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HEAT TRANSFER AND PRESSURE DROP CHARACTERISTICS OF HFC-134a IN A HORIZONTAL HEAT TRANSFER TUBE

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ABSTRACT

The evaporation and condensation heat transfer and pressure drop characteristics for HFC-134a in a horizontal tube have studied experimentally. During the courses of both evaporation and condensation experiments, the saturation temperature of the refrigerant, and mass flux and oil concentration in the refrigerant were varied parametrically. A smooth tube and an inner finned tube were used as the tube to be tested.

In addition to the oil-free evaporation and condensation experiments, another experiments were performed to investigate the effect of oil-refrigerant mixture on the heat transfer and pressure drop characteristics.

The present evaporation and condensation heat transfer coefficients for HFC-134a without oil in the smooth tube were found to be about 25% higher than those for CFC-12 at similar mass fluxes. Furthermore, it was found that the pressure drop through the smooth tube for HFC-134a become about 10% larger than those for CFC-12 in evaporation experiments.

In the oil-refrigerant mixture experiments, the results indicated that both evaporation and condensation heat transfer coefficients for HFC-134a were influenced on the oil concentration at a large mass flux.

NOMENCLATURE

A Surface area, m²
C Oil concentration, %
d Tube diameter, mm
f Fin height of inner finned tube, mm
G Mass flux, kg/m²s
hr Heat transfer coefficient, W/m²K
K Overall heat transfer coefficient, W/m²K
n Number of fins
Δp Pressure drop across tube, kPa/m
p Pitch of fins, mm
Q Heat quantity, W
Rm Thermal resistance in inner tube, m²K/W
Ts Saturated temperature, K
Δt Log mean temperature difference, K
t Tube wall thickness, mm

Greeks
θ Twisted angle, degree

Subscripts:
cond Condensation
eva Evaporation
i Inside
o Outside
w Water
INTRODUCTION

The refrigerants of CFC-11 and CFC-12 have been frequently used as the working fluids in refrigerators and air-conditioning machines. The production of their specific refrigerants of CFC-11 and CFC-12 is, however, regulated due to ozone depleting substances, since the agreement of the Montreal Protocol has been reached in 1987. The agreement of the Montreal Protocol has greatly influenced refrigeration and air-conditioning industries so that the development of the alternative refrigerants is intensified in response to the regulation of producing and consuming the specific refrigerants. With regard to the alternative refrigerant for the refrigerant of CFC-12, which is employed widely in freezers and air-conditioning machines for automobiles, the refrigerant of HFC-134a is considered as a potential replacement refrigerant for CFC-12 because HFC-134a is believed to be environmentally acceptable with a zero ozone depletion potential.

In addition to the thermal and chemical stability, non-toxicity and thermal properties, preliminary information about heat transfer characteristics of HFC-134a is needed before it is introduced commercially.

In spite of the practical importance of heat transfer information for HFC-134a to design air-conditioning machines and freezers, there have been very few works dealing with the evaporation and condensation heat transfer and pressure drop across heat transfer tube. Eckels and Pate[1] determined experimentally the evaporation and condensation heat transfer coefficients for HFC-134a and CFC-12 during in-tube two-phase flow. Their experimental results indicated the evaporation heat transfer coefficients for HFC-134a were 35 to 45% higher than those for CFC-12 and also the condensation heat transfer coefficients for HFC-134a were 25 to 35% higher than those for CFC-12 at the same mass fluxes. Further, Hambraeus[2] examined the evaporation heat transfer characteristics of HFC-134a inside smooth-horizontal tubes and compared the heat transfer results for HFC-134a with those for HCFC-22. The experimental results showed that oil-free HFC-134a had a higher heat transfer coefficient than HCFC-22 at the same heat and mass fluxes. In the study, a further finding indicated that there was a continuous decrease in the evaporation heat transfer coefficient with increasing oil content (20% lower at 2% m/m EXP-0275 oil). Moreover, Kudo, et al.[3] studied the effect of PAG oil on the local evaporation and condensation heat transfer coefficients for HFC-134a in a square tube of 3.5mm in inner diameter and in a small tube of 3.9mm in inner diameter. Their results showed that both local evaporation and condensation coefficients decreased with an increase in the oil concentration into the refrigerant.

In order to establish a design method of the new air-conditioning machines due to the use of HFC-134a, however, more detailed information about evaporation and condensation heat transfer characteristics for HFC-134a is still lacking. The present study has been performed to extend the previous heat transfer data necessary for the practical design of air-conditioning machines. In particular, the evaporation and condensation heat transfer experiments for HFC-134a were carried out using a horizontal smooth copper tube and an inner finned copper tube having 9.5mm in outer diameter which were different from those in the previous studies[1]-[3].

The present study done is one of the R&D programs of Technology Research Association of Super Heat Pump Energy Accumulation System, entrusted by New Energy Industrial Technology Development Organization (NEDO).

EXPERIMENTS

2.1 Experimental apparatus

A schematic diagram of the apparatus employed in the present study for determining both evaporation and condensation heat transfer coefficients in a
single horizontal tube for HFC-134a is shown in Fig. 1. As seen in the figure, the system is mainly made up of a refrigerant loop and a water loop.

In the design of the experimental apparatus, a special feature was incorporated to enable both evaporation and condensation experiments. Refrigerant flow directions in both evaporation and condensation experiments are indicated by arrows in Fig. 1, respectively. The main components of the refrigerant loop in the apparatus include a test section, a pump for circulating the refrigerant of HFC-134a into the refrigerant loop, a flow meter, a heating section and two heat exchangers. In place of a compressor, the pump was used to examine accurately the effect of a mixture of refrigerant and oil on evaporation and condensation heat transfer coefficients. The flow meter was connected upstream of the test section to measure a refrigerant flow rate. The refrigerant flow rate through the test section was regulated by valves and by controlling input power added to the pump. To control the quality entering the test section, the heating section was located just before the test section. The pressure drop of the refrigerant across the test section was measured with two pressure transducers located at the inlet and at the outlet of the test section. The main heat exchanger was installed in the refrigerant loop to regulate the pressure of the refrigerant. In addition, the auxiliary heat exchanger was connected downstream of the pump to liquidize completely the refrigerant entering the pump.

The water loop was used to supply water to the annulus side of the test section for the purpose of heating or cooling the refrigerant flowing in the tube to be tested. The water loop includes the double tube test section, a pump, a flow meter and a constant temperature water bath. The water flow rate was set by the pump. To measure the inlet and outlet temperatures of the water and the refrigerant in the test section, a pair of Pt resistance sensors were located at both the inlet and outlet of the refrigerant and water sides of the test section.

Details of the test section is illustrated in Fig. 2. As shown in the figure, the test section consists of the inner copper tube, whose dimensions are 9.5mm in an outer diameter and 4000mm in length, and the outer stainless steel tube having an inside diameter of 22.2mm and a length of 4000mm. The clearance between the inner tube and the outer tube of the annulus was maintained at 6.4mm.

In the present study, the smooth tube and the inner finned tube were used as the inner tube in which the refrigerant flowed. The geometry of the inner finned tube is schematically shown in Fig. 3.

The test section, the refrigerant and water loops were thermally well insulated by glass wool insulation. In particular, the test section was equipped with vacuum layer in the outer tube to minimize heat loss from annulus of the test section.

2.2 Experimental procedure

Prior to the initiation of data runs, noncondensables were removed from the refrigerant loop by a vacuum pump. Evaporation heat transfer experiments were performed under the conditions that the quality at the inlet of the test section and the superheat at the outlet of the test section were maintained at the desired values listed in Table 1, respectively. On the other hand, during the course of the condensation heat transfer experiments, the superheat at the inlet of the test section and the subcooling at the outlet of the test section were set at the desired values, as listed in the table. In both the evaporation and condensation heat transfer experiments, the mass flow rate ranged from 45 to 200kg/m²s.

In addition to the oil free refrigerant experiments, the effect of oil concentration in the refrigerant on the heat transfer characteristics during evaporation and condensation was examined within 0.7 to 6.5%. PAG oil was
used as lubrication oil. Further, the evaporation and condensation data runs for CFC-12 were carried out to compare with those for HFC-134a at similar conditions. The experimental conditions in the present study is summarized in Table 1.

During two different experiments on evaporation and condensation, all of the Pt resistance sensor, flow rate and pressure transducer readings were measured by a data logger when steady-state conditions were reached.

3 DATA REDUCTION

The main objective of the data reduction procedure was to yield the evaporation and condensation heat transfer coefficients for the refrigerant in a horizontal tube. The starting point of the data reduction procedure is the definition of the average heat transfer coefficients over the length of the test tube on the refrigerant-side:

\[ h_e = \frac{A_0 (1 - R_m - 1)}{A_1 \left( \frac{k}{h_w} \right)} \]  

where \( A_0 \) and \( A_1 \) are the surface areas of the outside and inside of the test tube, respectively. Further, the quantity \( R_m \) denotes the thermal resistance at the inner tube and \( h_w \) is the water side heat transfer coefficient. The heat transfer coefficient, \( h_w \) in the annulus was determined using the well-known Dittus-Boelter correlation.

In equation (1), the quantity \( k \) presents the overall heat transfer coefficient and is defined here as follows:

\[ k = \frac{Q_w}{A_1 \Delta T} \]  

where \( Q_w \) is the heat quantity transferred in the test section and \( \Delta T \) is the log mean temperature difference. The heat quantity, \( Q_w \), was calculated from an energy balance on the water-side flowing in the annulus. The temperature difference, \( \Delta T \), was determined from the inlet and exit temperatures of the annulus and from the saturation temperatures at the inlet and exit of the test tube. The value of the saturation temperature used in the present study was taken account of the pressure drop across the test tube.

To check heat balances on the water-side and the refrigerant-side of the test section, comparisons between both the heat balances were made. As a consequence, both the heat balances were found to be within 5% for all runs.

4 RESULTS AND DISCUSSION

4.1 Heat transfer and pressure drop characteristics of a smooth tube for oil-free refrigerant

(a) Evaporation characteristics The evaporation heat transfer coefficient results obtained for oil-free refrigerant of HFC-134a at three different saturation temperatures are plotted in Fig. 4 as a function of refrigerant mass flux. In addition to the heat transfers results for HFC-134a(open circle triangle and square symbols), the figure also shows the results for CFC-12. Inspection of the figure reveals that both evaporation heat transfer coefficient results for HFC-134a and CFC-12 increase with an increase in mass flux and also the results for HFC-134a increase with temperature. The increased values of the \( h_{eva} \) appearing at higher saturation temperatures are brought about by the increased enthalpy of vaporization. Further, a comparison between the evaporation results for
HFC-134a and those for CFC-12 shows clearly that the former results become about 25\% larger than the latter ones at the same mass flux. A significant increase in evaporation heat transfer coefficients for HFC-134a relative to those for CFC-12 is ascribed to the increased liquid thermal conductivity of HFC-134a.

Another very important issue for designer is to evaluate pressure drop through the test tube during evaporation. Both the pressure drop results for HFC-134a and CFC-12 are presented in Fig.5. The results in the figure are given for the oil-free refrigerants of HFC-134a and CFC-12.

The figure shows that the pressure drop for HFC-134a increases with decreasing the saturation temperature. Further inspection of the figure reveals that there is an evident difference between the results for HFC-134a and those for CFC-12. The fact that the pressure drop for HFC-134a becomes about 10\% larger than that for CFC-12 is mainly caused by the lower gas density of HFC-134a compared to that of CFC-12.

(b) Condensation characteristics

Condensation heat transfer coefficient and pressure drop across a horizontal smooth tube for HFC-134a will now be discussed and compared with heat transfer and pressure drop results for CFC-12. Condensation heat transfer coefficient results for HFC-134a are presented in Fig.6 together with the results for CFC-12. Data for HFC-134a were obtained at three temperatures of 40 \textdegree C, 50 \textdegree C and 60 \textdegree C.

The curve showing the heat transfer results for HFC-134a indicates that the heat transfer coefficient increases as the mass flux increases. Such a qualitative trend in the heat transfer result for HFC-134a is similar to that for CFC-12. A quantitative examination of the condensation heat transfer coefficient results for HFC-134a and those for CFC-12, however, shows that the results for HFC-134a are about 25\% larger than those for CFC-12. This is probably due to the higher liquid thermal conductivity, specific heat and latent heat of HFC-134a, when compared to those of CFC-12.

On the other hand, pressure drop information during condensation for HFC-134a is presented in Fig.7. The figure also shows the results for CFC-12. By examining the pressure drop results appeared in the figure, it is found that both the results for HFC-134a and CFC-12 are almost coincident.

4.2. Heat transfer and pressure drop characteristics of a smooth tube for oil-refrigerant mixture.

From the practical standpoint of designing air-conditioning machines and freezers, note should be taken of information about heat transfer and pressure drop characteristics for an oil-refrigerant mixture.

(a) Evaporation characteristics

The evaporation heat transfer coefficient results for an oil-refrigerant mixture are presented in Fig.8 as a function of mass flux. In the figure, data are given for four different concentrations of oil in the refrigerant of HFC-134a. An overall perspective on the evaporation heat transfer results for the oil-refrigerant mixture and those for the pure refrigerant reveals a complicated trend that the value of $h_{\text{eva}}$ increases with increasing the oil-concentration at small C, while the value of $h_{\text{eva}}$ decreases at large C. For instance, the 3\% concentration of oil leads to a 30\% increase of evaporation heat transfer coefficient relative to the pure refrigerant.

Further, the pressure drop results for an oil-refrigerant mixture are depicted in Fig.9. The figure shows that the pressure drop results increase monotonically with increasing the concentration of oil into the refrigerant. From both figures indicated above, it is evident that the heat transfer and pressure drop characteristics for an oil-refrigerant mixture are strongly influenced on the concentration of oil into the refrigerant.
(b) Condensation characteristics  

Representative condensation heat transfer coefficients for the oil-refrigerant mixture experiments at the temperature of 50 °C are presented in Fig.10. Inspection of Fig.10 reveals a pattern which is qualitatively similar to that encountered in the pure refrigerant experiment. That is, the heat transfer results to an oil-refrigerant mixture in the range from 1.5 to 5.5% during condensation increase with an increase in the mass flux and also the results for an oil-refrigerant mixture become almost the same results for the pure refrigerant.

The pressure drop results for an oil-refrigerant mixture at the temperature of 50 °C are presented in Fig.11 for all three concentrations of oil. To provide perspective on the effect of the concentration of oil, results are also shown for the case of the pure refrigerant. It is seen from the figure that the results for an oil-refrigerant mixture are insensitive to the concentration of oil into the refrigerant.

4.3 Heat transfer and pressure drop characteristics of an inner finned tube for pure refrigerant and oil-refrigerant mixture

An interesting and practically important issue is to evaluate the heat transfer and pressure drop characteristics of an augmented-inner finned tube which is frequently employed in air-conditioning machines. Figs.12 through 15 have been provided for this purpose.

(a) Evaporation characteristics

The evaporation heat transfer results for the inner finned tube are displayed in Fig.12 for two mass fluxes as a function of the concentration of oil. The figure also compares the results for the fined tube with those for smooth tube. Inspection of Fig.12 shows a pattern with the concentration of oil whereby the \( h_{eva} \) increases at first, attains a maximum, and then decreases. The extent of the augmentation is affected by the mass flux. Furthermore, a comparison between the results for the inner finned tube and those for the smooth tube reveals that the former results are larger than the latter ones. The behavior that the \( h_{eva} \) increases with increasing the concentration \( C \) at small \( C \) is that the oil in the refrigerant acts to augment the bubble nucleation. On the contrary, the reason for the decrease in the \( h_{eva} \) at large \( C \) is presumably brought about by the restriction of evaporation, because of the existence of oil in the refrigerant.

Further, the pressure drop results are presented in Fig.13. The figure shows that the pressure drop is dependent of the value of \( C \). It is seen that relation between the pressure drop result and the mass flux for the inner finned tube is nearly coincident with that for the smooth tube.

(b) Condensation characteristics

The condensation heat transfer coefficient results for inner finned tube are plotted in Fig.14 as a function of the value of \( C \). The figure shows that both the results for the inner tube at two cases of mass flux decrease monotonically with an increase in the concentration of oil into the refrigerant and are also different from those for the smooth. Such a monotonic decrease in the condensation heat transfer of the inner finned tube for an oil-refrigerant mixture is believed due to the existence of the oil film occurred at the wall of the inner finned tube. The aforementioned oil effect during condensation reflects to the increased pressure drop results for an oil-refrigerant mixture which are displayed in Fig.15.

5 Conclusions

The experiments reported herein were performed to investigate both heat transfer and pressure drop characteristics during evaporation and condensation for HFC-134a in a horizontal single tube. Of particular interest from the standpoint of practical applications is the effect of concentration of oil on the heat transfer and pressure drop characteristics.
In addition to the case of a smooth tube to be tested, the heat transfer and pressure drop characteristics of an inner finned tube were investigated. In the oil-free refrigerant experiments, both the evaporation and condensation heat transfer coefficients of a smooth tube for HFC-134a were found to be about 25% higher than those for CFC-12. The pressure drop results for HFC-134a became about 10% larger than those for CFC-12 in the evaporation experiments.

In the oil-refrigerant mixture experiments, the evaporation and condensation heat transfer results for HFC-134a were markedly influenced on the oil concentration. Furthermore, an interesting result for the inner finned tube indicated that the heat transfer characteristics were more strongly affected on the concentration of oil.

REFERENCES

**Fig. 1** Schematic diagram of experimental apparatus

**Fig. 2** Detail of test section

**Fig. 3** Geometrical parameters of test tubes

**Fig. 4** Evaporation heat transfer coefficients for HFC-134a and CFC-12 without oil

**Fig. 5** Pressure drop without oil during evaporation

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### Table 1 Experimental conditions

<table>
<thead>
<tr>
<th></th>
<th>Evaporation</th>
<th>Condensation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Saturation temperature</strong></td>
<td>5, 15, 30° C</td>
<td>40, 50, 60° C</td>
</tr>
<tr>
<td><strong>Inlet condition</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of test section</td>
<td></td>
<td></td>
</tr>
<tr>
<td>quality = 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>superheat = 45±1.0° C</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Outlet condition</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of test section</td>
<td></td>
<td></td>
</tr>
<tr>
<td>superheat = 5±0.5° C</td>
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<tr>
<td>subcooling = 4±0.5° C</td>
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<tr>
<td><strong>Oil concentration</strong></td>
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<td>0 - 6.5%</td>
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</table>

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- Pressure transducer
- Differential pressure transducer
- Pt resistance sensor

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- Vacuum layer
- Insulation 4000
- Outer tube
- ID = 22.2
- Inner tube
- OD = 9.5
- Refrigerant
- Water
- Water
- Refrigerant
- Water
- Refrigerant
Fig. 6 Condensation heat transfer coefficients for HFC-134a and CFC-12 without oil

Fig. 7 Pressure drop without oil during condensation

Fig. 8 Effect of oil concentration in refrigerant for HFC-134a on evaporation heat transfer coefficient

Fig. 9 Effect of oil concentration in refrigerant for HFC-134a on pressure drop

Fig. 10 Effect of oil concentration in refrigerant for HFC-134a on condensation heat transfer coefficient

Fig. 11 Effect of oil concentration in refrigerant for HFC-134a on pressure drop

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Fig. 12 Effect of oil concentration in refrigerant for HFC-134a on evaporation heat transfer coefficient

Fig. 13 Effect of oil concentration in refrigerant on pressure drop

Fig. 14 Effect of oil concentration in refrigerant for HFC-134a on condensation heat transfer coefficient

Fig. 15 Effect of oil concentration in refrigerant on pressure drop