EFFECT OF LUBRICATING OIL ON BOILING HEAT TRANSFER OF CARBON DIOXIDE

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ABSTRACT

In this study, the boiling heat transfer coefficient of carbon dioxide with PAG-type lubricating oil entrained from 0 wt% to 5 wt% in horizontal smooth tubes was experimentally investigated. Experiments were conducted using test tubes with inner diameters of 2–6 mm at mass fluxes of 170–320 kg/m²s and heat fluxes of 4.5–36 kW/m². The saturation temperature was 15°C.

In general, at a low oil concentration of approximately 0.5%–1%, the heat transfer coefficient decreased below half its value under the oil-free condition. This is because an oil-rich layer was formed near the heat transfer surface. However, no further decrease in the heat transfer coefficient was observed at higher oil concentrations.

Similar to the case of the oil-free condition, the heat flux positively influenced the heat transfer coefficient in low quality regions. As the heat flux increases from 4.5 kW/m² to 36 kW/m², the heat transfer coefficient increases by approximately 100%. However, no obvious influence was observed in high quality regions. This implies that nucleate boiling dominates in the low quality region, while it is suppressed in the high quality region. In contrast, when oil was used, the mass flux significantly influenced the heat transfer coefficient; as the mass flux increased from 360 kg/m²s to 720 kg/m²s, the maximum increase in the heat transfer was approximately 50%. In addition, the measured pressure drops increased monotonously due to the effect of lubricating oil.

Keyword: Carbon dioxide; heat transfer coefficient; pressure drop; lubricating oil; boiling heat transfer; dryout

1. INTRODUCTION

Due to the depletion of the ozone layer and global warming caused by chlorofluorocarbon and hydrofluorocarbon refrigerants, carbon dioxide (CO₂) was proposed by Lorentzen and Pettersen (1993,1994,1995) as a promising alternative refrigerant for air-conditioning applications and heat pumps. The advantages of CO₂ are that it is non-toxic and inflammable; in particular, it exhibits an excellent thermodynamic property with a low critical temperature and high operating pressure in...
comparison with other refrigerants. Therefore, studies of the heat transfer performance of CO₂ at supercritical and subcritical pressures and the optimization of the CO₂ heat pump system have attracted increasing attention.

Dang et al. (2005) conducted a systematic study of the boiling heat transfer of CO₂ with tube diameters of 1–6 mm under various conditions of saturation temperature, mass flux, and heat flux. Experimental data revealed that nucleate boiling is the dominant mechanism in the flow boiling of CO₂ due to its low density ratio of liquid to vapor. In a real heat pump cycle, lubricating oil is commonly used in the compressor for cooling and sealing purposes. It is important to understand the boiling heat transfer performance of CO₂ entrained with a small amount of lubricating oil; this has not been studied thoroughly. Katsuda et al. (2003) determined the boiling heat transfer coefficient of CO₂ by using a tube with an inner diameter of 3 mm at heat fluxes of 5–15 kW/m² and mass fluxes of 200–600 kg/m²s. It was reported that the heat transfer coefficient decreased sharply at an oil concentration of 0.3%. Gao & Honda (2004a, 2004b) visually observed the flow pattern of lubricating oil flowing with CO₂ at heat fluxes of 5–40 kW/m² and mass fluxes of 230–1200 kg/m²s. They reported that lubricating oil flowed along the inner wall of the test tube, which may lead to the suppression of nucleate boiling.

Although only limited information is available, the abovementioned studies indicate that the introduction of lubricating oil into subcritical CO₂ significantly influences the heat transfer performance. This implies that it is important to conduct a systematic investigation on the effect of lubricating oil over a wide range of experimental conditions. The purpose of this report is to provide a systematic study of flow boiling heat transfer over a wide range of experimental conditions. Experiments are conducted using horizontal tubes with inner diameters of 1, 2, 4, and 6 mm at oil concentrations of 0.5%–5%, heat fluxes of 4.5–36 kW/m², and mass fluxes of 360–1440 kg/m²s. The heat transfer coefficient in both pre- and post-dryout regions and the dryout quality are measured. This report presents only experimental results because it is difficult to correlate them over a wide range of experimental conditions; this correlation is currently under investigation.

2. EXPERIMENTAL APPARATUS AND DATA REDUCTION

2.1 Experimental apparatus

Figure 1 shows a schematic diagram of the experimental apparatus used in this study. The test loop comprised a magnetic gear pump for working fluid circulation, a mass flow meter (±0.5% accuracy), a heater, an oil sampling section, a test section, an oil separator, and a heat exchanger for cooling the refrigerant. The vapor quality at the inlet of the test section was controlled by the heater. The oil concentration was measured in the oil sampling section and controlled by the oil separator. The test section was made of stainless steel, and it was heated by electric power supplied by a DC power source.

The detailed structure of the test section is shown in Figure 2. The electrical resistance of the test tube was approximately 0.6 Ω. The outside wall temperature of the test section was measured using
T-type thermocouples with an uncertainty of ±0.1 °C; these thermocouples were attached to the top, bottom, and sides of the test tube. To avoid the influence of the electric current, the tips of all thermocouples were electrically insulated from the heated test tube by using a very thin Teflon film. The pressure of the working fluid at the inlet and outlet of the test section was monitored using a precision pressure sensor with an uncertainty of ±0.1%.

The specific enthalpy of the working fluid entering the test section was calculated from the measured temperature and pressure at the inlet of the preheater and the power input to the preheater. The thermophysical properties of CO$_2$ were determined using REFPROP 7.0. The inside wall temperature $T_w$ was calculated from the measured outside wall temperature using an equation of one-dimensional heat conduction. The local heat transfer coefficient $\alpha$ was estimated from the measured heat flux $q$, the saturation temperature $T_{sat}$ calculated from the measured pressure, and $T_w$.

$$\alpha = \frac{q}{T_w - T_{sat}}$$ (1)

In order to reduce the heat loss from the test tube to the surroundings, it was covered with insulation of 20 mm thickness and placed in a wind tunnel; air in the tunnel was maintained at a temperature near the outside wall temperature of the test tube. According to uncertainty analysis, the maximum measurement uncertainty of the heat transfer coefficient was between 8.9% and 13%.

2.2 Experimental conditions

The experimental conditions are summarized in Table 1. The inner diameters of the smooth tubes were 1, 2, 4, and 6 mm. PAG-type lubricating oil was used at concentrations of 0.5–5.0 wt%; its kinematic viscosity is 105 mm$^2$/s at 40°C and 20 mm$^2$/s at 100°C. Experiments were conducted by controlling the heat and mass fluxes at 4.5–36 kW/m$^2$ and 360–1440 kg/m$^2$s, respectively.

| Table 1 Experimental conditions |
3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Effect of oil on heat transfer coefficient

Figures 3 and 4 show the measured heat transfer coefficients of the 2 mm and 4 mm tubes at oil concentrations of 0%–5%, respectively. In general, the addition of a small amount of lubricating oil resulted in a sharp decrease in the heat transfer coefficient. Figure 3 compares the heat transfer coefficients of the 2 mm tube at oil concentrations of 0%, 0.5%, 1%, and 5% at heat flux of 9 kW/m², and mass flux of 360 kg/m²s. In comparison with the average value of 8–9 kW/m²K in the pre-dryout region under the oil-free condition, the heat transfer coefficient reduces to 3–5 kW/m²K at the oil concentration of 0.5%. It does not decrease further as the oil concentration increases to 5%. It appears that the heat transfer coefficient decreases sharply at a critical oil concentration; thereafter, the effect of oil on the heat transfer coefficient is saturated. For the 2 mm tube, the critical oil concentration is 0.5%. However, the addition of lubricating oil does not influence the dryout quality and the post-dryout heat transfer coefficient. In Figure 4, similar results are shown for the 4 mm tube at a heat flux of 18 kW/m² and mass flux of 720 kg/m²s. When lubricating oil is added, the heat transfer coefficient in the pre-dryout region decreases from 9–10 kW/m²K to approximately 4 kW/m²K. The critical oil concentration at which the heat transfer coefficient decreases significantly is approximately 1%. As in the case of the 2 mm tube, the dryout quality and post-dryout heat transfer are not influenced by the addition of lubricating oil.

![Figure 3. Measured heat transfer coefficients of 2 mm tube at oil concentration of 0%–5%. Q = 9 kW/m² and G = 360 kg/m²s.](image)

![Figure 4. Measured heat transfer coefficients of 4 mm tube at oil concentration of 0%–5%. Q = 18 kW/m² and G = 720 kg/m²s.](image)

3.2 Effect of heat flux on heat transfer coefficient

Figures 5 and 6 show the effect of the heat flux on the heat transfer coefficient of the 2 mm tube of SUS316 material. The inner diameter of the tube is 2, 4, 6 mm. The oil type is PAG100, and the oil concentration is 0.5~5.0 wt%. The mass velocity is 360, 720, 1440 kg/(m²·s). The heat flux is 4.5, 9, 18, 36 kW/m². The evaporating temperature is 15°C. The quality is approximately 0~1.0.

<table>
<thead>
<tr>
<th>Tube material</th>
<th>SUS316</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter of tube [mm]</td>
<td>2, 4, 6</td>
</tr>
<tr>
<td>Oil type</td>
<td>PAG100</td>
</tr>
<tr>
<td>Oil concentration [wt%]</td>
<td>0.5~5.0</td>
</tr>
<tr>
<td>Mass velocity [kg/(m²·s)]</td>
<td>360, 720, 1440</td>
</tr>
<tr>
<td>Heat flux [kW/m²]</td>
<td>4.5, 9, 18, 36</td>
</tr>
<tr>
<td>Evaporating temperature [°C]</td>
<td>15</td>
</tr>
<tr>
<td>Quality</td>
<td>Approximately 0~1.0</td>
</tr>
</tbody>
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mm tube at an oil concentration of 1\% and mass fluxes of 360 kg/m$^2$s and 1440 kg/m$^2$s, respectively. In general, the heat flux positively influences the heat transfer coefficient in the low quality region at a small mass flux. However, in the high quality region or at a large mass flux, no obvious influence of the heat flux on the heat transfer coefficient is observed.

Since the density ratio of liquid to vapor is low in the case of CO$_2$, nucleate boiling is considered the dominant mechanism in the flow boiling of CO$_2$. Further, the heat transfer coefficient mainly depends on the heat flux and is independent of the mass flux. The entrainment of lubricating oil in CO$_2$ results in the suppression of nucleate boiling to some extent depending on the mass flux. Figure 5 shows the measured heat transfer coefficient at heat fluxes of 4.5–36 kW/m$^2$ and a small mass flux of 360 kg/m$^2$s. The heat transfer coefficient increases with the quality in the pre-dryout region at heat fluxes of 4.5 kW/m$^2$ and 9 kW/m$^2$, indicating the influence of convective boiling. In contrast, at heat fluxes of 18 kW/m$^2$ and 36 kW/m$^2$, the pre-dryout heat transfer coefficient does not change with the quality. In the low quality region, as the heat flux increases from 4.5 kW/m$^2$ to 36 kW/m$^2$, the heat transfer coefficient increases by approximately 100\%. However, no obvious influence is observed in the high quality region. This implies that nucleate boiling dominates in the low quality region, while it is suppressed in the high quality region. Moreover, the dryout quality and the post-dryout heat transfer coefficient do not change with the heat flux.

Figure 6 shows the effect of the heat flux at a large mass flux of 1440 kg/m$^2$s. The heat transfer coefficient in both pre- and post-dryout regions and the dryout quality are not influenced by the heat flux. As in the case of the oil-free condition, dryout occurs at a small quality of 0.4 when the mass flux is 1400 kg/m$^2$s. In the post-dryout region, the heat transfer coefficient increases with the quality.

![Figure 5. Measured heat transfer coefficients of 2 mm tube at different heat fluxes. $x = 1\%$ and $G = 360$ kg/m$^2$s.](image1)

![Figure 6. Measured heat transfer coefficients of 2 mm tube at different heat fluxes. $x = 1\%$ and $G = 1440$ kg/m$^2$s.](image2)
3.3 Effect of mass flux on heat transfer coefficient

Figure 7 shows the measured heat transfer coefficients of the 2 mm tube at mass fluxes of 360–1440 kg/m²s and a heat flux of 18 kW/m². Similar results at a heat flux of 36 kW/m² are shown in Figure 8. Under the oil-free condition, the heat transfer coefficient at a large mass flux is slightly less than that at a small mass flux, and dryout occurs at a small quality for a large mass flux. When lubricating oil is entrained, the heat transfer coefficient increases significantly with the mass flux in the pre-dryout region at a low heat flux. This increase is attributed to the influence of convective boiling since the influence of nucleate boiling is suppressed by the oil. However, at a high heat flux of 36 kW/m², no obvious difference is observed in the heat transfer coefficients at different mass fluxes in the pre-dryout region, as shown in Figure 8. Dryout occurs early at the high mass flux, and it is not influenced by the heat flux. The tendency of the heat transfer coefficient to vary with the quality in the post-dryout region differs according to the mass flux. At a large mass flux, the heat transfer coefficient increases with the quality, while at a low mass flux, the reverse tendency is observed.

![Figure 7. Measured heat transfer coefficients of 2 mm tube at different mass fluxes.](image)

![Figure 8. Measured heat transfer coefficients of 2 mm tube at different mass fluxes.](image)

3.4 Effect of tube diameter on heat transfer coefficient

Figure 9 shows the measured pre-dryout heat transfer coefficients at tube diameters of 2–6 mm. The heat transfer coefficient is compared at different heat fluxes from 4.5 kW/m² to 36 kW/m² at an oil concentration of 1% and a mass flux of 360 kg/m²s. At all tube diameters, the heat transfer coefficient increases with the heat flux. This tendency becomes more significant in the case of small tubes. Because the ratio of the heating surface to the mass flux increases with a decrease in the inner diameter of the tube, the increase in the heat transfer effect of the heat flux becomes significant in the case of small tubes. As shown in Figure 9, at the heat flux of 36 kW/m², the heat transfer coefficient increases by 15% when the tube diameter decreases from 4 mm to 2 mm. However, when the tube diameter decreases from 6 mm to 2 mm, the heat transfer coefficient increases by 100%.

![Figure 9. Measured heat transfer coefficients of 2 mm tube at different mass fluxes.](image)
3.5 Effect of oil concentration on pressure drop

Figure 10 shows the effect of the oil concentration on the pressure drop. The pressure drop is compared at the tube diameters of 2–4 mm, heat flux of 18 kW/m², and mass flux of 720 kg/m²s. The pressure drop is calculated from the difference in the pressure at the inlet and outlet of the test section. The pressure drop increases with the tube diameter because a longer tube is needed to evaporate the CO₂ from saturation liquid state \((x = 0)\) to saturation vapor state \((x = 1)\). At the same tube diameter, the pressure drop monotonously increases with the oil concentration. At the oil concentration of 5%, the pressure drop increases by 80% of its value under the oil-free condition. This result is attributed to the formation of an oil layer along the inner wall of the tube and an increase in viscosity due to the entrainment of lubricating oil in CO₂.

![Figure 9. Measured heat transfer coefficients at different tube diameters and heat fluxes. \(G = 360\) kg/m²s and \(x = 1\%\).](image)

![Figure 10. Measured heat transfer coefficients of 4 mm tube at different oil concentrations. \(Q = 18\) kW/m² and \(G = 720\) kg/m²s.](image)

4. CONCLUSIONS

In this study, the flow boiling heat transfer of CO₂ with a small amount of PAG-type lubricating oil was studied experimentally. The main conclusions are summarized as follows:

1. The heat transfer coefficient decreases sharply at a critical oil concentration. The critical oil concentration for a tube with an inner diameter of 2 mm is approximately 0.5%, while that for tubes with inner diameters of 4–6 mm is approximately 1%. However, the heat transfer coefficient does not decrease further at higher oil concentrations.

2. The heat flux positively influences the pre-dryout heat transfer coefficient at a small mass flux in the low quality region. This is due to the effect of nucleate boiling. At a large mass flux or in the high quality region, no obvious difference is observed when the heat flux is varied. Moreover, the heat flux does not influence the dryout quality and the post-dryout heat transfer coefficient.

3. At a low heat flux, the heat transfer coefficient in the pre-dryout region increases with the mass flux. However, at a large heat flux, the influence of the mass flux on the pre-dryout heat transfer...
The coefficient is not significant. The dryout quality decreases at a large mass flux.

(4) As the tube diameter decreases, the increase in the heat transfer coefficient due to the heat flux in the pre-dryout region becomes significant.

(5) The pressure drop monotonously increases with the oil concentration. This is attributed to an increase in the viscosity of the CO₂-oil mixture and the formation of an oil layer along the inner wall of the tube.

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REFERENCES


