論文の内容の要旨

Condensation Heat Transfer of Low-GWP Refrigerant Mixtures inside Horizontal Smooth Tubes

（水平平滑管内における低 GWP 混合冷媒の凝縮熱伝達に関する研究）

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1 Introduction

Increasing concerns regarding the environment have resulted in the evolution of refrigerants from CFCs, and HCFCs, to HFCs in developed countries. Although HFC refrigerants have no ozone depletion potential (ODP), many of them have a relatively high global warming potential (GWP). For example, R134a, having a GWP of 1300, is used extensively in automobile air conditioners (ACs).

R1234yf was jointly developed by Honeywell and DuPont to be a promising candidate for use in mobile air conditioners owing to its low GWP of 4 and thermophysical properties similar to those of R134a. It has been proposed as a promising alternative refrigerant applied in MACs. They have almost same molecular weight and normal boiling point, so the heat transfer coefficients of both fluids are almost same. However, the latent of R1234yf is almost 20％of that of R134a. When operating in MACS, lower latent heat leads to large mass flow rate and large pressure drop, then the COP of AC system become lower.

In order to increasing COP, another fluid can be mixed with R1234fy is being considered, for example R32. The COP of mixed refrigerant with R1234yf can become higher than of pure R1234yf. But mixture’s GWP usually becomes larger than that of pure R1234yf, because the GWP of R32 is several ten times higher than that of R32, for example. Therefore, low GWP and high COP will be a trade off problem.

In the present research, condensation heat transfer characteristics of HFO1234yf were experimentally studies, and the results were compared to those of R134a and R32. The effects of various parameters, including mass flux, vapor quality, saturation temperature and thermophysical properties on the condensation heat transfer performance were discussed. And the experimental heat transfer coefficient was compared with four heat transfer coefficient correlations.

Then, the condensation heat transfer characteristics of nonazeotropic mixtures R1234yf and R32 inside a horizontal smooth tube (inner diameter 2mm and 4 mm) were experimentally studied. The measured local heat transfer coefficients were compared with that of pure refrigerant and evaluated by a prediction model for the forced convective condensation heat transfer characteristics of nonazeotropic refrigerant mixtures to predict the heat transfer deterioration by taking into consideration the mass transfers at both the vapor side and liquid side.

2 Experiments

The refrigerant loop comprises a test section, two sight glasses, a post-condenser, an accumulator, an expansion valve, a filter, a liquid pump, a mass flow meter, an evaporator, and three water baths. The saturation temperature and pressure of the test section is controlled by the opening of the expansion valve, and one water bath are used to adjust the inlet superheating of test section, one provides cooling water to test section, and one subcool the refrigerant flowing out of the test section, respectively.

The test condensation tube is made of copper with an inner diameter of 4 mm and 2mm and an overall length of 2.25 m and 1.15 m. It is divided into five sub-sections; with each sub-section has an effective length of 0.45 m and 0.23 m. All the sub-sections were cooled separately by the cooling water and the average condensation heat transfer coefficient of each sub-section was measured. The refrigerant flows inside the copper tube, and the cooling water flows in reverse direction within annular region between the inner tube and outer tube. For each sub-section, the mass flow rate of the cooling water was controlled independently. In order to make average heat flux in each sub-section is almost same, the inlet temperature and mass flow rate of cooling water were controlled. The inlet and outlet temperatures of the cooling water were measured using platinum resistance thermometers. Nine T-type thermocouples were soldered at the outer surface of copper tube with an interval of 12.5 cm for ID 4mm and 7.5 cm for ID 2mm between thermocouples. To reduce the heat loss to the surroundings, the entire apparatus including the refrigerant loop and the coolant loop was heavily insulated.

The cooling water loop includes a re-circulating chiller, mass flow meters, filters, and flow rate controlling valves. The re-circulating chiller provides cooling water for each sub-section at the desired temperature. The temperatures at the inlet and outlet of each sub-section were measured using platinum resistance sensers. The cooling water flow rate of each sub-section was measured using a positive displacement flow meter attached to that path.

The experiment were conducted using refrigerant of R1234yf, R32, R134a, R1234yf/R32(0.77:0.23) and R1234yf/R32(0.48:0.52) with mass flux from 100 to 400 kg/m2s, vapor quality from 0.9-0.1, and at saturation temperature from 40 ºC, 45 ºC, 50 ºC within ID4mm and ID2mm.

3 Discussion

3.1 Pure Refrigerant

The condensation experiments were carried out in a horizontal tube with an inner diameter of 4 mm and 2mm at mass fluxes ranging from 100 kg m^{-2} s^{-1} to 400 kg m^{-2} s^{-1} and saturation temperatures of 40 ºC, 45 ºC, and 50 ºC using R1234yf, R134a, and R32 as the working fluid. The main conclusions of this part are as follows:

1. The effects of mass flux and vapor quality on the heat transfer coefficient are primarily observed in the shear-force dominated flow regimes when the mass flux is high or the vapor quality is high.

2. The effects of thermophysical properties on the heat transfer coefficient at different saturations temperature using different refrigerants were analyzed. The results show that the thermal conductivity, density ratio and viscosity ratio play an important role in the variation of the heat transfer coefficient.

3. Flow patterns were also observed to help in the analysis of the changing tendency of the heat transfer coefficient, and the tendencies were compared with the flow pattern map. The flow pattern map proposed by Tandon et al (1982) could predict the annular flow well.

4. The Haraguchi correlation for predicting the local frictional pressure drop can predict the measured pressure drop best compared to the Lockhart-Martinelli correlation and Huang correlation.

5. The experimental heat transfer coefficient within ID4mm was compared with four heat transfer coefficient correlations. The results showed that the Haraguchi correlation agrees reasonably with the experimental data values, with a mean deviation of 10.8%.

6. The experimental heat transfer coefficient within ID2mm was compared with Haraguchi and Shah heat transfer correlations. The results showed that the Haraguchi and Shah correlation agrees with the experimental data values with a mean deviation of 40.1% and 15.2%.

7. When comparing the heat transfer coefficient within ID4mm and 2mm, here shows the influence of tube diameter on heat transfer coefficient have different results by using different pure refrigerants R1234yf, R134a and R32. With decrease tube diameter, the influence of surface tension on heat transfer coefficient show more obviously. But if the surface tension influence is merit or demerit depends on not only tube diameter but the thermophysical properties, so, the comprehensive consideration is necessary.

3.2 Refrigerant Mixtures

The experiments and calculation of condensation heat transfer were carried out in a horizontal tube with an inner diameter of 4 mm and 2mm at mass fluxes ranging from 100 kg m^{-2} s^{-1} to 400 kg m^{-2} s^{-1} using R1234yf/R32 at mass fraction of 0.77:0.23 and 0.55:0.45. The main conclusions of this part are as follows:

1. The heat transfer coefficient of refrigerant mixtures increases with an increase in mass flux and decrease with decrease in vapor quality no matter how much is the mass flux due to the influence of mass transfer.
2. The heat transfer coefficient of R1234yf /R32 (0.5:0.5) shows higher than that of R1234yf /R32 (0.77:0.23) with mass flux from 100 to 400 kg/m^2s because the more mass fraction of R32 included.

3. When comparing the heat transfer coefficient of R1234yf/R32 (0.77:0.23) and (0.5:0.5)within ID2mm and ID4mm at saturation temperature of 40 ºC, with mass flux from 100 to 400 kg/m2s, the heat transfer coefficient is almost same. The inner diameter shows no effects on the heat transfer of refrigerant mixtures of R1234yf/R32.

4. The heat transfer coefficients of R1234yf are higher than that of refrigerant mixtures R1234yf/R32 (0.77:0.23), especially at low mass flux and at beginning of condensing where the mass transfer resistance is largest. As mass flux increasing and with condensing, mass transfer resistance decrease, heat transfer coefficients of refrigerant mixtures R1234yf/R32 (0.77:0.23) closer to that of R1234yf.

5. For refrigerant mixtures R1234yf/R32 at mass fraction of (0.5:0.5), even the heat transfer coefficients are lower than that of R1234yf at the beginning of condensing, along the tube when condenses, the heat transfer coefficients of R1234yf/R32 at mass fraction of (0.5:0.5) become higher gradually than that of R1234yf due to mass transfer resistance decreases. Moreover, with increasing mass flux, the heat transfer degradation of R1234yf/R32 at mass fraction of (0.5:0.5) decreases because the convective contribution to heat transfer when condensing become stronger than that at low mass flux.

6. The heat transfer degradation of R1234ze/R32 (0.75:0.25) is larger than that of R1234yf/R32 (0.77:0.23) mostly at almost same mass flux and vapor quality, because the temperature glide of R1234ze/R32 (0.75:0.25) is about 10 ºC that larger than that of R1234yf/R32 (0.77:0.23) is about 6.7 ºC.

7. The heat transfer degradation of R1234yf/R32 (0.77:0.23) is larger than that of R407c at almost same mass flux and vapor quality.

8. The heat transfer degradation of R1234yf/R32 is larger than that of R134a/R32 at almost same mass fraction, mass flux and vapor quality.

9. The calculated results of heat transfer coefficient with considering the mass transfer can reflect the tendency of heat transfer degradation which decreases with increasing the mass flux within ID4mm, with mean deviation of about 18.5% at mass fraction of 0.77:0.23(R1234yf/R32), and with mean deviation of about 16.1% at mass fraction of 0.48:0.52 (R1234yf/R32).

10. The calculated results of the effects of R32 composition on heat transfer coefficient shows that the heat transfer degradation at vapor quality 0.9 is obvious larger than that at other vapor qualities and decreases with increase in mass flux.

11. For calculation using physical model of refrigerant mixtures, the calculated results reflects the mass transfer influencing on the heat transfer，including the heat transfer degradation coefficient, variation of R32 mass fraction, Sherwood number，diffusion flux of R32 at vapor side and variation of mass transfer coefficient of vapor side.

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