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# BRIEF COMMUNICATION

# FLOW PATTERN, VOID FRACTION AND PRESSURE DROP OF REFRIGERANT TWO-PHASE FLOW IN A HORIZONTAL PIPE—III

## COMPARISON OF THE ANALYSIS WITH EXISTING PRESSURE DROP DATA ON AIR/WATER AND STEAM/WATER SYSTEMS

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## 1. INTRODUCTION

In Part II of this series of papers (Hashizume *et al.* 1985) an analysis was presented of two-phase flows in horizontal pipes. This analysis was compared with pressure drop data presented in Part I (Hashizume 1983a) and other existing data on refrigerants, and good agreement was observed between them. In this paper, it is demonstrated that this analysis can be applicable to air/water and steam/water systems also.

## 2. COMPARISON OF THE ANALYSIS WITH EXISTING DATA ON AIR/WATER AND STEAM/WATER SYSTEMS

Experimental data on the horizontal pipes to be compared here are listed in tables 1 and 2. They are taken from the HTFS (Heat Transfer and Fluid Flow Service, England) data bank. These data include experimental data concerning the effect of surface roughness on the frictional pressure drop (AW-08 to AW-13), therefore, some correction terms must be introduced into the analysis to compare with these data.

One of the proposed correction terms for rough surfaces is that of Bandel (1973):

$$\left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\mathrm{rough}} = \left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\mathrm{smooth}} \cdot \left(10^3 \cdot \frac{k}{d}\right)^{0.25} \quad \text{for} \quad \frac{k}{d} \geqslant 10^{-3}, \qquad [1]$$

where $\mathrm{d}P/\mathrm{d}L$ is the pressure drop per unit length, $k$ is the surface roughness and $d$ is the pipe diameter.

In figure 1 this analysis, coupled with the surface roughness correction after [1], is compared with experimental data for each quality $x$ range in the form of mean relative error $\epsilon$ defined as

$$(\pm)\epsilon = \frac{\displaystyle\sum^{N}(\pm)\frac{\left[\left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\mathrm{measured}} - \left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\mathrm{calculated}}\right]}{\left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\mathrm{calculated}}}}{N}, \qquad [2]$$

where $N$ is the number of data points for $[(\mathrm{d}P/\mathrm{d}L)_{\mathrm{measured}} - (\mathrm{d}P/\mathrm{d}L)_{\mathrm{calculated}}]$ to be either positive or negative.

Table 1. Experimental data for air/water systems in horizontal pipes (taken from the HTFS data bank)

| Source | | $d$ | $P$ | $G$ | | |
|---|---|---|---|---|---|---|
| Label | Author (year) | (mm) | (MPa) | (kg/m$^2$ s) | $x$ | $k/d$ |
| AW-01 | Wicks (1958) | 26.0 | 0.16–0.93 | 153–864 | 0.05–0.48 | $1.00 \times 10^{-4}$ |
| AW-02 | Wicks (1958) | 26.0 | 0.16–0.91 | 153–856 | 0.04–0.47 | $1.00 \times 10^{-4}$ |
| AW-03 | Jenkins (1947) | 25.4 | 0.10–0.42 | 44–741 | 0.00–0.53 | $1.00 \times 10^{-4}$ |
| AW-04 | Chenoweth & Martin (1955) | 40.7 | 0.10–0.67 | 27–3157 | 0.00–0.97 | $1.10 \times 10^{-3}$ |
| AW-05 | Chenoweth & Martin (1955) | 78.0 | 0.10–0.22 | 13–2638 | 0.00–0.97 | $6.00 \times 10^{-4}$ |
| AW-06 | Reid (1957) | 102.3 | 0.11–0.17 | 758–1538 | 0.00–0.04 | $7.00 \times 10^{-4}$ |
| AW-07 | Reid (1957) | 154.1 | 0.10–0.13 | 651–1707 | 0.00–0.02 | $7.00 \times 10^{-4}$ |
| AW-08 | Chisholm & Laird (1958) | 27.0 | 0.10–0.85 | 191–2796 | 0.00–0.33 | $1.00 \times 10^{-4}$ |
| AW-09 | Chisholm & Laird (1958) | 26.5 | 0.10–0.92 | 208–3019 | 0.00–0.33 | $2.50 \times 10^{-3}$ |
| AW-10 | Chisholm & Laird (1958) | 26.9 | 0.10–0.91 | 192–2833 | 0.00–0.33 | $1.30 \times 10^{-2}$ |
| AW-11 | Chisholm & Laird (1958) | 27.4 | 0.10–0.88 | 180–2632 | 0.00–0.33 | $3.70 \times 10^{-2}$ |
| AW-12 | Chisholm & Laird (1958) | 26.2 | 0.14–0.88 | 642–3130 | 0.00–0.10 | $4.50 \times 10^{-2}$ |
| AW-13 | Chisholm & Laird (1958) | 25.9 | 0.11–0.90 | 228–2938 | 0.00–0.26 | $6.80 \times 10^{-2}$ |
| AW-14 | Beggs (1972) | 38.1 | 0.57–0.68 | 60–1621 | 0.00–0.82 | $4.20 \times 10^{-5}$ |
| AW-15 | Beggs (1972) | 25.4 | 0.47–0.67 | 65–2622 | 0.00–0.83 | $6.30 \times 10^{-5}$ |

Table 2. Experimental data for steam/water systems in horizontal pipes (taken from the HTFS data bank)

| Source | | $d$ | $P$ | $G$ | | |
|---|---|---|---|---|---|---|
| Label | Author (year) | (mm) | (MPa) | (kg/m$^2$ s) | $x$ | $k/d$ |
| SW-01 | Wairakei (1966) | 198.8 | 0.13–1.91 | 407–1635 | 0.16–0.62 | — |
| SW-02 | Wickey (1956) | 12.3 | 2.86–5.62 | 444–4716 | 0.30–0.88 | $4.0 \times 10^{-3}$ |
| SW-03 | Moen (1956) | 12.3 | 6.91–9.76 | 482–3728 | 0.01–0.98 | $4.0 \times 10^{-4}$ |
| SW-04 | Baldina & Petterson (1966) | 29.5 | 1.09–19.71 | 66–1101 | 0.00–0.93 | $6.78 \times 10^{-4}$ |
| SW-05 | Janssen & Kervinen (1964) | 24.3 | 4.12–9.65 | 334–1372 | 0.09–0.98 | $3.70 \times 10^{-5}$ |
| SW-06 | Janssen & Kervinen (1964) | 32.2 | 6.89–6.90 | 378–774 | 0.10–0.89 | — |
| SW-07 | Janssen & Kervinen (1964) | 18.9 | 6.87–6.89 | 1125–2278 | 0.10–0.90 | — |
| SW-08 | James (1970) | 304.8 | 0.44–0.49 | 176–650 | 0.19–0.52 | — |

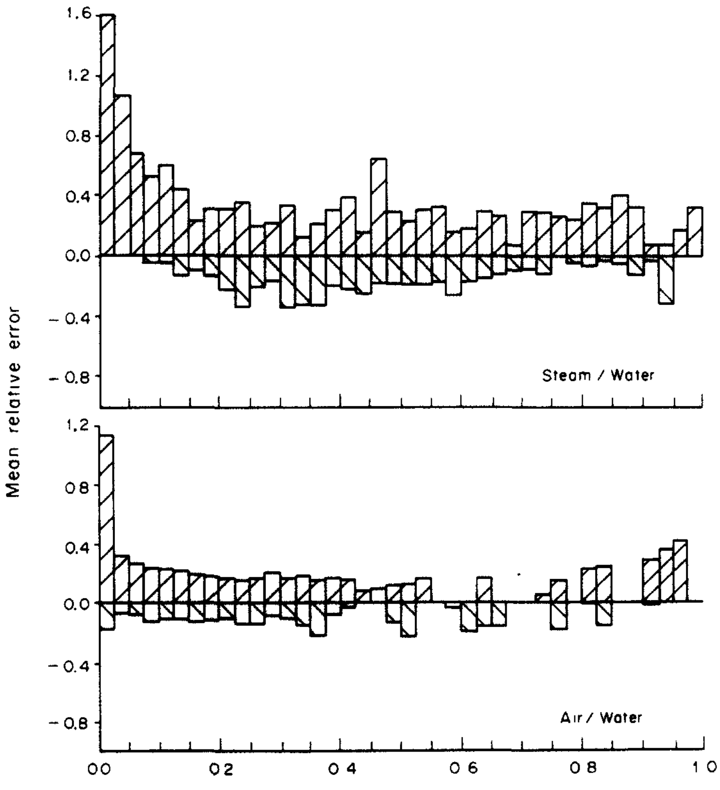


Figure 1. Mean relative errors for each quality range.

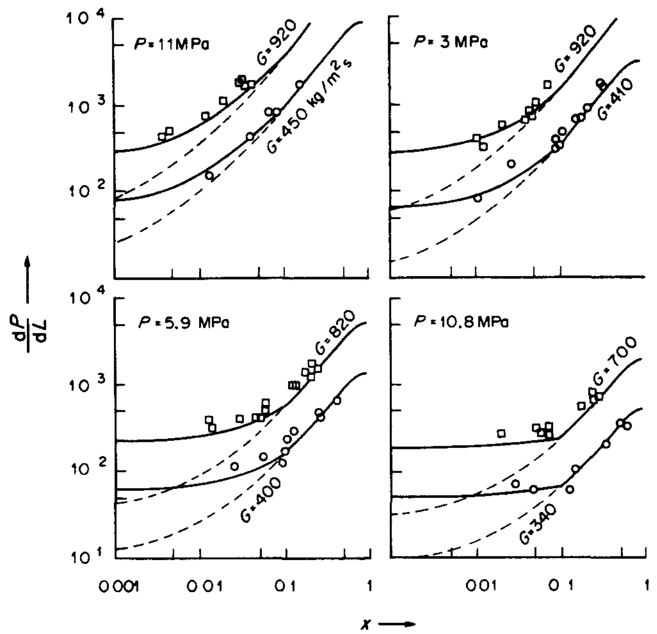


Figure 2. Comparison of this analysis with experimental data with (——) and without (---) linear interpolation [3] ($x_0 = 0.1$, data from SW-04 in table 2).

It is observed in figure 1 that $|\epsilon|$ becomes large in the small-quality region. This may be because the two-phase flow model presented in Part II considered only two flow patterns, annular and stratified flow. Therefore, the applicability of this analysis should be limited.

To predict the pressure drop in the small-quality region using this analysis, one can use the following linear interpolation without a large error:

$$\left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{0\leqslant x\leqslant x_0} = \left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\mathrm{L0}} + \left[\left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{x_0} - \left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\mathrm{L0}}\right]\cdot\left(\frac{x}{x_0}\right), \quad [3]$$

where the subscript L0 represents the value for $x = 0$, i.e. liquid single-phase flow, and $x_0$ is the smallest quality at which the pressure drop can be predicted from the analysis without the interpolation. This approximation is based on the notion that the pressure drop for $x \to 0$ must approach the value of single-phase flow.

In figure 2, data from SW-04 (see table 2) are compared with the predictions with (—) and without (---) linear interpolation after [3]. The value $x_0 = 0.1$ is chosen and the following expressions for single-phase flows, after Friedel (1979), are used:

$$\left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\mathrm{L0}} = \zeta\frac{G^2}{2\rho_{\mathrm{L}}d} \quad [4]$$

and

$$\left.\begin{aligned} \zeta &= \frac{64}{\mathrm{Re}_{\mathrm{L0}}} \quad \text{for} \quad \mathrm{Re}_{\mathrm{L0}} \leqslant 1055 \\ &= \left[0.86859\ln\left(\frac{\mathrm{Re}_{\mathrm{L0}}}{1.964\ln\mathrm{Re}_{\mathrm{L0}} - 3.8215}\right)\right]^{-2} \quad \text{for} \quad \mathrm{Re}_{\mathrm{L0}} > 1055 \end{aligned}\right\} \quad [5]$$

where $G$ is the mass flux, $\rho_{\mathrm{L}}$ the liquid density, $\mathrm{Re}_{\mathrm{L0}}(=Gd/\mu_{\mathrm{L}})$ the Reynolds number and $\mu_{\mathrm{L}}$ the liquid viscosity. One can see in figure 2 that [3] with $x_0 = 0.1$ gives relatively good prediction, although this may not be the best value.

It is possible to use a similar approximation in the large qualities, i.e. an interpolation between the value for a certain quality and that for gas single-phase flow. The data listed in tables 1 and 2, however, are not enough to determine the limit quality, and in figure 1 $|\epsilon|$ does not increase in the large-quality region.

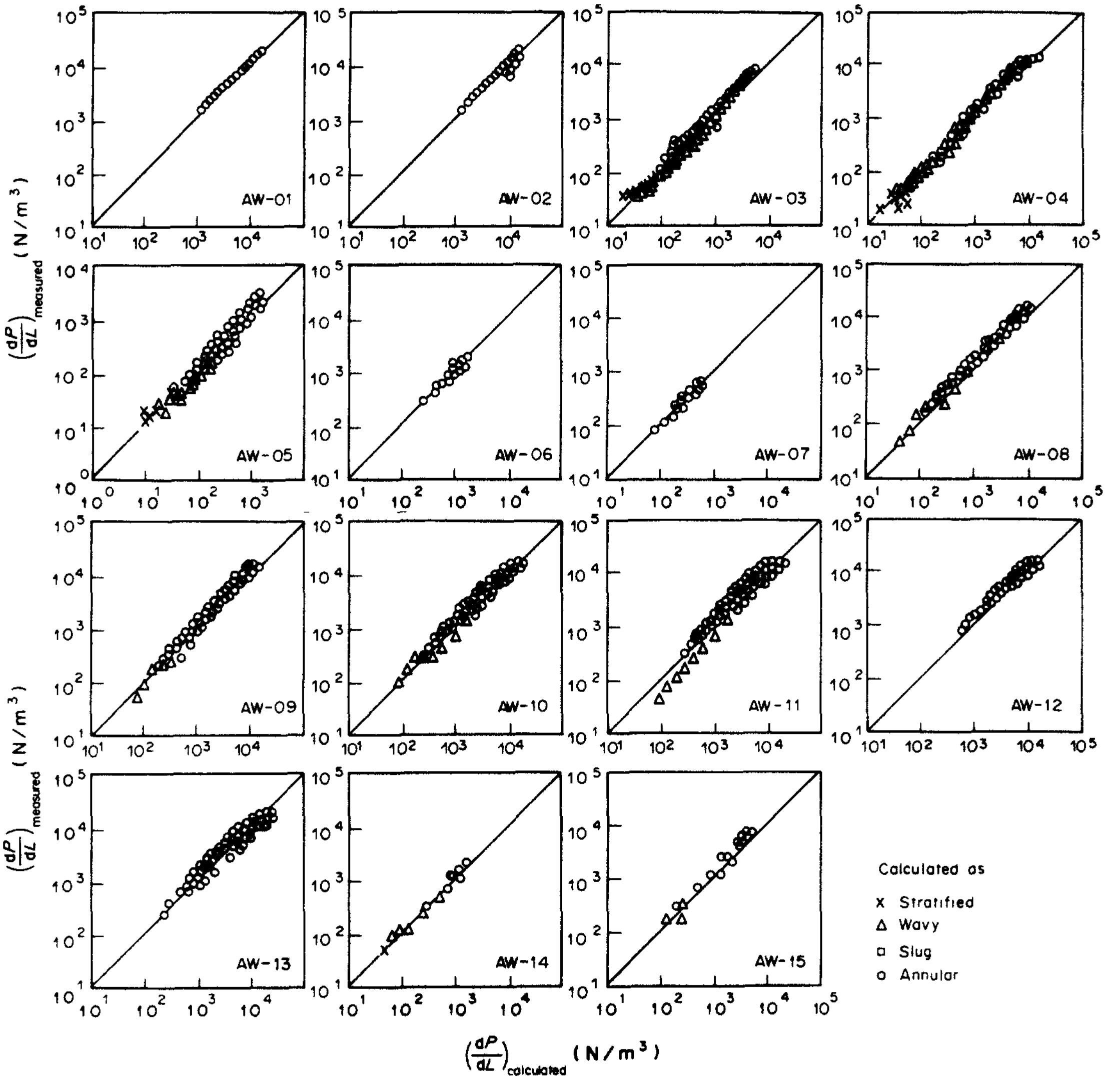


Figure 3. Comparison of this analysis with air/water systems data (labels given in table 1).

Figures 3 and 4 show comparisons of this analysis with all the data listed in tables 1 and 2, along with [1] for rough surfaces and [3] for small qualities. In these figures the symbols represent the data points calculated as: a stratified flow, ×; as a slug flow, □ (using the annular flow model); as an annular flow, ○; and as a wavy flow, △ (linear interpolation between stratified flow and annular flow models). Flow patterns of the data points of qualities $<0.1$ are represented by those for $x = 0.1$. These flow patterns were predicted according to the modified Baker map by Hashizume (1983b). Table 3 shows the percentage-wise fraction of data points predicted within $\pm 30\%$ for each flow pattern. About 2/3 of the total data points and about 2/3 of the annular flow data are predicted within $\pm 30\%$. Better agreements are seen for the data of stratified and wavy flows. In the analysis of stratified flows, one empirical correlation, the relationship between the distance of two parallel plates and the pipe diameter, is included and this was based on only refrigerant data. Nevertheless, figures 3 and 4 and table 3 show that the anlaysis of stratified flows can be applicable to air/water and steam/water systems also.

## 3. COMPARISONS WITH EXISTING CALCULATION METHODS FOR THE FRICTIONAL PRESSURE DROP

There exist some well-known calculation methods for the frictional pressure drop of two-phase flows in horizontal pipes (Lockhart & Martinelli 1949; Bandel 1973; VDI-Wärmeatlas 1974; Storek

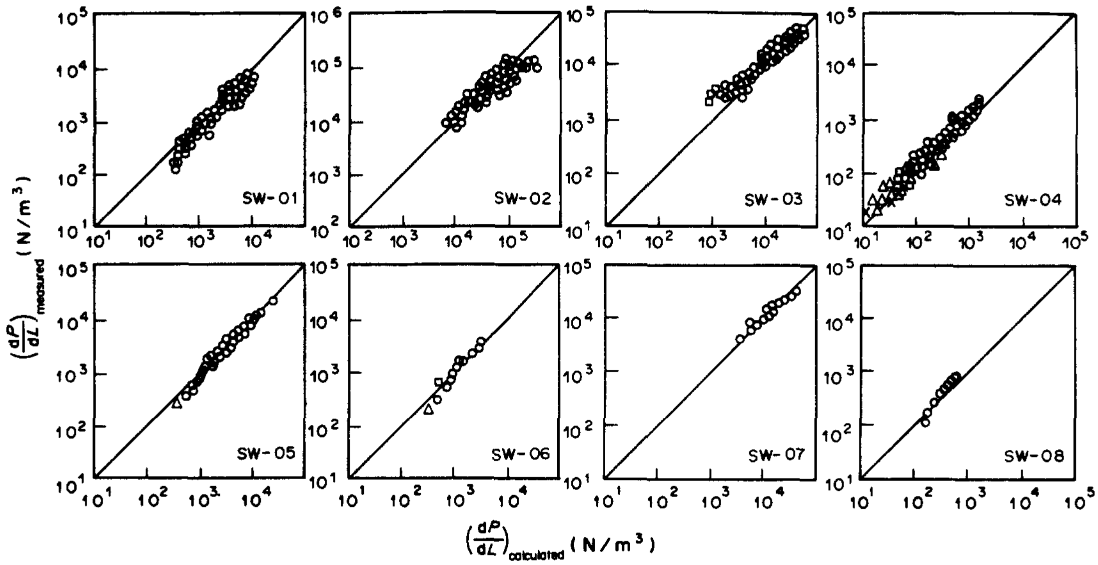


Figure 4. Comparison of this analysis with steam/water systems data (labels given in table 2).

& Brauer 1980), where the surface roughness correction is taken into account—except in Lockhart & Martinelli (1949).

Figure 5 shows comparisons of these calculation methods and this analysis with all the data listed in tables 1 and 2. Figure 6 shows comparisons with refrigernat data, listed in table 4. In these figures

Table 3. Percentage-wise fraction of data points predicted by this analysis within ±30%

| | | | Flow pattern | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total | | Stratified | | Wavy | | Slug | | Annular | |
| Source | NDP | ±30% | NDP | ±30% | NDP | ±30% | NDP | ±30% | NDP | ±30% |
| AW-01 | 114 | 79.8 | 0 | | 0 | | 0 | | 114 | 79.8 |
| AW-02 | 110 | 95.5 | 0 | | 0 | | 0 | | 110 | 95.5 |
| AW-03 | 573 | 86.6 | 44 | 93.2 | 214 | 94.4 | 0 | | 315 | 80.3 |
| AW-04 | 173 | 82.7 | 9 | 66.7 | 37 | 89.2 | 0 | | 127 | 81.9 |
| AW-05 | 110 | 51.8 | 6 | 66.7 | 27 | 55.6 | 2 | 100.0 | 75 | 48.0 |
| AW-06 | 15 | 93.3 | 0 | | 0 | | 0 | | 15 | 93.3 |
| AW-07 | 24 | 91.7 | 0 | | 0 | | 0 | | 24 | 91.7 |
| AW-08 | 76 | 38.2 | 0 | | 7 | 71.4 | 0 | | 69 | 34.8 |
| AW-09 | 79 | 53.2 | 0 | | 5 | 80.0 | 0 | | 74 | 51.4 |
| AW-10 | 76 | 40.8 | 0 | | 8 | 62.5 | 0 | | 68 | 38.2 |
| AW-11 | 75 | 29.3 | 0 | | 8 | 12.5 | 0 | | 67 | 31.3 |
| AW-12 | 44 | 47.7 | 0 | | 0 | | 0 | | 44 | 47.7 |
| AW-13 | 65 | 40.0 | 0 | | 0 | | 0 | | 65 | 40.0 |
| AW-14 | 14 | 50.0 | 1 | 100.0 | 5 | 60.0 | 0 | | 8 | 37.5 |
| AW-15 | 16 | 50.0 | 0 | | 3 | 100.0 | 0 | | 13 | 38.5 |
| SW-01 | 135 | 72.6 | 0 | | 0 | | 0 | | 135 | 72.6 |
| SW-02 | 105 | 40.0 | 0 | | 0 | | 0 | | 105 | 40.0 |
| SW-03 | 131 | 74.8 | 0 | | 0 | | 3 | 0.0 | 128 | 76.6 |
| SW-04 | 269 | 61.7 | 3 | 66.7 | 40 | 80.0 | 60 | 43.3 | 166 | 63.9 |
| SW-05 | 37 | 83.8 | 0 | | 1 | 100.0 | 0 | | 36 | 83.3 |
| SW-06 | 14 | 78.6 | 0 | | 1 | 100.0 | 1 | 0.0 | 12 | 83.3 |
| SW-07 | 14 | 92.9 | 0 | | 0 | | 0 | | 14 | 92.9 |
| SW-08 | 12 | 50.0 | 0 | | 0 | | 0 | | 12 | 50.0 |
| Total | 2281 | 69.2 | 63 | 85.7 | 356 | 85.7 | 66 | 42.4 | 1796 | 66.4 |

Flow patterns were predicted according to the modified Baker map by Hashizume (1983b). Slug flow data were predicted using the annular flow model. NDP means number of data points. ±30% Means the percentage-wise fraction of data predicted within ±30%.

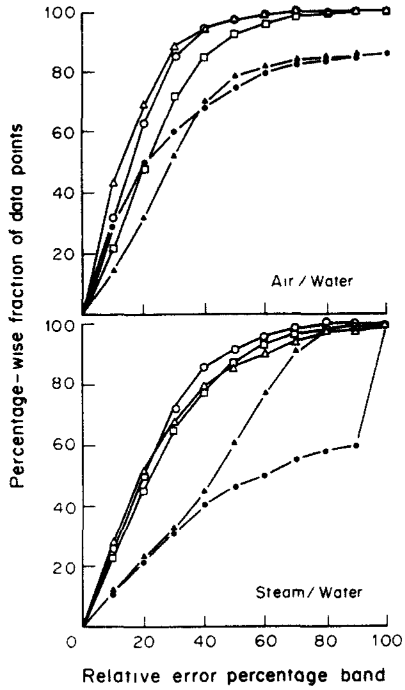


Figure 5. Comparisons of calculation methods with air/water and steam/water systems data (data given in tables 1 and 2): ▲, Lockhart & Martinelli (1949); △, Bandel (1973); ●, *VDI-Wärmeatlas* (1974); ○, Storek & Brauer (1980); □, this analysis.

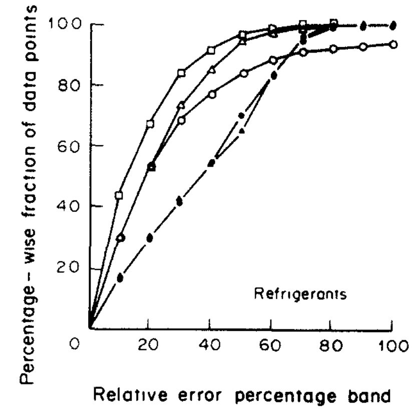


Figure 6. Comparisons of calculation methods with refrigerant data (data given in table 4): ▲, Lockhart & Martinelli (1949); △, Bandel (1973); ●, *VDI-Wärmeatlas* (1974); ○, Storek & Brauer (1980); □, this analysis.

comparisons are made in the form of relative errors, defined as

$$\frac{\left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\text{measured}} - \left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\text{calculated}}}{\left(\frac{\mathrm{d}P}{\mathrm{d}L}\right)_{\text{calculated}}} \times 100, \qquad [6]$$

and the percentage-wise fraction of data points within each relative error band is shown.

For air/water and steam/water systems, the Bandel and Storek & Brauer methods give very good prediction—this analysis predicts slightly less accurately.

For refrigerant data, this analysis gives the best prediction. This outcome may be partly because the qualities of these data are not small, therefore, the linear interpolation [3] is not used, and partly because the other calculation methods, especially the best two, Bandel and Storek & Brauer, are empirical correlations based mainly on the data from data banks, which do not include refrigerant data.

Table 4. Experimental data for refrigerants in horizontal pipes

| Source | | | | | | |
|---|---|---|---|---|---|---|
| Label | Author (year) | Refrigerant | $d$ (mm) | $P$ (MPa) | $G$ (kg/m$^2$ s) | $x$ |
| RF-01 | | | | 0.57 | | 0.09–0.81 |
| RF-02 | | R12 | | 0.94 | | 0.10–0.80 |
| RF-03 | Hashizume (1983a) | | 10.0 | 1.21 | 88–354 | 0.09–0.81 |
| RF-04 | | | | 0.92 | | 0.10–0.80 |
| RF-05 | | R22 | | 1.52 | | 0.09–0.90 |
| RF-06 | | | | 1.96 | | 0.08–0.91 |
| RF-07 | | | 6.0 | | 40–252 | 0.10–0.80 |
| RF-08 | Chawla (1967) | R11 | 14.0 | 0.06 | 25–135 | 0.10–0.90 |
| RF-09 | | | 25.0 | | 15–60 | 0.10–0.90 |
| RF-10 | | R11 | | 0.06 | 109–726 | 0.09–0.81 |
| RF-11 | Bandel (1973) | R12 | 14.0 | 0.31 | 104–726 | 0.08–0.91 |
| RF-12 | | R22 | | 0.36 | 88–755 | 0.09–0.82 |

## 4. CONCLUSION

The analysis of two-phase flows in horizontal pipes presented in Part II of this article was compared with existing data for air/water and steam/water systems, the surface roughness correction, after Bandel (1973), and linear interpolation in the small-quality region being taken into consideration. A good agreement was seen between this analysis and experimental data. Comparisons of this analysis and some well-known calculation methods wtih air/water, steam/water and refrigerant data showed that for refrigerant data this analysis gives the best prediction among the tested methods and for air/water and steam/water data it gives a slightly poorer prediction than the best two, i.e. Bandel (1973) and Storek & Brauer (1980).

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