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On the comparison of new pressure drop and hold-up data for horizontal air–water flow in a square cross-section channel against existing correlations and models

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Abstract

New data on pressure drop and liquid hold-up obtained in a horizontal square cross-section channel ($H = 0.02425$ m) were compared against several existing correlations and models for gas–liquid flow. The hold-up data were taken for conditions of wavy-stratified and pseudo-slug flow. Pressure drop results were only obtained for wavy-stratified flow. The correlation developed by Friedel correlates well the pressure drop results, according to the test method used. For the hold-up data, none of the correlations and models tested was able to predict the results. However, a modification in the constants of the model by Turner and Wallis was introduced, and the new expression fits the hold-up data well.

Keywords: Two-phase horizontal flow; Square cross-section channel; Pressure drop; Hold-up

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1. Introduction

Different flow patterns are observed when gas and liquid flow simultaneously through a pipe. These are governed by the physical properties of the fluids, the ratio of gas/liquid flow rates and the system geometry. In horizontal flow, gravity introduces an asymmetry into the system: the density difference between the two-phases causes the liquid to travel preferentially along the bottom of the tube. According to Hewitt et al. (1994), the following regimes can be identified: bubbly flow, plug flow, stratified flow (smooth and wavy), slug flow, pseudo-slug flow and annular flow.

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Stratified flow is characterized by the liquid flowing at the bottom of the tube whilst the gas passes over it. At low gas and liquid flow rates the gas–liquid interface is smooth (smooth stratified flow), but as gas flow rate increases the interface becomes wavy, with the waves traveling in the direction of the flow (wavy-stratified flow). For even higher gas flow rates, drops are torn from the surface of these waves giving drop entrainment in the gas.

The pseudo-slug flow occurs near the annular/slug, stratified/slug and stratified/annular flow transitions. Pseudo-slug flow is characterized by the presence of liquid flow patterns that have the appearance of slugs, but which do not give the identifying pressure pattern a liquid slug does. The liquid can touch the top of the tube momentarily, but do not block the entire pipe section.

Two-phase pressure drop and hold-up are parameters of great importance in the design of adiabatic and non-adiabatic systems. Numerous correlations and models have been developed to predict these two parameters, which are affected by the flow regime. Several authors have studied the performance of published correlations and models used to predict pressure drop and hold-up in horizontal gas–liquid flow against experimental data (e.g. Chen and Spedding, 1983; Sen and Spedding, 1991; Ferguson and Spedding, 1995; Tribbe and Muller-Steinhagen, 2000). These studies report mostly results obtained for two-phase flow in circular cross-section pipes.

In this paper, new data on pressure drop and liquid hold-up obtained in a horizontal square cross-section channel by Ferreira (2004) for wavy-stratified and pseudo-slug flows were compared against several existing correlations and models. For friction pressure drop, the correlation by Lockhart and Martinelli (1949) and the model by Beattie and Whalley (1982), developed for circular section tubes, the correlation by Friedel (1979) based on data for circular, rectangular and annular cross-section channels, and the correlation by Troniewski and Ulbrich (1984) developed for rectangular cross-section channels were tested. The hold-up data were compared against the models by Turner and Wallis (1965), by Abdul-Majeed (1996), and by Spedding and Cooper (2002), all developed for horizontal flow in circular cross-section tubes. Also, both sets of data were tested against the models for stratified flow proposed by Taitel and Dukler (1976), by Andritsos (1986) and by Spedding and Hand (1997) for circular tubes.

2. Experimental details

2.1. Experimental facility

The experimental apparatus used to obtain hold-up and pressure drop data was a horizontal perspex tube with an ID of 0.032 m, followed by a square cross-section channel where the experiments were carried out. The apparatus is fully described by Ferreira (2004). The air was delivered from a rotative compressor, was controlled by a pressure regulator and a valve, and was measured using a calibrated rotameter. The water was stored in a 100 L tank and was pumped through the system by a centrifugal pump and metered by a calibrated rotameter before flowing into the pipe. The air and the water entered the tube by a tee and were allowed to travel for 5 m to reach developed conditions, before entering the square test section.

The test section was constructed in perspex having a square cross-section ($H = 0.02425$ m), and a length of 2.3 m. Both ends included converging pieces that made a very smooth transition from the circular to the square geometry, and then from the square section back to the circular tube. The length of the square channel was chosen in order to be longer than 50 D_h, as specified by Troniewski and Ulbrich (1984), and where D_h is the hydraulic diameter of the channel ($D_h = H$ for the channel in study). The mixture of air/water returned to the stock tank through a section of PVC tube, where the air was vented and the water was re-circulated.

2.2. Pressure drop measurements

Pressure drop was measured using Validyne differential pressure transducers (1-N-24-S-4, 1-N-1-26-S-4 and 1-N-1-30-S-4) operating in the range of 225–500 mm H_2O. The pressure taps were located 5 mm from the base of the channel and were 0.825 m apart. The acquisition system consisted of a PC-LABCard-818HG data acquisition board connected to a computer. The pressure drop signal was recorded at a frequency of 250 Hz for a period of 5 min, using Labtech data acquisition software.

2.3. Hold-up measurements

A high precision digital video camera (Canon XM1) with a recording frequency of 25 Hz was mounted perpendicular to the frontal surface, close to the end of the test section. Two light stops were placed behind, making angles of 60° with the posterior surface, illuminating a white sheet of paper used to reflect and diffuse light onto the test section. The flow was recorded for a period of 5 min. The videos were treated using the Adobe Premiére 6.0 software package, in order to crop the area of interest, and assure conversion to Microsoft AVI format. A Matlab code was developed to analyze the resulting videos. Each individual frame was converted to gray scale mode (256 grey levels, with 0 representing black and 255 representing white) and the associated pixel intensity value was used as an indication of its luminosity. Frame binarisation was accomplished by using a threshold value, based on the average air–water interface contrast. This procedure allowed the definition of the interface height (at the same flow section) for all of the recorded video frames. Millimetric rulers placed on the front and rear faces allowed the conversion factor (pixels into length) to be calculated for calibration purposes. Using sufficient data to assure statistical significance, the mean liquid height was obtained.

3. Pressure drop and hold-up data

Hold-up and pressure drop data obtained is fully presented by Ferreira (2004). The hold-up data were obtained for liquid flow rates between 2.77×10^{-2} kg/s and 2.88×10^{-1} kg/s and gas flow rates in the range from 7.73×10^{-3} kg/s to 1.49×10^{-2} kg/s (Table 1 and Fig. 1). The wavy-stratified flow pattern was observed for liquid flow rates of 2.77×10^{-2} kg/s and 5.14×10^{-2} kg/s and for all gas flows. For higher liquid flow rates, the flow pattern was always pseudo-slug flow. A decrease, not far from linear, in the liquid hold-up was observed as the gas flow increases.

Pressure drop data was measured for the same range of gas flow rates, but for liquid flow rates of 2.77×10^{-2} kg/s and 5.14×10^{-2} kg/s (Table 2 and Fig. 2). This set of data consists of only 12 points due to the work conditions. The data on pressure drop refers solely to wavy-stratified flows, as mentioned previously. In the experiments, the flow patterns were determined by using video and still photography techniques.

The new data on pressure drop and liquid hold-up obtained in the horizontal square cross-section channel were compared against several existing correlations and models.

4. Test method

To evaluate the performance of the models and empirical correlations used, graphs of the experimental values (x) versus the calculated values from correlations and models (y) were constructed. These data were subjected to a least squares fitting of a straight line, $y = A + Bx$. Following this, an inference method related to the least squares fitting of a straight line, as proposed by Vardeman (1994), was used. This method estimates the mean response for a fixed value of the system variable x, and assumes that simultaneous two-side confidence intervals for all mean system responses can be taken by using respective end points, calculated by

$$(A + Bx) \pm \sqrt{2f}\sqrt{s_{\mathrm{LF}}^2}\sqrt{\frac{1}{n} + \frac{(x - x_{\mathrm{M}})^2}{\sum_{i=1}^{n}(x - x_{\mathrm{M}})^2}} \tag{1}$$

where

A	intercept of the linear relationship;
B	slope of the straight line obtained;
f	value obtained from an F table distribution, F_{n_1}, F_{n_2} with the degrees of freedom $n_1 = 2$ and $n_2 = n - 2$;
n	number of data points (x, y);
s_{LF}^2	line fitting sample variance;
x_{M}	arithmetic mean of the x values.

Table 1
Experimental hold-up data obtained in the square section channel

Liquid mass flow rate × 10^2 (kg/s)	Gas mass flow rate × 10^3 (kg/s)	Liquid hold-up × 10^1
2.77	7.73	1.76
2.77	9.85	1.55
2.77	11.6	1.34
2.77	13.1	1.25
2.77	14.1	1.14
2.77	14.9	1.09
5.14	7.73	1.92
5.14	9.85	1.65
5.14	11.6	1.52
5.14	13.1	1.38
5.14	14.1	1.32
5.14	14.9	1.23
7.51	7.73	2.58
7.51	9.85	2.30
7.51	11.6	1.98
7.51	13.1	1.89
7.51	14.1	1.80
7.51	14.9	1.70
9.88	7.73	2.69
9.88	9.85	2.43
9.88	11.6	2.30
9.88	13.1	2.13
9.88	14.1	2.03
9.88	14.9	1.97
12.2	7.73	2.74
12.2	9.85	2.48
12.2	11.6	2.38
12.2	13.1	2.26
12.2	14.1	2.14
12.2	14.9	2.05
14.6	7.73	2.87
14.6	9.85	2.62
14.6	11.6	2.48
14.6	13.1	2.31
14.6	14.1	2.21
14.6	14.9	2.12
17.0	7.73	2.98
17.0	9.85	2.80
17.0	11.6	2.69
17.0	13.1	2.66
17.0	14.1	2.52
17.0	14.9	2.35
19.4	7.73	3.27
19.4	9.85	3.05
19.4	11.6	2.81
19.4	13.1	2.78
19.4	14.1	2.64
19.4	14.9	2.63
21.7	7.73	3.53
21.7	9.85	3.20
21.7	11.6	3.07
21.7	13.1	3.03
21.7	14.1	2.97
21.7	14.9	2.93
24.1	7.73	3.70
24.1	9.85	3.29
24.1	11.6	3.09
24.1	13.1	3.08

Table 1 (continued)

Liquid mass flow rate × 10^2 (kg/s)	Gas mass flow rate × 10^3 (kg/s)	Liquid hold-up × 10^1
24.1	14.1	3.05
24.1	14.9	2.97
26.5	7.73	3.78
26.5	9.85	3.58
26.5	11.6	3.43
26.5	13.1	3.28
26.5	14.1	3.14
26.5	14.9	3.14
28.8	7.73	3.79
28.8	9.85	3.67
28.8	11.6	3.60

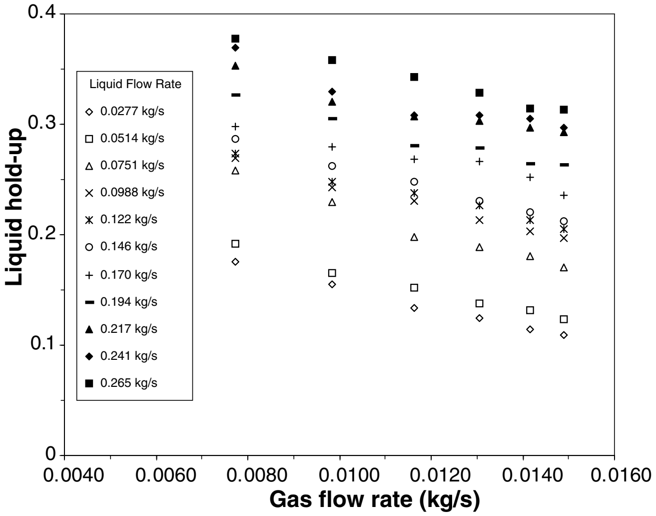

Fig. 1. Hold-up data obtained in the square section channel.

Table 2
Experimental pressure drop data obtained in the square section channel

Liquid mass flow rate × 10^2 (kg/s)	Gas mass flow rate × 10^3 (kg/s)	Pressure drop gradient × 10^{-2} (Pa/m)
2.77	7.73	2.63
2.77	9.85	4.06
2.77	11.6	5.15
2.77	13.1	6.11
2.77	14.1	6.84
2.77	14.9	8.17
5.14	7.73	4.46
5.14	9.85	5.43
5.14	11.6	7.34
5.14	13.1	9.04
5.14	14.1	10.2
5.14	14.9	11.9

In practical terms, the set of intervals given by Eq. (1) defines a region in the (x, y) plane, which is expected to contain the line $y = A + Bx$. To test if the chosen correlation (or model) fits the data well, it is considered that the line $y = x$ should fall within that region (Lopes (2004)).

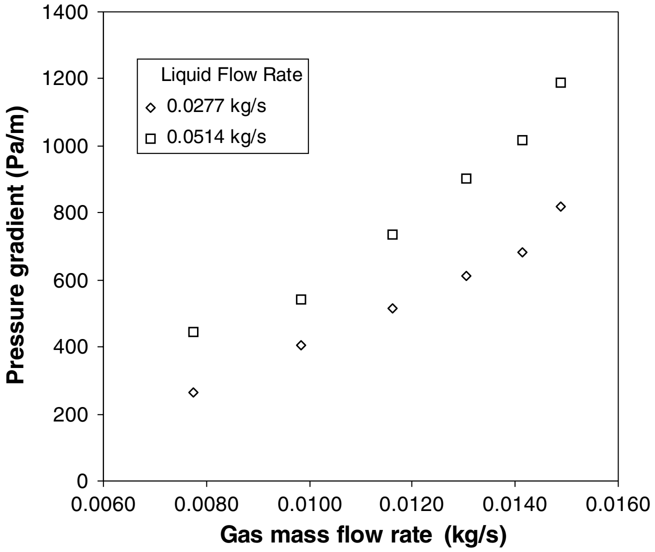

Fig. 2. Pressure drop data obtained in the square section channel.

5. Comparison of the experimental data

The correlations and models mentioned in Section 1 were used to fit the new experimental data obtained in the square cross-section channel. All these correlations and models, except the one by Troniewski and Ulbrich (1984), were developed for circular tubes. So, when the diameter of the tube appeared in the expressions, it was substituted by the hydraulic diameter of the channel. The parameters that are included in the models by Taitel and Dukler (1976), Andritsos (1986) and Spedding and Hand (1997) for stratified flow in circular tubes were adapted to the square section geometry.

In the method chosen to test the validity of the expressions to fit the experimental data (Section 4), the F distribution used was for an interval of confidence of 95%. Graphs were constructed, where the experimental data for the square cross-section channel were plotted against the calculated values by the various correlations and models. These graphs also contained the boundary lines calculated by Eq. (1) and the bisector of first quadrant ($y = x$).

For the pressure drop data, the model by Beattie and Whalley (1982) and the correlation by Troniewski and Ulbrich (1984) both under predicted the data. The same behaviour was observed for the stratified models by Taitel and Dukler (1976), Andritsos (1986) and Spedding and Hand (1997). It should be noted that although the models do not fit the data, it is not because the model is wrong, but rather that the model was applied to physical conditions outside the range for which it had been developed. A better result was obtained with the correlation of Lockhart and Martinelli (1949): the bisector of first quadrant was very close to the boundary curves, which define the region in the (x, y) plane, where the line of best fit of the data is supposed to be. Finally, the correlation of Friedel (1979) was the best of the correlations and models tested to fit the data, as seen in Fig. 3. The line $y = x$ falls completely within the space between the two limiting curves. This correlation was developed by using a data bank that included pressure drop data for rectangular cross-section channels and horizontal flow.

In addition to graphs for the pressure drop data, graphs of the experimental hold-up versus calculated hold-up were drawn, containing the line $y = x$ and the limiting curves defined by Eq. (1). Depending on the correlation (or model) tested, the liquid hold-up, R_L, or the gas hold-up, R_G, was used.

For the hold-up data, the models by Spedding and Cooper (2002) and by Abdul-Majeed (1996) under predicted the data. The model by Turner and Wallis (1965) over predicted the data. The stratified models by Taitel and Dukler (1976), Andritsos (1986) and Spedding and Hand (1997) presented a different behaviour: one part of the experimental points were over predicted by the expressions proposed in the models and the other part was under predicted, as the line $y = x$ crosses the set of experimental points.

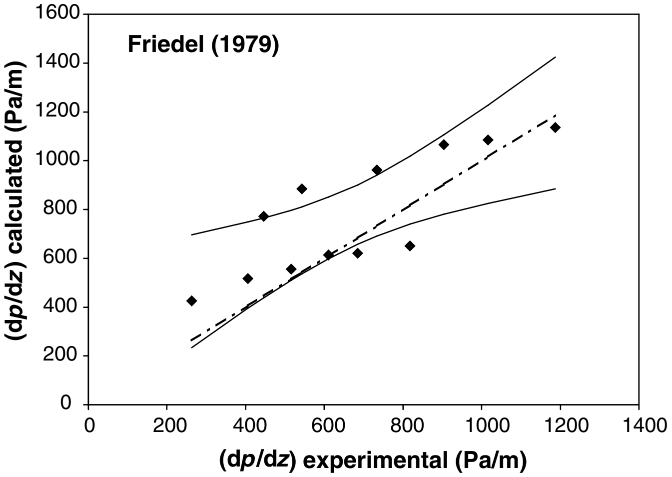

Fig. 3. Experimental versus calculated pressure drop using the correlation of Friedel (1979).

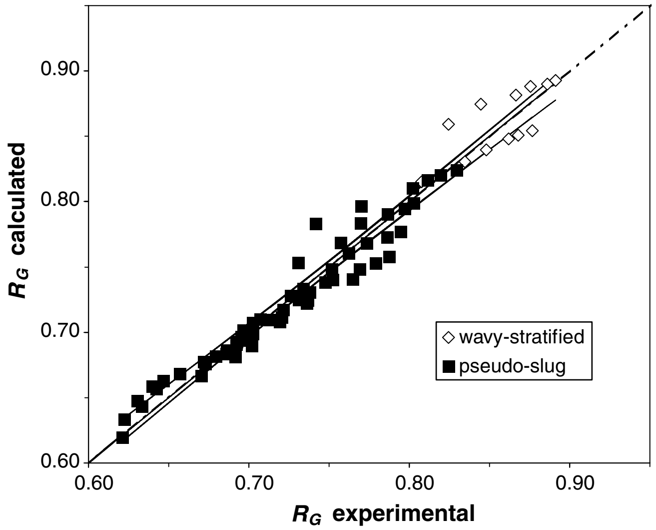

Fig. 4. Experimental versus calculated gas hold-up using the modification introduced in the model of Turner–Wallis (1965).

As all the correlations and models tested failed to preview the hold-up data for the square section channel according to the test method used, a modification in the constants of the model by Turner and Wallis (1965) was introduced. This was achieved by using an optimization process and the final expression obtained was

$$R_G = (1 + X^{0.666})^{-0.524} \tag{2}$$

where X represents the Martinelli parameter, defined by $X^2 = (\mathrm{d}p/\mathrm{d}z)_L/(\mathrm{d}p/\mathrm{d}z)_G$. The pressure gradients for the liquid and the gas flowing alone in the tube are, respectively, $(\mathrm{d}p/\mathrm{d}z)_L$ and $(\mathrm{d}p/\mathrm{d}z)_G$.

Fig. 4 shows the performance of Eq. (2) to represent the experimental data. It can be seen that the fit is accurate, as the line $y = x$ is inside the limits of the region defined by Eq. (1).

6. Conclusions

In the present study new experimental data on pressure drop and hold-up, in a horizontal square cross-section channel, were tested against several existing correlations and models. The following conclusions can be drawn:

- the model by Beattie and Whalley (1982), the correlation by Troniewski and Ulbrich (1984), and the stratified models by Taitel and Dukler (1976), Andritsos (1986) and Spedding and Hand (1997), under predict the experimental data on pressure drop;
- the correlation by Friedel (1979) correlates well the pressure drop results according to the test method used;
- the models by Spedding and Cooper (2002) and by Abdul-Majeed (1996) under predict the data on hold-up;
- the model by Turner and Wallis (1965) over predict the hold-up results;
- for the hold-up data, the stratified models by Taitel and Dukler (1976), Andritsos (1986), and Spedding and Hand (1997), have the following behaviour: one part of the experimental points is over predicted by the expressions proposed in the models and the other part is under predicted;
- a modification in the constants of the model by Turner and Wallis (1965) was introduced and the new expression fits the data on hold-up well.

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