Flow Pattern and Void Fraction of Refrigerant
Two-phase Flow in a Horizontal Pipe

By Kenichi HASHIZUME

An experiment on a refrigerant two-phase flow in a horizontal pipe was performed for flow pattern observation and void fraction measurement. Refrigerants used were R12 and R22, and the saturation pressure range was from 5.7 to 19.6 bar.

From obtained data it was found that the flow pattern of the refrigerant two-phase flow can be presented on a revised Baker map, where the property correction factor on surface tension was modified. It was also found that the influence of the shut-off speed in void fraction measurement is negligible. Experimental data on void fraction agree well with Zivi, Thom and Baroczy correlation approximated by Butterworth.

Multiphase Flow, Refrigerants, Vapor-Liquid, Two-phase Flow, Experimental Data, Flow Pattern, Void Ratio

1. Introduction

Because of the complexity in flow behavior, theoretical treatment of a gas/liquid two-phase flow is not easy. Therefore most investigations on two-phase flows have been carried out experimentally, and many empirical correlations to predict the flow pattern, void fraction and pressure drop have been proposed. To clarify the range of applicability and the accuracy of these correlations, much experimental data are necessary. The purpose of this investigation is to collect data on flow pattern and void fraction of refrigerants in such a pressure range as encountered in practical situations. Obtained data are compared with existing correlations.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Subscripts</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>Pipe diameter</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Mass flux</td>
<td>AA Air at ambient</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>conditions</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>C Critical</td>
</tr>
<tr>
<td>x</td>
<td>Quality</td>
<td>G Gas phase</td>
</tr>
<tr>
<td>α</td>
<td>Void fraction</td>
<td>L Liquid phase</td>
</tr>
<tr>
<td>η</td>
<td>Viscosity</td>
<td>WA Water at ambient</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>conditions</td>
</tr>
<tr>
<td>σ</td>
<td>Surface tension</td>
<td></td>
</tr>
</tbody>
</table>

2. Range of Experimental Conditions

A large amount of data has been obtained on gas/liquid two-phase flows. The data are compiled in data banks, for example of Dukler[1]. Most data, however, relate to air/water two-component systems, and only limited data are available for one-component systems of refrigerants in the higher pressure ranges[2].

Chawla[3] performed experiments with refrigerant R11, and Bandel[3] experimented with R11, R12 and R22, where only one of three parameters, i.e. saturation temperature (pressure), flowrate and quality, was changed systematically. In these experiments, however, due to limitations of the apparatus, the pressure was relatively low (from 0.6 to 3.6 bar), and the void fraction was not measured.

Taking this background into consideration, the pressure range in this experiment was chosen to be from 5.7 to 19.6 bar; and the refrigerants chosen were R12 and R22, which are used in practical applications, such as refrigerators or Rankine-cycle engines.

The inner diameter of the horizontal test section was 10 mm. The experimental conditions are summarized in Table 1.

3. Experimental Equipment

To produce a controlled two-phase flow in the test section, a natural circulation loop, Fig. 1, was used. From the condenser, which is located about 10 metres above the horizontal measuring section, the refrigerant in liquid phase flows via the downcomer, strainer, flowmeter and control valves into the pre-cooler. After the quality settles in the pre-heater, the refrigerant two-
Table 1 Experimental Range and Conditions

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>R12</th>
<th>R22</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_b$ (°C)</td>
<td>20</td>
<td>39</td>
</tr>
<tr>
<td>$P_b$ (bar)</td>
<td>5.7</td>
<td>9.4</td>
</tr>
<tr>
<td>$P_g / P_c$</td>
<td>0.14</td>
<td>0.23</td>
</tr>
<tr>
<td>$W$ (kg/h)</td>
<td>25, 35, 50, 70, 100</td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>0.1, 0.3, 0.5, (0.7), 0.8, (0.9)</td>
<td></td>
</tr>
</tbody>
</table>

Phase flow reaches the measuring section, which consists of the entrance region, the pressure drop measuring section, the void fraction measuring section, the flow pattern observation section and the exit region. When the refrigerant two-phase flow leaves the measuring section, it is heated into a superheated gas in the after-heater, and returns, via the riser, to the condenser. Bypass opens only during void fraction measurement, when the shut-off valves are closed.

Loop piping consists of 3/8-inch Cu-pipe (9.53 mm OD x 0.8 mm thick) for the liquid phase and 3/8-inch Cu-pipe (15.9 mm OD x 1.0 mm thick) for the gas phase. The inner diameter of the test tube and the opening of two shut-off valves are 10 ± 0.05 mm.

All piping and components of the loop were thermally insulated with 50 mm glass wool, except for some parts of the void fraction measuring section and the flow pattern observation section. Further the loop except the condenser was in a room with an air conditioner. The room temperature was held at a constant value, which was 5 to 10 K below the saturation temperature in the measuring section.

For cooling the condenser and the pre-cooler, cold brine pumped from cold brine tanks was used. The three heaters, i.e. the pre-heater, the after-heater and the start-up-heater, were heated electrically. The flowmeter was a Rota-meter with electrical output.

Figure 2 shows the measuring section. In this experiment, pressure drop was also measured, the results, however, will be discussed in another paper.

4. Flow Pattern Observation and Results

The two-phase flow pattern was determined by visual observation through the Pyrex glass of the flow pattern observation section shown in Fig. 3. Flow patterns observed in this experiment were 5 types, i.e. stratified, wavy, slug, semi-annular, and annular flow as classified by Akagawa. Semi-annular is a transient flow pattern to an annular flow, where a continuous liquid film flow can be observed, but the liquid film at the top of the pipe is too much thinner than that at the bottom to be determined as an annular flow.

The experimental results are shown in Fig. 4, presented on the Baker map, which is most widely known and used. Here, two property correction factors are:

$$\lambda = \left( \frac{\rho_g}{\rho_w} \right)^{1/2} \left( \frac{\rho_w}{\rho_{wa}} \right)^{1/2}$$  \hspace{1cm} (1)

$$\psi = \frac{\sigma_{wa}}{\sigma_w} \left( \frac{\rho_w}{\rho_{wa}} \right)^{2/3} \left( \frac{\rho_{wa}}{\rho_g} \right)^{1/3}$$  \hspace{1cm} (2)

It can be seen in Fig. 4, that the Baker boundaries differ considerably from experimental results, and the boundaries of this experiment move systematically with saturation temperature (pressure).

The magnitude of each correction term in Eqs. (1) and (2) is shown in Fig. 5 in this experimental range, compared with air/water system. Because the property correction term on surface tension $\sigma$ in refrigerants differs mostly from air/water system, it can be said that the influence of surface tension is overestimated in the Baker map.

The obtained correction factor, by which the boundaries do not move with saturation temperature, is
Fig. 2 Test Section

Fig. 4 Experimental Results of Flow Pattern
Presented on the Baker Map
ambient conditions), are also shown. They coincide approximately with the boundaries obtained by the author.

Because the correction term \( \eta_{\text{WA}} / \eta_{L} \) for air/water system is nearly unity, the modified Baker map with Eq. (3) is practically identical with the original Baker map for air/water system.

5. Void Fraction Measurement and Results

Void fraction measurement was performed by the shut-off method, using the apparatus shown in Fig. 7. A signal from the electrical circuit causes 3-way air valves to move, and so causes the air at about 5 bar from the compressed air tank to activate the shut-off valves. The shut-off time, i.e., the time from the beginning to the end of shut-off, could be set at 0.05 to 2 seconds by speed controllers. The time was measured with photocouplers and discs on the rotating axis of the shut-off valves. The signals from the photocouplers were recorded on a recorder via an electrical circuit. After the two shut-off valves have closed, the magnetic valve opens, allowing the refrigerant to flow through the bypass.

The gas/liquid mixture of refrigerant, which was trapped between the two shut-off valves, was expanded to the ambient pressure through a needle valve. Then, in a heat exchanger, it was heated to the room temperature, with its volume measured by a gas meter. Void fraction \( \omega \) was calculated from the measured total volume of refrigerant under ambient conditions. The influence of shut-off time on void fraction measurement was investigated in this experiment, because this has not been discussed in other publications. Figure 8 shows the results. It is evident that the influence of shut-off time is negligible. During the experiments, which produced the data, shut-off time was kept at about 0.1 second, and the two shut-off valves always closed within ±0.5% of the shut-off time.

Figure 9 shows the results with existing correlations approximated by Butterworth (8) (see Appendix). Among them the correlation of Zivi, Thom and Baroczy agreed well with that of this experiment. It is because of the sluggish flow pattern that the
obtained data scatter in small quality region.

6. Conclusions

Experiments with a refrigerant two-phase flow in a horizontal pipe were performed for observation of flow pattern and void fraction. The collected data were compared with existing correlations. Conclusions within this experimental range can be summarized as follows:
1) Boundaries of flow pattern for refrigerant two-phase flow differ considerably from those of Baker map.
2) Flow pattern can be presented well on the modified Baker map, where only the property correction factor on surface tension is modified.
3) The boundaries coincide approximately with the boundaries by Schlicht for air/water.
4) The influence of shut-off time on void fraction measurement is negligible, provided the two shut-off valves can be closed simultaneously.
5) Measured void fraction agrees well with existing correlations of Zivi, Thom and Baroczy approximated by Butterworth.

Fig. 7 Measuring system of void fraction

Fig. 8 Influence of Shut-Off Time on Void Fraction Measurement

Fig. 9 Experimental Results of Void Fraction
Appendix: Void fraction correlation approximated by Buttersouth

\[
\alpha = \frac{1}{1 + A \left( \frac{1 - \rho_p}{\rho_a} \right) \left( \frac{\eta_a}{\eta_p} \right) \left( \frac{\rho_a}{\rho_p} \right)^{1-q} \left( \frac{B}{\rho_p} \right)^{r}}
\]  

(4)

Values of constants \( A, p, q \) and \( r \) are given in Table 2.

<table>
<thead>
<tr>
<th>Correlation or model</th>
<th>A</th>
<th>p</th>
<th>q</th>
<th>r</th>
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<tr>
<td>Homogeneous model</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Sivi model</td>
<td>1</td>
<td>1</td>
<td>0.67</td>
<td>0</td>
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<tr>
<td>Turner &amp; Wallis model</td>
<td>1</td>
<td>0.72</td>
<td>0.40</td>
<td>0.08</td>
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<tr>
<td>Lockhart &amp; Martinelli</td>
<td>0.28</td>
<td>0.64</td>
<td>0.36</td>
<td>0.07</td>
</tr>
<tr>
<td>Thom</td>
<td>1</td>
<td>1</td>
<td>0.89</td>
<td>0.18</td>
</tr>
<tr>
<td>Barošov</td>
<td>1</td>
<td>0.74</td>
<td>0.65</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 2 Values of Constants in Eq. (4)

References
(1) Dukler, A. E., Univ. Houston (1962-4)
(2) Choudhury, J. M., VDI-Forsch.-h. 523 (1967)
(3) Bandel, J., Diss. Univ. Karlsruhe (1973-2)
(5) Baker, G., Oil Gas J., July 1954, p. 185