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HEAT TRANSFER CHARACTERISTICS AND HEAT EXCHANGER PERFORMANCES FOR R407C USING HERRINGBONE HEAT TRANSFER TUBE

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ABSTRACT

The new advanced heat transfer tube called, "Herringbone Heat Transfer Tube", having a unique inner surface geometry, have been experimentally investigated with the aim to enhance the heat transfer and to improve the heat exchanger performance for R407C. Experimental examinations have been done to obtain the air-cooled heat transfer coefficient and pressure drop for R407C flowing inside the horizontal herringbone tube, and the data have been compared with those for the existing inner grooved tube. Both the air-cooled heat exchanger performances using the herringbone tube and the inner grooved tube have been compared as the practical examination for designing the heat exchanger using the herringbone tube. As the results of the experiments, the heat transfer coefficients for the herringbone tube have been verified to be much superior to the existing inner grooved tube, but the significant increase in heat transfer has been accomplished with an increase in pressure drop. The practical comparison of the heat exchanger performance showed that the evaporator performance have been improved only at the relatively high refrigerant flow rate, while the condenser performance using the herringbone tube have been better than that using the inner grooved tube for all the refrigerant flow rates.

NOMENCLATURES

D = diameter (m)
Q = heat capacity (kW)
T = temperature (K)
x = local vapor quality (-)
G = mass flux (kg/m^{2}s)
q = heat flux (W/m^2)
u = air velocity (m/s)

Greek Symbols

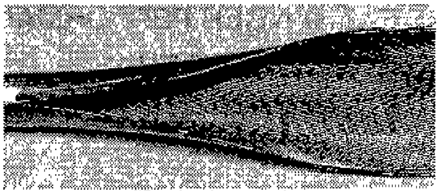
α = heat transfer coefficient (W/m^{2}K)
Δx = change in vapor quality (-)
ΔP = pressure drop (kPa/m)

Subscripts

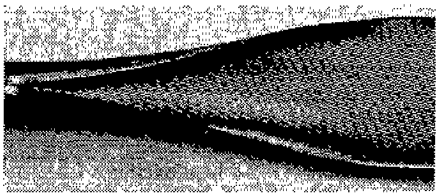
r = refrigerant
w = tube wall

INTRODUCTION

With respect to the evaporation/condensation heat transfer characteristics for R407C, which has been just employed as the alternative working fluid for R22 in the air-conditioning machines, several energetic heat transfer investigations have been performed for reliable engineering design of the air-cooled heat exchangers installed into the air-conditioning units. Consequently, it has been found that R407C introduces some heat transfer problems into practical use of air-conditioning units, that is, the degradation of heat transfer coefficients caused by the zeotropic characteristic of R407C. In the representative studies, Ebisu & Torikoshi (1994) have provided the experimental data on the evaporation/condensation heat transfer coefficients and pressure drops for R407C flowing inside a horizontal heat transfer tube. Their results demonstrated that the average evaporation and condensation heat transfer coefficients fell about 40% and 50% below those for the existing refrigerant R22, respectively. And the evaporation and condensation pressure drop for R407C was found to be even or larger than that for R22. Recently, Sundersan et al. (1994) and Uchida et al. (1996) have undertaken the experimental investigations on evaporation and condensation heat transfer characteristics for R407C inside a horizontal tube. Their experimental results showed the similar trends to Ebisu & Torikoshi (1994) that R407C had the significantly lower heat transfer coefficients than those for R22. Moreover, Ebisu et al. (1997) have also examined the effects of the lower heat transfer coefficients for R407C on the air-cooled heat exchanger performances. They obtained the experimental data that the heat exchanger performance for R407C was about 5 to 10% lower than those for R22 in both cooling and heating modes due to the degradation of the heat transfer coefficients of R407C. They suggested in their papers that the successful application of R407C as the alternative working fluid to the air-conditioning machines would require the evaporation/condensation heat transfer enhancement for R407C inside the heat transfer tube.

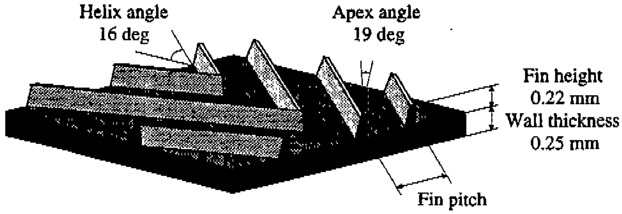


Herringbone tube

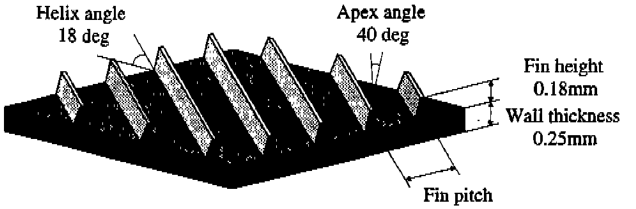


Inner grooved tube

Figure 1 Photos of tested tubes



Herringbone tube



Inner grooved tube

Figure 2 Geometries of tested tubes

The overall purposes of this study are to develop the heat transfer enhancement techniques and to improve the air-cooled heat exchanger performances for R407C. To fulfill these purposes, we are presenting the new heat transfer tube having the unique inner advanced surface, which is named "Herringbone heat transfer tube" in this study. Experiments have been done to provide the data of local evaporation/condensation heat transfer coefficients and pressure drops for R407C flowing inside the horizontal herringbone tube, and comparisons have been made for the data of the herringbone tube with those for the existing inner grooved tube. In addition to the heat transfer data, we have investigated the heat exchanger performance improved by using the herringbone heat transfer tube under the practical conditions of both evaporator and condenser operations of the air-conditioning machine.

EXPERIMENTS

Heat Transfer Tubes Tested

Figure 1 shows the photos of the herringbone heat transfer tube and the existing inner grooved tube. The existing inner grooved tube is routinely used in air-conditioning applications, and is conventionally made by forming a set of grooves inside a seamless smooth tube, while the herringbone tube is fabricated by embossing a flat strip of copper to form the desired herringbone geometry, thereafter the embossed strip is rolled into a round tube and axial seam is inductively welded. Figure 2 illustrates the detailed specifications of the tubes tested. The new herringbone tube has a pair of groove patterns like a herringbone inside a tube. As the fin height for the herringbone tube is much higher than the inner grooved tube, the increase in inside surface area compared to a smooth tube is attained to be 1.6 and 2.1 times for the inner grooved tube and the herringbone tube, respectively. The outer diameters D_o of both the tubes are 7.0mm.

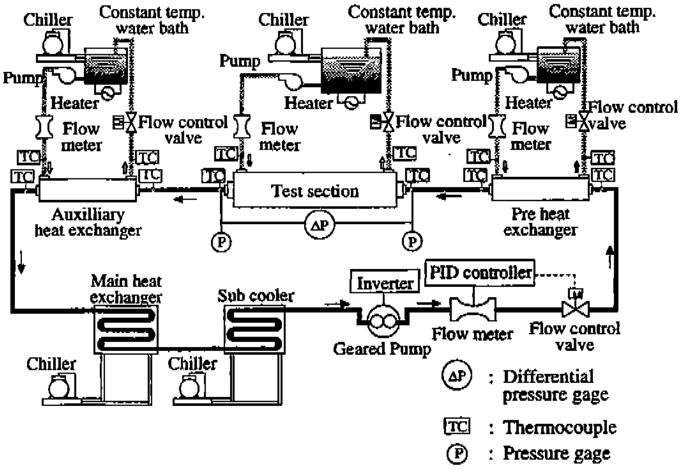


Figure 3 Experimental apparatus

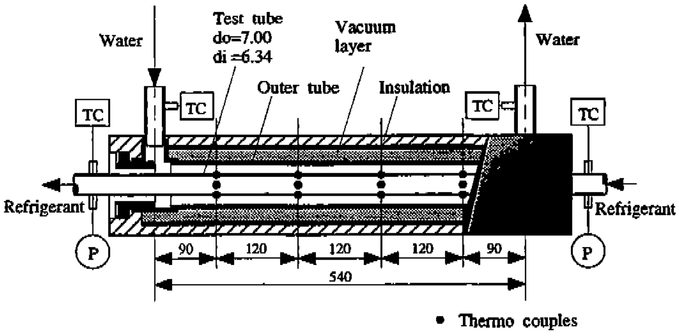


Figure 4 Test section

Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Figure 3. It mainly consists of a refrigerant loop and three independent water loops. The components of the refrigerant loop are a main heat exchanger, a subcooler, a circulating pump, a mass flow meter and in-a-line three heat exchangers. The large capacity of the main heat exchanger allows the operation pressure of whole of the refrigerant loop, and the subcooler makes the refrigerant completely subcooled before entering the circulating pump. The geared pump is employed instead of a compressor to circulate the refrigerant so that this test rig achieves measurements of the heat transfer characteristics of the refrigerant without a lubricant oil. After the refrigerant flow rate is adjusted by the flow control valve and the frequency of the pump, it is measured with the mass flow meter.

There situate horizontally three series of heat exchangers, a pre heat exchanger, a test section and an auxiliary heat exchanger. They are all the double tube type heat exchangers with refrigerant flowing in an inner tube and countercurrent water flowing in a surrounding annulus. The pre heat exchanger adjusts the refrigerant vapor quality at the inlet of the test section, and the auxiliary heat exchanger make the refrigerant evaporate or condense completely before the refrigerant returns to the main heat exchanger. The independent water loop is connected to each of series of the heat exchangers to supply heat-source or heat-sink water into the annulus side. Each loop has its own heating and chilling unit in order to obtain the desired temperature.

Figure 4 shows the test section to evaluate the heat transfer characteristics of the horizontal heat transfer tube. The test section has 700 mm overall length, and the test tube is just horizontally situated in the center of the test section with the effective heat transfer length of 540 mm. The surface temperatures of the inner tube are measured with the 16 thermocouples soldered at the top, both sides and bottom of the tube wall at 4 locations along the tube. A couple of calibrated platinum resistance sensors with an accuracy of 0.02K and pressure gages with 1.0kPa accuracy are located at the inlet and outlet of the test section to measure the bulk temperatures and the pressures of the refrigerant, respectively. The pressure drop of the refrigerant across the test section is measured with a differential pressure transducer. The water side temperatures are measured by the platinum resistance sensors with the same accuracy as the refrigerant side. The test section has a vacuum layer outside the outer tube, and is thermally insulated using a 50mm thick piece of a plastic foam.

It is noted that the heat transfer characteristics for the herringbone tube would be varied with the position of the weld seam, because the axial seam may influence the liquid film layer and the flow pattern of the refrigerant. In order to eliminate the effect of the weld seam on the heat transfer performance, the herringbone tube has been always set up in the test section to constrain the axial seam line just situated at the top of the tube in the present experiments.

Experimental Conditions

The experimental conditions are listed in Table 1. The evaporation and condensation temperatures of the refrigerant at the test section are maintained at 278K and 323K, respectively. The refrigerant mass flux varied from G=150 to 400kg/m^{2}s. The water temperature in the test section has been controlled to attain the constant heat flux, q=7.5kW/m^2.

Table 1 Experimental conditions

	Evaporation	Condensation
Pressure	588.4 kPa	2091 kPa
Mass flux	150 , 250 , 300 , 400 kg/m^{2}s	
Heat flux	7.5 kW/m^{2}K	

Data Reduction

The quasi-local refrigerant heat transfer coefficient, α, is determined from the following equation:

$$\alpha = \frac{q}{T_w - T_r} \tag{1}$$

where, the overall heat flux based on the outside area of the tube, q, is calculated from the water side. T_w represents an averaged tube wall temperature for 16 thermocouples soldered on the tube wall surface. The temperature of the refrigerant, T_r, is defined as the equilibrium saturation temperature of the refrigerant corresponded to the pressure and enthalpy in the test section. The REFPROP Ver. 5.0 by NIST is used as the database of the refrigerant in the present study.

To check the energy balance between water and refrigerant sides of the pre heat exchanger and the test section, the single phase refrigerant flow tests have been preliminarily carried out. Comparisons between both heat quantities are made and found to be within 5% for all data runs.

RESULTS AND DISCUSSION

Heat Transfer Characteristics of Herringbone Tube

Figure 5 shows the typical results of the evaporation heat transfer coefficients for R407C between the herringbone tube and the inner grooved tube. The data are plotted as a function of refrigerant vapor qualities at refrigerant mass flux, G=300kg/m^{2}s. In the figure, the heat transfer coefficients for R22 are also included for reference. The figure reveals that the evaporation heat transfer coefficients are obviously augmented by the use of the herringbone tube, that is, the herringbone tube shows approximately 90% larger heat transfer coefficients than the inner grooved tube. The similar performance improvement of the evaporation heat transfer

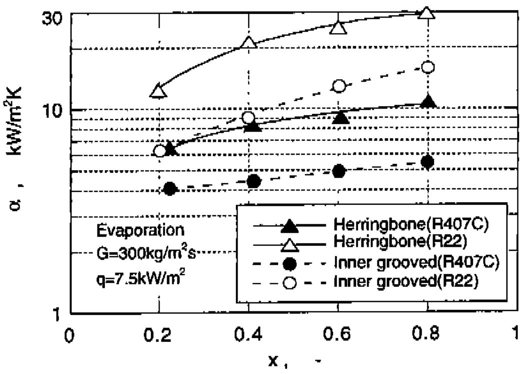


Figure 5 Comparisons of evaporation heat transfer coefficients between the herringbone and inner grooved tubes

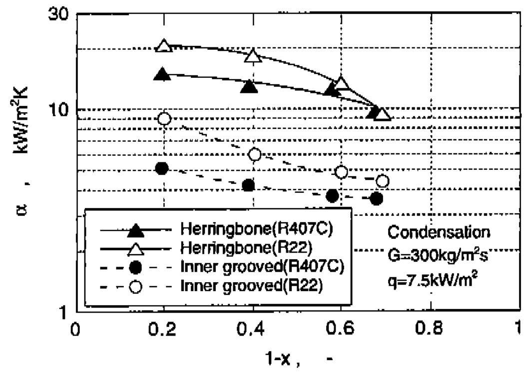


Figure 6 Comparisons of condensation heat transfer coefficients between the herringbone and inner grooved tubes

by the herringbone tube can be recognized in the results for R22.

Practically considered the drop-in application of R407C to the units running on R22, the comparison of the heat transfer coefficients between R407C using the herringbone tube and R22 using the inner grooved tube provides the very important information on the heat exchanger performance. The present results imply that the heat transfer coefficient for R407C using the herringbone tube is even up to that for R22 using the existing inner grooved tube at the low vapor quality, but the former is about 30% lower than the latter on average.

Presented in Figure 6 are the results of the heat transfer coefficients during condensation. The heat transfer enhancement by the herringbone tube is readily apparent, as the heat transfer coefficients for both the refrigerants using the herringbone tube are much larger than those using the inner grooved tubes. Quantitatively, the former is as much as 200% higher than the latter, thereby, the heat transfer coefficient for R407C using the herringbone tube surpasses those for R22 using the inner grooved tube.

The noteworthy heat transfer augmentation of the herringbone tube is believed due to the heat transfer enhancement mechanism proposed by Ebisu & Torikoshi (1998). Inside the inner grooved tube, the heat transfer enhancement is achieved due to the circumferential uniform film layer around the entire tube wall caused by the capillary wetting of the helical narrow grooves, while the herringbone groove pattern is expected to carry liquid film to two different directions by V shape grooves, thus circumferential non-uniform liquid film layer is yielded inside the herringbone tube. Ebisu & Torikoshi have insisted that this non-uniform film layer contributes to high heat transfer coefficients. They have already made the detailed examination to have verified their original consideration of the heat transfer enhancement mechanism qualitatively.

Pressure Drop Characteristics

Comparisons of the evaporation and condensation pressure drops between the herringbone tube and the inner grooved tube are shown in Figure 7. The pressure drop increases with an increase of the vapor qualities for both heat transfer tubes. However, the pressure drops per unit length for the herringbone tube are about 50% and 30% higher than those for the inner grooved tube during evaporation and condensation, respectively. The higher pressure drop results for the herringbone tube is attributed to the higher fin height and the greater surface area of the herringbone tube rather than the existing inner grooved tube.

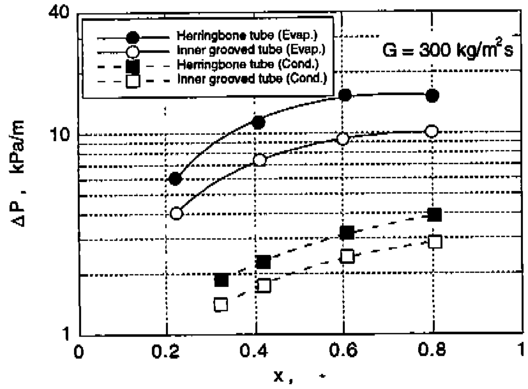


Figure 7 Comparison of pressue drops between the herringbone and innergrooved tubes

Effect of Refrigerant Mass Flux

The influence of the refrigerant mass flux on the heat transfer coefficient and the pressure drop has been investigated for designing the air-cooled heat exchanger using the herringbone tube. Figure 8 shows the experimental results of the evaporation heat transfer coefficient for R407C. The data at x=0.6 are typically plotted for both the herringbone and inner grooved tubes. As the refrigerant mass flux increases, the heat transfer coefficients for both tubes increase, but the trend for the herringbone tube is steeper than that for the inner grooved tube. Consequently, the herringbone tube provide a bit of positive effect on the evaporation heat transfer enhancement for lower mass flux than G=200kg/m²s, while the larger the refrigerant flow rates, the larger the herringbone

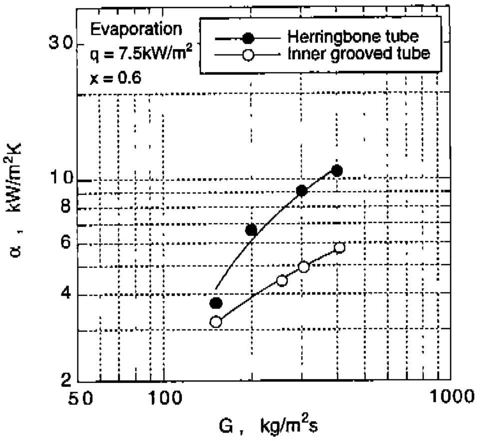


Figure 8 Effect of refrigerant mass flow rate on evaporation heat transfer coefficient

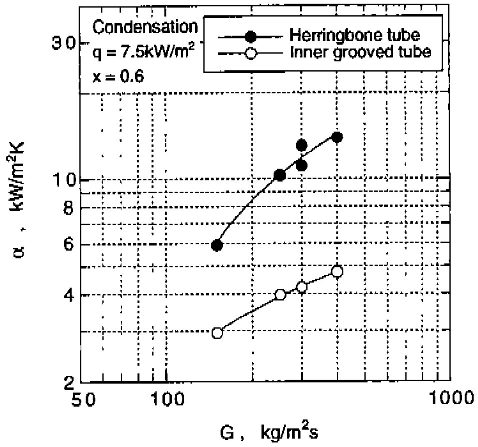


Figure 9 Effect of refrigerant mass flow rate on condensation heat transfer coefficient

tube contributes to evaporation heat transfer enhancement.

Figure 9 shows the results of the condensation heat transfer coefficients. The curve for the herringbone tube seems to be more inclined than that for the inner grooved tube, however, as the condensation heat transfer coefficients for the herringbone tube are highly enhanced compared to the those for the inner grooved tube, the former show the better heat transfer performances than the latter for all the refrigerant mass fluxes. The quantitative comparison of the heat transfer coefficient between both the tubes shows that the herringbone tube achieves about 100% and 200% higher performance than the inner grooved tube at G=150kg/m²s and G=300kg/m²s, respectively.

The evaporation and condensation pressure drops are shown in Figure 10. The pressure drops for both tubes increase with an increase of the refrigerant mass flux, but the trend for the herringbone tube seems to be slightly steeper than that for the inner grooved tube. Quantitatively, the herringbone tube shows about 50% and 30% higher pressure drops than the inner grooved tube during evaporation and condensation, respectively.

Heat Exchanger Performance

A couple of the same size air-cooled heat exchanger, one using the herringbone tube and another using the existing inner grooved tube, have been prepared in order to examine the improvement of the heat exchanger performance due to the use of the herringbone heat transfer tube. Figure 11 shows the test heat exchanger configuration to investigate the heat exchanger performance. The test heat exchangers are 2 rows of the fin and tube heat exchanger which have the cross-countercurrent flow configuration of the refrigerant and air. The working fluid employed here has been R407C. As the experimental apparatus and the test conditions are as same as those in Ebisu et al. (1996), the detailed presentation has been shown in the reference paper.

Figure 12 shows the experimental results of the evaporator performance. The data are plotted as a function of u which corresponds to the air velocity through the test heat exchanger. Compared to the heat exchanger performance between the

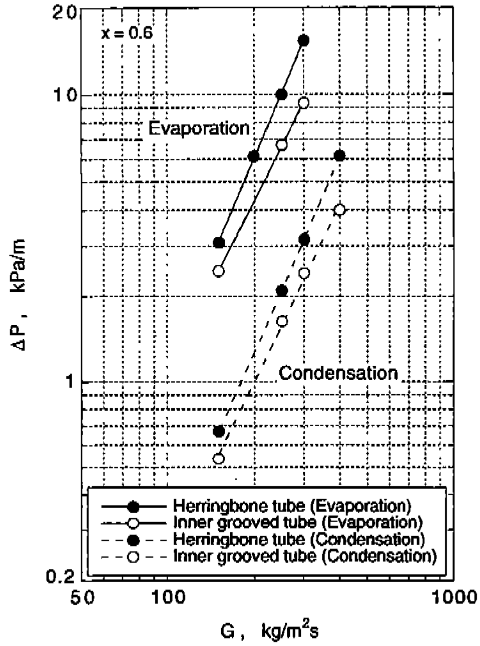


Figure 10 Effect of refrigerant mass flow rate on pressure drop

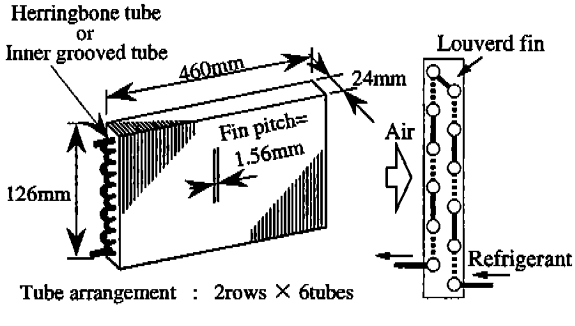


Figure 11 Air-cooled heat exchanger tested

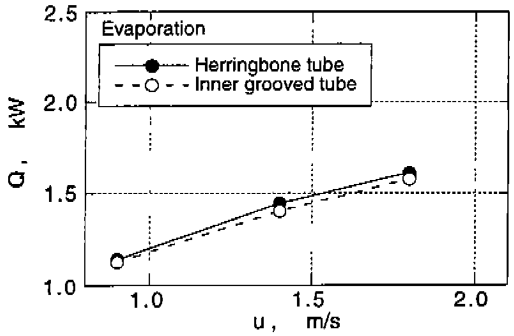


Figure 12 Comparisons of evaporator performance between herringbone and inner grooved tubes

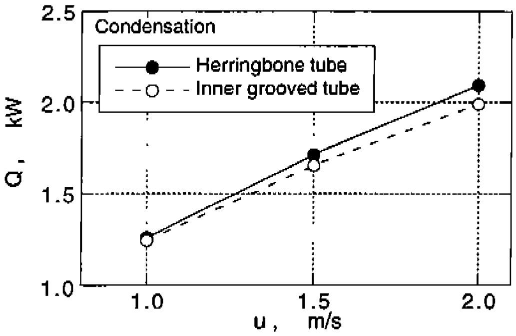


Figure 13 Comparisons of condenser performance between herringbone and inner grooved tubes

herringbone tube and the inner grooved tube, the performance improvements seem to depend on the air-velocities, that is, the performances for the herringbone tube are about 3% better than those for the inner grooved tube at u=1.8m/s and 1.4m/s, while both the performances at u=0.9m/s are almost the same. These results are considered due to the findings that the evaporation heat transfer coefficients for the herringbone tube are enhanced only at the relatively high refrigerant mass fluxes.

Condenser performances are compared between the herringbone tube and the existing inner grooved tube in Figure 13. The herringbone tube has improved the condenser performance about 3 to 5% compared to the inner grooved tube. Since the heat transfer coefficients during condensation are enhanced by the herringbone tube for all the refrigerant mass fluxes, all the condenser performances in the present experimental ranges surpass those using the inner grooved tube. However, as the air-side heat transfer is exceedingly dominant to the air-cooled heat exchanger performance rather than the refrigerant-side, the significant heat transfer enhancement of the herringbone tube contributes to slight improvement of the heat exchanger performance.

CONCLUSIONS

The new advanced heat transfer tube called, "Herringbone Heat Transfer Tube", having a unique inner surface geometry, have been experimentally investigated in order to enhance the heat transfer for R407C and improve the air-cooled heat exchanger performance. The experiments to examine the heat transfer characteristics for R407C flowing inside the horizontal herringbone heat transfer tube have been performed, and the data have been compared to those inside the existing inner grooved tube. Additionally, the performance of the air-cooled heat exchangers which have employed the herringbone tube and the inner grooved tube have been measured to evaluate the improvement of the heat exchanger performance using the herringbone tube.

The results of the present experiments have revealed that the evaporation heat transfer coefficient for the herringbone tube is about 90% higher than those for the inner grooved tube at the high mass flow rate, while it provides a small positive effect on the evaporation heat transfer enhancement under G=200kg/m^{2}s. For condensation performance, the herringbone tube has achieved about 100 to 200% higher heat transfer coefficient rather than the inner grooved tube for any refrigerant flow rates. However, the significant increase in heat transfer has been accomplished with about 30 to 60% increase in pressure drop.

The practical comparison of the heat exchanger performance shows that the evaporator performance has been improved about 3% only at the relatively high refrigerant flow rate, while the condenser using the herringbone tube have been 3% to 5% better than that using the inner grooved tube for all the refrigerant flow rates.

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