Experimental investigation on pool boiling heat transfer of pure refrigerants and binary mixtures

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Heat transfer coefficients in nucleate boiling on a smooth flat surface were measured for pure fluids of R-134a, propane, isobutane and their binary mixtures at different pressure from 0.1 to 0.6 MPa. A wide range of heat flux and mixture concentrations were covered in the experiment. The influences of pressure and heat flux on the heat transfer coefficient for different pure fluids was studied. Isobutane and propane were used to make up binary mixtures. Compared to the pure components, binary mixtures showed lower heat transfer coefficients. This reduction was more pronounced as heat flux was increased.

INTRODUCTION

Heat transfer performance is one of the important factors for the efficiency of refrigeration applications. Therefore, it is necessary to know the mechanism of heat transfer in the whole refrigeration system. Extensive studies of the boiling heat transfer of pure refrigerant have been made. And many generalized correlations for predicting the coefficients have been proposed, which can be applicable to various substances[1]. Boiling behavior of binary mixtures is more complex than that of pure refrigerants, because it is dependent upon many combinations of substances and their liquid-vapor equilibrium curves. So the study of binary systems is much more tedious due to the large number of experiments required to cover the whole composition range [2]. No complete set of data was published where the Heat Transfer Coefficient (HTC) are presented as a function of mixture concentration and heat flux.

The object of this study is to measure heat transfer coefficient in nucleate boiling of pure fluids and their binary mixtures. Special emphasis is laid on the question, how the influence of the heat flux and pressure on the heat transfer coefficient is predicted at different saturation pressures. Several pool boiling heat transfer correlations for pure refrigerants will be compared, and a new correlation will be proposed based on the experimental data. Mixture concentrations are fully covered and heat flux also varied for a wide range of nucleate boiling. Based on the measured data the mixture effects on boiling heat transfer coefficients will be discussed.

EXPERIMENTAL APPARATUS

Figure 1 shows the schematics of experimental apparatus used in the present measurements. It consists of a boiling vessel, a refrigerant tank and a liquid nitrogen condensing system, an AC regulator and a data acquisition system. The boiling vessel is a hollow vertical tube of stainless steel with an inner diameter of 151 mm and a height of 300 mm. Boiling takes place on the upper end of a copper cylinder, 25 mm in diameter, which is fixed on the bottom of boiling vessel. Heat flux is supplied by a loop heater intertwined at the bottom of copper cylinder. And different power can be obtained by adjusting the AC regulator.

Nine platinum resistance thermometers were installed in the boiling vessel at four different depths from the top to end. The boiling surface temperature and heat flux were determined from measured copper cylinder temperatures assuming one-dimensional heat conduction along the copper cylinder. Axial temperature distributions at the center and at a half radius of the copper cylinder agreed well within measurement errors, conforming one-dimensional heat flow and negligible heat loss from the side of cylinder. One thermometer was set in the liquid pool and another one in the vapor in equilibrium with it. These liquid and vapor temperatures conform the system being maintained at the saturation state during the experiments. And the internal pressure of boiling vessel was measured by a pressure transducer. The boiling vessel and heating unit were well insulated inside the stainless vacuum chamber by a vacuum pump. Electrical signals from the platinum resistance thermometers were processed by a data acquisition system (a 22 bit Model 2700 Keithley Multimeter with 40 channels).

Mixture supplied to the boiling vessel was prepared by mixing pure fluids on a weight base. Sampling liquid and sampling vapor were extracted for measurement of their composition by a gas chromatograph. The measured values agreed within ± 0.01 accuracy with the prepared concentrations. The repeatability of the experiment was always within 5% of the measurement error.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Pure refrigerants

In this paper, pure refrigerant R134a was used to verify the experimental apparatus. Measured heat transfer coefficients of R-134a were compared with correlations by Nishikawa et al. [2] and by Fujita [3], which run as:

$$\alpha = \frac{31.4 P_c^{1/5}}{M^{1/10} T_c^{9/10}} (8R_p)^{0.2(1-P/P_c)} \frac{(P/P_c)^{0.23}}{[1-0.99(P/P_c)]^{0.9}} q^{4/5} \tag{1}$$

where M is average molecular weight, P_c and T_c is critical pressure and density, and $R_p = 0.4\mu m$.

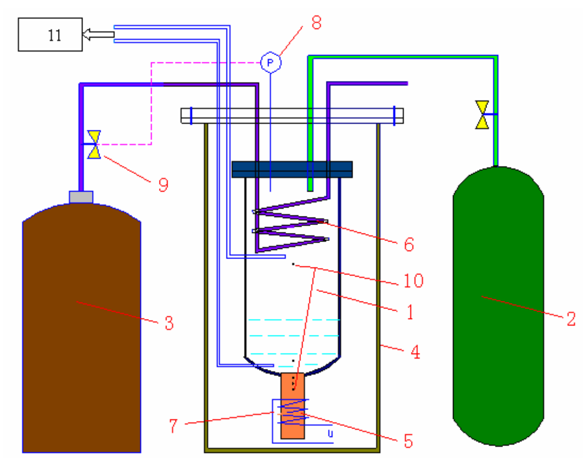
$$\alpha = 1.21 q^{0.83} \tag{2}$$

Figure 2 shows the comparison of experimental results and the correlations from references for R-134a. The present measured heat transfer coefficients agree well with the predication of Nishikawa et al. and Fujita correlations. Therefore the experimental apparatus and experimental method were found appropriate in performing other pure refrigerants and their binary mixtures experiment.

Figure 3 shows the heat transfer coefficient of pure refrigerant propane at 0.5 MPa. The heat transfer coefficients agreed well with Nishikawa et al. correlation. And the experimental data are very close to the heat transfer correlation of literature [4]. A correlation with a simple expression was also obtained from this experimental measurement, which is expressed as:

$$\alpha = 4.84 \cdot q^{0.73} \tag{3}$$

Figure 4 is the comparison of heat transfer coefficients between R-134a and isobutane at 0.5MPa. It



1. boiling vessel 2. refrigerants tank
3. liquid nitrogen cryostat 4. vacuum chamber
5. copper cylinder 6. condenser
7. electric heater 8. pressure transducer
9. electric-magnetic valve
10. platinum resistance thermometers
11. gas chromatograph instrument

Figure1 Experimental Apparatus

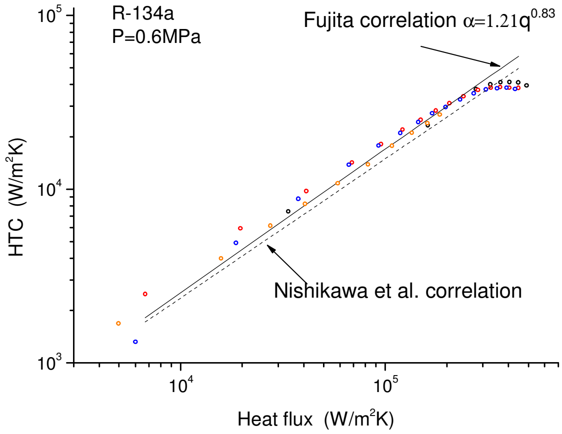


Figure 2 Heat transfer coefficient of pure fluid R-134a

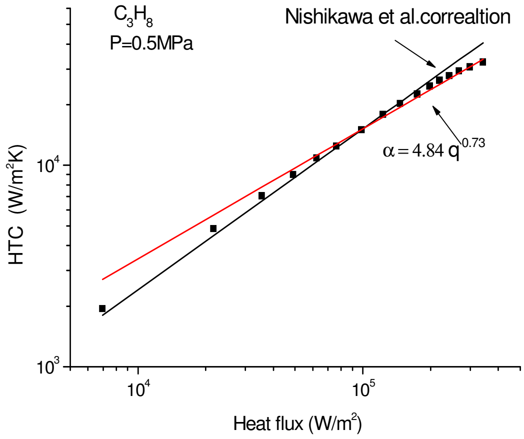


Figure 3 Heat transfer coefficient of pure fluid propane

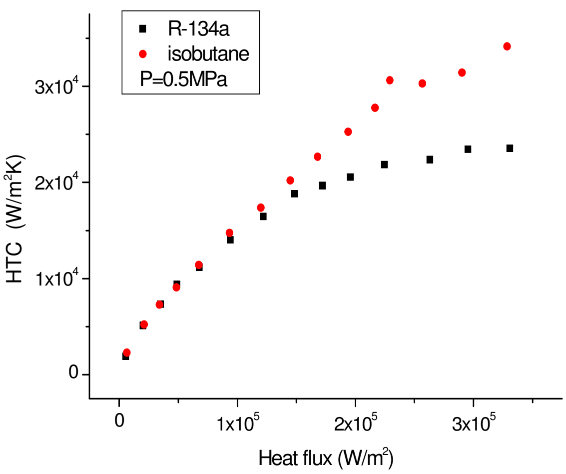


Figure 4 The comparison between R-134a and isobutane

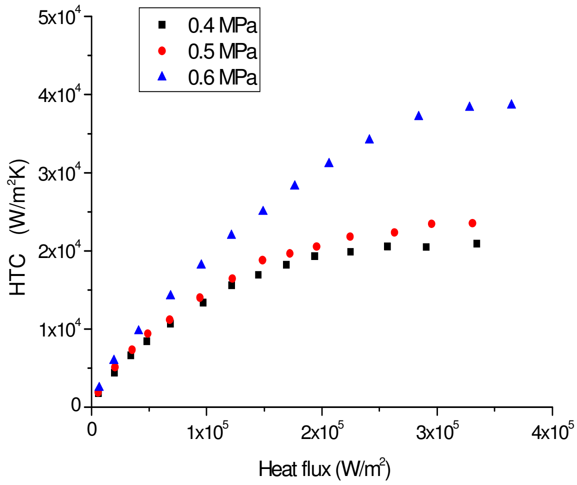


Figure 5 The comparison for R-134a at different pressures

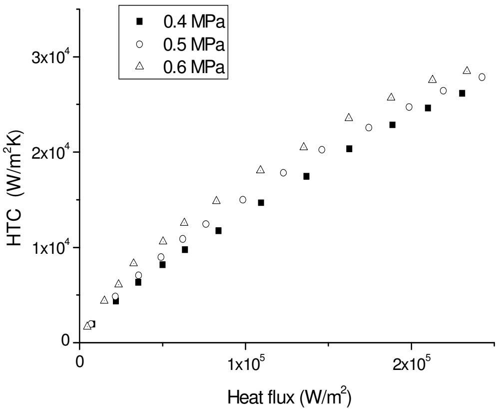


Figure 6 The comparison for propane at different pressure

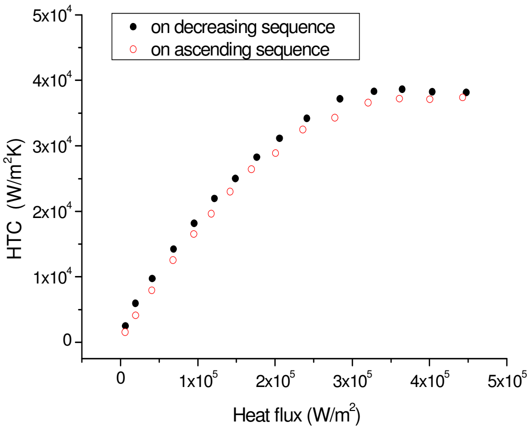


Figure 7 The hysteresis effect for R-134a

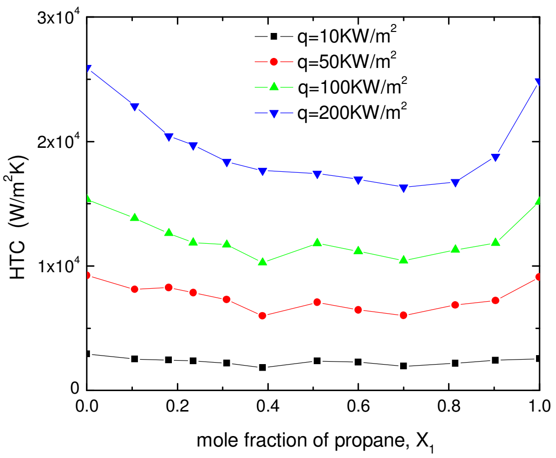


Figure 8 HTC of binary mixture propane/isobutane

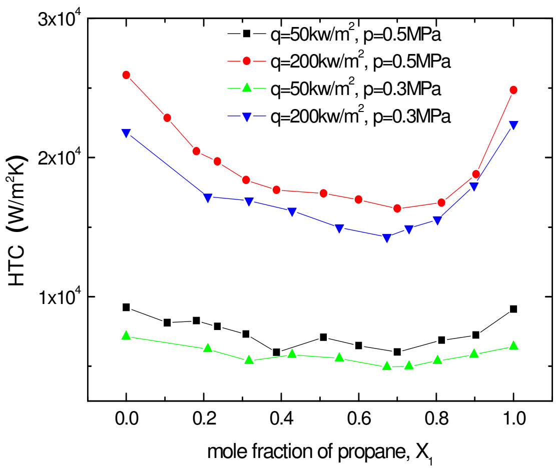


Figure 9 HTC of propane/isobutane at different pressures

is shown that the heat transfer coefficient of isobutane is higher than that of R-134a. And the trend become bigger as the heat flux increases.

Figure 5 shows the heat transfer coefficient curve of R-134a at different pressures from 0.4 MPa to 0.6 MPa, and Figure 6 shows the results of pure fluid propane at the same conditions. From the HTC curve, when the pressure increases, heat transfer coefficient of R-134a will enhance accordingly. And it is more distinct at higher pressure. But for pure fluid propane, it becomes less sensitive to the change of pressure.

Figure 7 shows the experimental data on ascending sequence and decreasing sequence of heat flux. It can be noted that heat transfer coefficients on the decreasing sequence heating are higher than that on ascending sequence heating. In order to obtain the proper pool nucleate boiling data, decreasing sequence heating method should be adopted to avoid the effect of boiling hysteresis.

Binary mixtures

Figure 8 shows the measured heat transfer coefficients against the mixture concentration with heat flux as parameter for propane (X_1). As shown in Figure 8, heat transfer coefficient of binary mixture is reduced in an intermediate range of the mixture concentration. As the heat flux increases, the reduction becomes larger and the minima are more pronounced at a higher heat flux. In other words, the heat transfer coefficient of mixtures are significantly lower than those of single component substances and dramatically deteriorate in the vicinity of single component substances, reaching their lowest values in the range of $0.3<X_1<0.7$ in which the coefficients are independent of the concentration. There are two reasons. One is the change of physical and transport property for binary mixture. The other is the mass diffusion effect. And the latter one is mostly the main reason on pool nucleate boiling. One important parameter required to characterize the mixture is the boiling range, that is dew-point temperature minus the bubble-point temperature for the bulk liquid mixture. Boiling range has a large influence on pool boiling heat transfer, so many heat transfer correlations include it to simulate pool nucleate boiling.

Figure 9 shows the boiling curve of binary mixture of propane and isobutane at different pressure. It is explained that the effect of pressure on heat transfer coefficient tends to be smaller in the mixtures than in the single component substances.

CONCLUSIONS

An experimental apparatus is designed and built to investigate pool boiling heat transfer characteristics for pure refrigerants and their binary mixtures. Experimental data are obtained for pure fluid R-134a, propane, isobutane and binary mixture of propane and isobutane. Based on the present measured data, pressure, heat flux and different refrigerants are studied as influencing factors of pool boiling heat transfer. Heat transfer reduction is found in binary mixtures due to the mixture effects. More binary mixtures and ternary mixtures will be investigated and new heat transfer correlations will be developed according to the experimental data in future.

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