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EXPERIMENTAL STUDY ON THE HEAT TRANSFER PERFORMANCE OF A ZEOTROPIC REFRIGERANT MIXTURE IN HORIZONTAL TUBES

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ABSTRACT

In the present study, the condensation and evaporation heat transfer performance of a zeotropic refrigerant mixture (HFC32/HFC125/HFC134a) inside horizontal tubes with smooth, grooved or cross-grooved inner surfaces was investigated experimentally. The cross-grooved tube showed the highest heat transfer coefficient for both condensation and evaporation with the zeotropic mixture. Its heat transfer coefficient was nearly three times as high as that of the smooth tube, and 20 to 40% higher than that of the grooved tube. Thus, the cross-grooved tube appears suitable for practical use in heat exchangers using zeotropic mixtures.

1. INTRODUCTION

In accordance with the regulations introduced at the 7th meeting of the parties to the Montreal Protocol, there will be a complete phase-out of HCFC22 by the end of 2020. Ternary zeotropic (i.e., non-azeotropic) mixtures are among the probable substitutes for HCFC22 and their heat transfer performance has been investigated by several researchers [1-3]. Goto et. al. have performed experiments on a binary zeotropic mixture (HFC32/HFC125) and reported that the condensation and evaporation heat transfer coefficients of zeotropic mixtures are both lower than those of HCFC22 regardless of the tube diameter. Ebisu & Torikoshi [2] investigated the heat transfer characteristics of binary (HFC32/HFC134a) and ternary (HFC32/HFC125/HFC134a) refrigerant mixtures with various compositions. They showed that the minimum heat transfer coefficient was attained at 25 to 30 wt% of HFC32 in the binary mixture, and that the heat transfer coefficients for ternary mixtures were lower than the values interpolated linearly between the results for HFC32/HFC134a (30/70 wt%) and HFC125. Zhang et. al. [3] theoretically predicted the heat transfer coefficients of the ternary mixture HFC32/HFC125/HFC134a (23/25/52 wt%) inside a smooth tube, and their results agreed with the experimental data within ±30%. Uchida et. al. [4] showed that the condensation heat transfer coefficients of the binary zeotropic mixture HFC32/HFC134a (30/70 wt%) are lower than those of pure refrigerants, especially in internally grooved tubes as compared with smooth ones. The decrease with the grooved tube was as much as 50%, while the smooth tube showed only a moderate drop (30%). All of these experimental and theoretical results demonstrate the low heat transfer performance of zeotropic refrigerant mixtures, and it appears that special treatment will be required to attain an adequate heat transfer performance if zeotropic refrigerant mixtures are to be used in practical heat exchangers.

The condensation and evaporation heat transfer performance of a zeotropic refrigerant mixture HFC32/HFC125/HFC134a (30/10/60 wt%) inside horizontal tubes with smooth, grooved or cross-grooved inner surfaces was investigated experimentally in this study. We also discuss the possibility of improving the evaporation and condensation heat transfer performance of zeotropic mixtures.

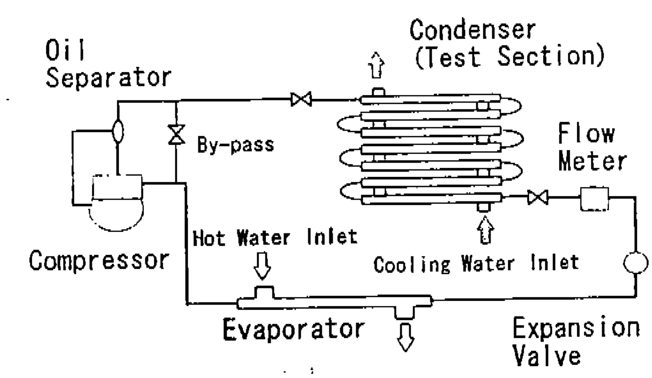
2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Condensation Experiment

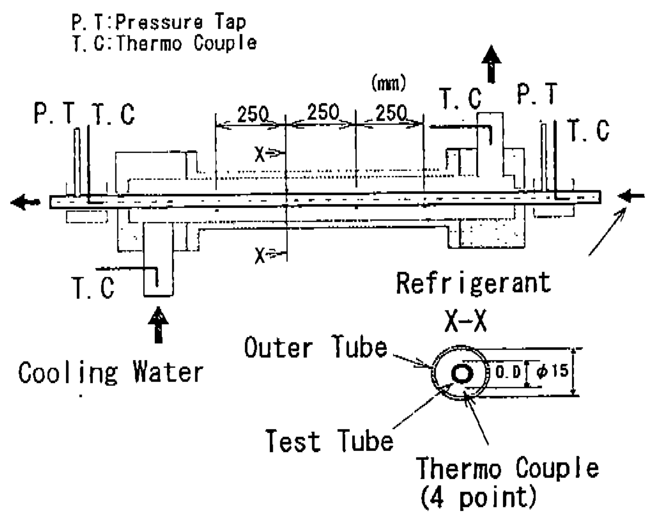
Figure 1 shows a schematic of the experimental setup for condensation. The main components of the apparatus are the compressor, oil separator, condenser, flow meter, expansion valve, and evaporator. The oil is removed by the oil separator from the superheated refrigerant vapor discharged from the compressor, and the refrigerant is completely condensed in the condenser (the test section). The test section is composed of seven units, each unit being a 1.09-m-long straight tube-in-tube counter-flow heat exchanger, and the cooling water flows between the inner and outer tubes. For each test section unit, shown in Fig. 1(b), the local pressure was measured at the inlet, while copper-constantan (C-C) thermocouples were soldered to the outer surface of the inner tube to measure the wall temperature at four circumferential × four longitudinal positions (16 locations for each test section unit). The vapor sample drawn at the compressor exit was analyzed by gas chromatography to check the refrigerant composition for each experimental run.

2.2 Evaporation Experiment

The experimental apparatus for evaporation is shown in Fig. 2. There are two pre-evaporators and one post-evaporator to control the quality of the refrigerant in the test section. The 0.6-m-long test tube is heated by a electric heater coiled around the tube. The wall temperature is measured by C-C thermocouples soldered at the exposed surface of the tube in between the heater coils. Pressure measuring taps are located 0.8 m apart at both sides of the test section. As in the condensation experiment, the oil is removed by the oil separator and the refrigerant composition is measured by sampling the vapor at the compressor exit.

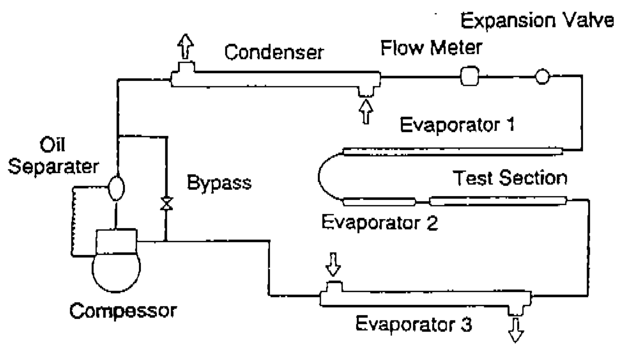


(a) Experimental Setup

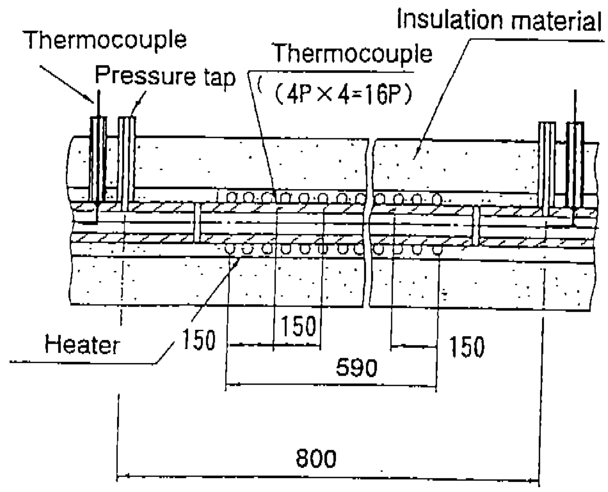


(b) Detail of the Test Section

Fig. 1 Experimental Apparatus for Condensation



(a) Experimental Setup



(b) Detail of the Test Section

Fig. 2 Experimental Apparatus for Evaporation

Table 1 Experimental Conditions

	Condensation	Evaporation
Test Refrigerant	HFC32/HFC125/HFC134a (30/10/60 wt%)	
Mass Flow Rate G	100 to 500 kg/m^{2}s	
Quality χ	0.0 to 1.0	0.1 to 0.9
Heat Flux q	2.3 to 37.2 kW/m^2	10.0 kW/m^2

2.3 Experimental Conditions

The experiments were performed within the parameters listed in Table 1. The mass flow rate was varied in the range G=100 to 500 kg/m^{2}s, The data was taken over the entire quality range for condensation, but only for χ=0.1 to 0.9 for evaporation. The geometries of the tested tubes are shown in Table 2. As can be seen from the table, the cross-grooved tube, which is a seam tube, has notches on the inner fins. The notches are intended to reduce the mass transfer resistance by stirring up the flow field.

The heat transfer coefficient h is defined as follows:

$$h = \frac{q}{(T_W - T_R)} \quad \cdots\cdots (1)$$

where q is the heat flux transported in the axial direction, and T_W and T_R denote the wall and refrigerant temperatures, respectively. The saturation temperature, calculated from the pressure and the enthalpy of the refrigerant, is used to determine the refrigerant temperature T_R. The heat flux during condensation was measured from the temperature difference and the flow rate of the cooling water. In the case of evaporation, the heat flux from the heater was kept at 10 kW/m^2.

Table 2 Detailed Dimensions of the Test Tubes

	Smooth	Grooved (Condensation / Evaporation)	Cross-grooved
Mean Inner Diameter d	6.4 mm	6.4 mm	6.1 mm
Outer Diameter d_o	8.0 mm	7.0 mm	7.03 mm
Fin Height f_h	—	0.163 / 0.2 mm	0.29 mm
Groove Helical Angle β	—	18 deg	19 deg
Number of Fins n	—	60 / 53	43
			

3. EXPERIMENTAL RESULTS

Figures 3 and 4, respectively, show the experimental results for the condensation and evaporation heat transfer coefficients. The cross-grooved tube showed the highest heat transfer coefficient with the zeotropic mixture. This coefficient was nearly three times as high as that of the smooth tube, and 20 to 40% higher than that of the grooved tube. However, this was not the case for evaporation of a pure refrigerant (HCFC22), as is shown in Fig. 5. The evaporation heat transfer coefficient of the cross-grooved tube was lower than that of the grooved tube, even though it had higher inner fins (cross-grooved: f_h =0.29 mm, grooved: f_h =0.2 mm). This indicates that the notches are effective only for the zeotropic refrigerant mixture during evaporation, possibly due to the stirring effect of the liquid phase, i.e., reduced composition variation in the liquid phase. The notches also had a favorable effect on the condensation of the zeotropic mixture. The results for grooved tubes with and

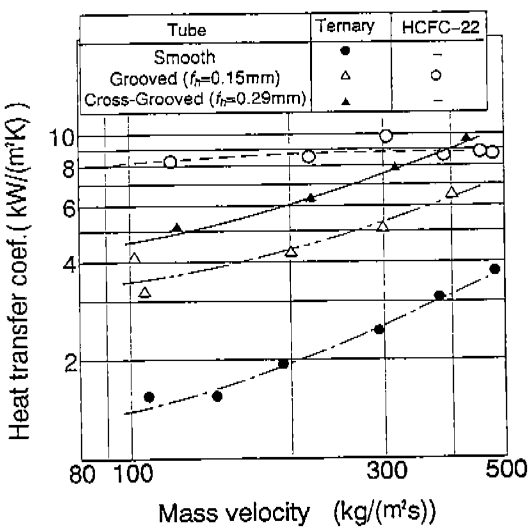


Fig. 3 Condensation Heat Transfer Coefficient

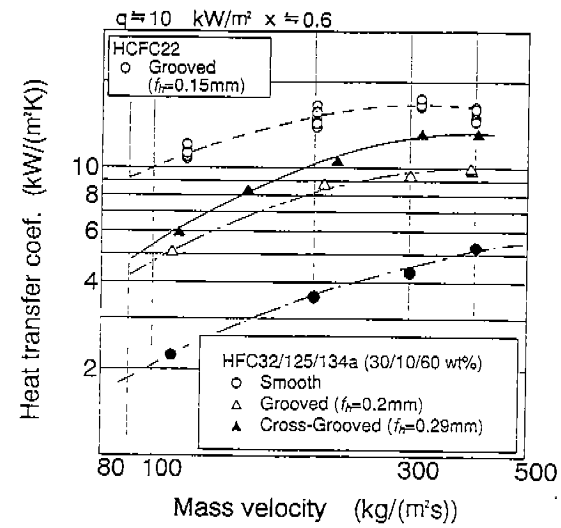


Fig. 4 Evaporation Heat Transfer Coefficient

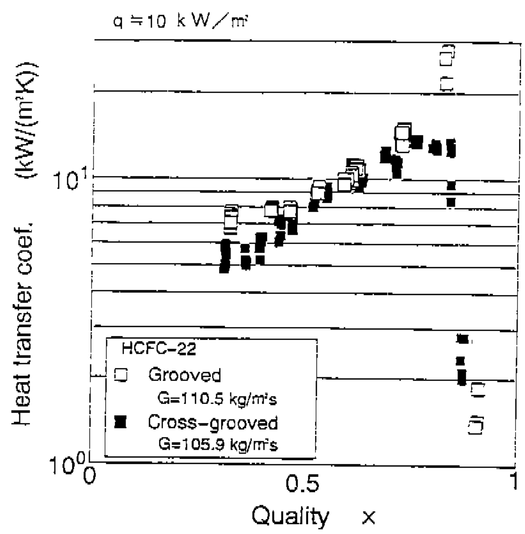


Fig. 5 Evaporation Heat Transfer Coefficient for HCFC22

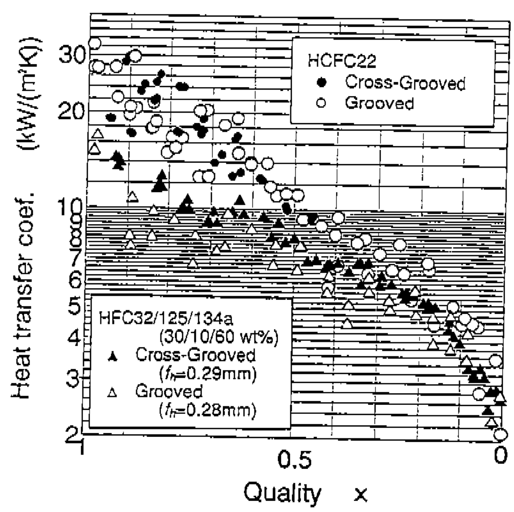


Fig. 6 Condensation Heat Transfer Coefficient of Tubes with and without Notches

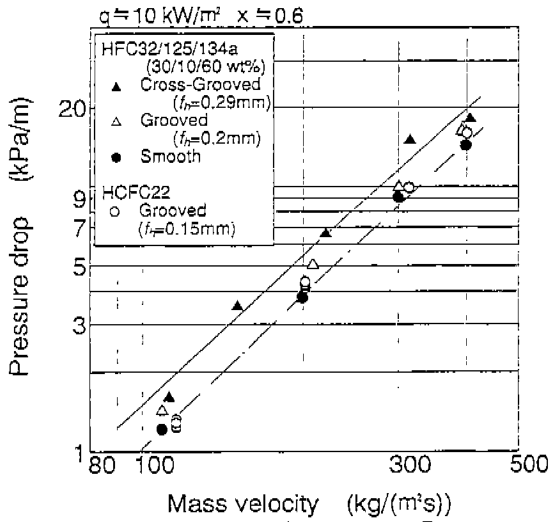


Fig. 7 Evaporation Pressure Drop

without notches are shown in Fig. 6. Note that both tubes had nearly the same inner surface configuration in this case. The tube with notches showed somewhat higher condensation heat transfer performance for the zeotropic mixture, although both tubes showed nearly the same results for HCFC22. In this case, the notches seem to have helped to stir the vapor phase as well, and thus enhanced the vapor phase mass transfer rate.

Unfortunately, as a consequence of stirring up the flow field, the cross-grooved tube showed the largest pressure drop during evaporation: its pressure drop is nearly 40% larger than that in the smooth tube (Fig. 7). However, with a zeotropic mixture, the enhanced heat transfer performance may compensate for the increase in pressure drop to some extent, since in-tube heat resistance may account for a relatively large proportion of the total heat transfer resistance. Also, the pressure drop is much larger when devices such as twisted tape or wire coils are inserted. Therefore, we continue to believe that cross-grooved tubes are suitable for practical use in heat exchangers using zeotropic mixtures.

4. CONCLUSIONS

Experiments were performed to investigate the condensation and evaporation heat transfer performance of a zeotropic refrigerant mixture (HFC32/HFC125/HFC134a) inside horizontal tubes with smooth, grooved, or cross-grooved inner surfaces. The cross-grooved tube showed the highest heat transfer coefficients for both condensation and evaporation with the zeotropic mixture. Its heat transfer coefficients were nearly three times as high as that of the smooth tube, and 20 to 40% higher than that of the grooved tube. Thus, the cross-grooved tube appears suitable for practical application in heat exchangers using zeotropic mixtures.

ACKNOWLEDGMENTS

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