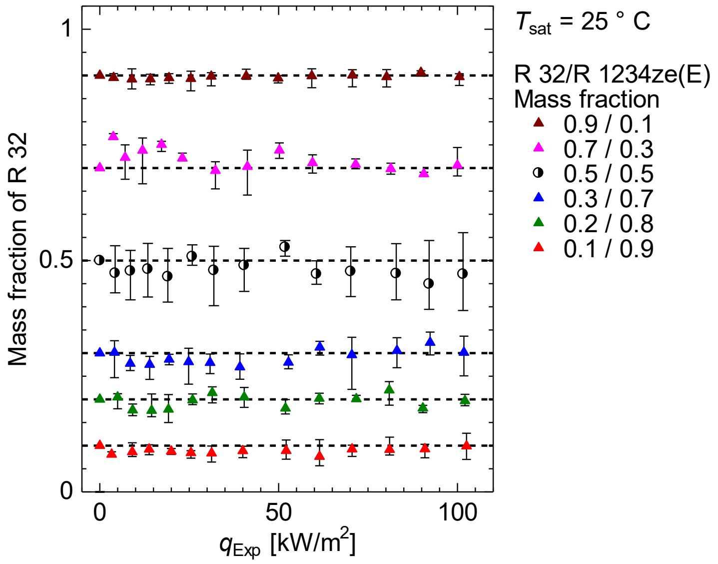

Fig. 9. Mass fraction of R 32 of R 32 / R 1234ze(E)

4. Conclusions

This study measured the pool boiling heat transfer coefficient for R 32, R 1234ze(E) and refrigerant mixture R 32 / R 1234ze(E) and the mass ratio near the heating copper surface for R 32 / R 1234ze(E) under experimental conditions of 25 °C saturation temperature and heat flux from 3 to 100 kW/m^2. Based on the results of this experiment, the following conclusions can be drawn.

1. For all refrigerants, the increase in heat transfer coefficient decreased as the heat flux increased, but for the zeotropic mixtures, the increase was significantly less. Especially, the heat transfer coefficient of the refrigerant mixture R 32 / R 1234ze(E) with a mass ratio of 0.2/0.8 was minimal.
2. In case of a mass ratio of 0.5/0.5 for the refrigerant mixture R 32 / R 1234ze(E), there was a large variation in the mass ratio near the heating surface and a noticeable decrease in the mass ratio of R 32.
3. The variation of the mass ratio near the heating surface that was not observed for the near-azeotropic refrigerant mixture occurred for the zeotropic refrigerant. In zeotropic mixtures, it was clear that the change in properties occurred in the boiling region.

Since there is little information on the local boiling properties of azeotropic refrigerant mixtures, more detailed investigation and further research are needed. We will develop our discussion and research based on these results and conclusions in the future.

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Nomenclature

dT/dx	Temperature gradient, K/m
q	heat flux, W/m^2
S	peak area determined by gas chromatography before boiling
S'	peak area determined by gas chromatography while boiling in optional heat flux
T_{c1}	temperatures measured at the first point from the top of the thermocouple inserted in the copper block, °C
T_{c2}	the temperatures measured at the second, °C
T_{c3}	the temperatures measured at the third, °C
T_l	liquid temperature, °C
T_w	wall temperature, °C
w	mass ratio before boiling
W	mass ratio while boiling in optional heat flux.
α	heat transfer coefficient, W/m^{2}K
λ	thermal conductivity, W/mK

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