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Pressure drop and void fraction profiles during horizontal flow through thin and thick orifices

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Abstract

Two-phase flow pressure drop through singularities such as thin and thick orifices has been experimentally investigated. The study refers to air–water horizontal flows in 60 and 40 mm pipes. The operating conditions cover the gas and liquid superficial velocity ranges $V_{sg} = 0.3$–4 m/s and $V_{sl} = 0.6$–2 m/s, respectively. Intermittent flows have been observed. The local pressure drop has been obtained by means of extrapolation from upstream and downstream linearized pressure profiles. Single-phase measurements have been carried out for local liquid Reynolds values ranging from 3×10^4 to 2×10^5 to obtain the discharge coefficient and calculate the two-phase local multiplier. The effect of orifice geometry has been considered by selecting six different singularities with two different area contraction ratios ($\sigma = 0.73$ and $\sigma = 0.54$) and different thickness (from 0.025 to 0.59 restriction diameters). The analysis of the results and their comparison with available relationships revealed a lack in the prediction capability of literature correlations for high values of the flow area ratio. Finally the void fraction profiles obtained by means of ring impedance probes showed that generally the effect of the singularity is to increase the void fraction values just downstream the orifice with differences up to 50% with respect to the straight pipe values. © 2002 Published by Elsevier Science Inc.

Keywords: Two-phase flow; Flow in singularity; Void fraction measurement

1. Introduction

Pressure drop versus mass flow rate relations for two-phase flows through valves, orifices and other pipe fittings are important for the control and operation of such industrial plants as chemical reactors, power generation units, refrigeration apparatuses, oil wells, and pipelines.

Orifice plates are mainly used for single-phase and two-phase flow measurement but single orifices or arrays of them constituting perforated plates, are often used to reduce flow non-uniformities or to increase the heat–mass transfers in thermal and chemical processes (e.g. distillation trays).

The proper design and control of such systems, where pipe fittings changing the flow area (valves, orifices, nozzles) are inserted, need reliable predicting procedures to evaluate local pressure losses as well as upstream and downstream effects. This problem becomes crucial with two-phase mixtures due to the uncertainty about phase distribution as an effect of singularity action.

Single-phase flows across singularities have been extensively studied, as shown by Idelchik in his handbook [1]. On the other hand available correlations do not always take into account Reynolds number effect or a complete set of geometrical parameters.

Major uncertainties exist with reference to two-phase flows: few studies devoted to the argument are available and often refer to a limited set of operating conditions. With particular reference to orifice plates, most correlations and models [2–4] are discussed in a paper by Friedel [5]. Other references are the early study by Janssen [6], the work by Lin on two-phase flowmeters [7], the recent experimental investigation by Saadawi et al., which refers to two-phase flows across orifices in large diameter pipes [8], and the work by Kojasoy et al. on multiple orifice plates [9].

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Nomenclature

A	flow area (m^2)
C_d	discharge coefficient
D	pipe diameter (m)
d	restriction diameter (m)
g	acceleration of gravity (m/s^2)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
S	slip ratio
s	orifice thickness (m)
V	velocity (m/s)
V_s	superficial velocity (m/s)
x	mixture quality
x_v	gas volume fraction ($x_v = V_{sg}/(V_{sg} + V_{sl})$)
z	distance from phase injection (m)
z'	distance from restriction (m)
Greek symbols	
α	void fraction
ρ	density (kg/m^3)
σ	area ratio ($\sigma = (d/D)^2$)
σ_c	contraction coefficient
ϕ^2_{lo}	two-phase multiplier
Subscripts	
c	vena contracta
g	gas
l	liquid
sp	single phase

Some aspects of the two-phase flow in such singularities appear to need further insight. One question is related to the effect of the orifice thickness, which does not directly appear in available correlations. Furthermore most of experimental data refer to restrictions having an area ratio $\sigma < 0.5$. Finally most models require the knowledge of local void fraction, which is usually calculated by means of correlations for straight pipes without singularities and hence the actual void fraction distribution due to constriction interactions is not considered.

The present work is part of a research program aimed at developing new correlations and models for pressure drops in straight pipes and singularities [10–12]. In the present study the local pressure drop and void fraction profiles have been evaluated for sharp-edge orifices with area contraction ratios σ equal to 0.73 and 0.54 during horizontal intermittent flow of air and water. The effect of orifice thickness has been also considered since thin and thick orifices have been tested according to Chisholm classification [3].

2. Experimental setup and procedures

The experimental apparatus consists of a horizontal test section where air and water can be mixed to generate the two-phase flow under bubble, stratified and intermittent flow regimes. A sketch of the test loop is shown in Fig. 1 while complete description of the plant is available in [11]. Transparent pipes, carefully chosen to match the inner diameters at the tube ends, allow the inspection of the flow pattern; the test section is 12 m long. Two different horizontal test pipes were employed, having inner diameters D equal to 60 and 40 mm respectively.

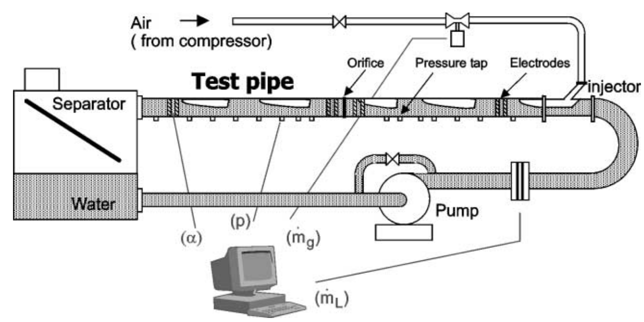

Fig. 1. Experimental apparatus.

The singularity is located 6 m downstream the phase mixer. The effect of orifice geometry has been considered by selecting 12 different singularities as a result of two different area contraction ratios ($\sigma = 0.73$ and $\sigma = 0.54$) and three different thickness, nominally $s/d = 0.025$ (or 0.027 or 0.05), 0.20 and 0.59, being d the restriction diameter. According to Chisholm criteria [3] the restriction having $s/d = 0.59$ can be classified as a "thick" orifice. The fluid used were air and water near atmospheric pressure (reference pressure 1.1–1.4 bar). The gas and liquid superficial velocities were imposed to get intermittent flows. In particular plug flows were observed for gas superficial velocities up to 0.7 m/s and slug flows for higher gas flow rate, irrespective of the liquid flow rate [13]. Gas superficial velocities (calculated according to the pressure measurements collected 5 m downstream the phase mixer) turned out to be in the range $V_{sg} = 0.3$–4 m/s, while liquid superficial velocities were found to be in the range $V_{sl} = 0.6$–2 m/s.

The test pipe is equipped with 15 pressure taps that are connected by means of electrovalves to the pressure transducers. Air purge of connecting pipes is carried at each run. The local pressure values are calculated as average of 4096 samples collected at 100 Hz frequency. The pressure profiles upstream and downstream the singularity allows the singular pressure drop to be extrapolated according to the typical method employed in single-phase flow studies. The procedure was repeated for single and two-phase flows in order to infer the singular two-phase multiplier ϕ_{lo}^2, calculated at liquid mass flux equal to the overall two-phase mass flux [11]. In particular here the multiplier is the ratio between the measured two-phase pressure drop in the singularity over the single-phase pressure drop calculated by means of the average value of the orifice discharge coefficient C_d pertinent to each restriction for Re_d values greater than 50,000 (see next paragraph).

The test apparatus is also equipped with resistive probes at different locations from the mixer. The probes, whose characteristics and calibration procedure are described in [14,15], allowed the area void fraction α to be inferred. In this study only the time-average value of α is discussed.

Three probes were employed in the 60 mm pipe, located at $z/D = 33$, 100 and 160 respectively from the injection. With reference to the distance from singularity z', the probes were located at -66, 1 and 61 pipe diameters D. The 40 mm test pipe was equipped with four probes, two of which were mounted just upstream and just downstream the discontinuity (at $z'/D = -2$ and $z'/D = 1$), while the remaining two were mounted at $z'/D = -55$ and 105 ($z/D = 95$ and 255 respectively).

For what concerns the uncertainties in evaluating the local two-phase multiplier, the deep analysis of available data (more than 300 experiments) shows that random errors prevail over the errors introduced by the instrumentation (flow meters and pressure transducers) that were carefully calibrated before (and checked during) the investigation. Random errors yield data scatter around the regression lines that describes the upstream and downstream pressure profiles. According to Moffat suggestions [16] on computerised analysis of errors, experimental values of residuals in the regression lines were employed to calculate the uncertainties in estimating the single and two-phase pressure drop in the singularity. It was found that in single-phase flows the 95% uncertainty is about 3% and 10% for restrictions having respectively 0.54 and 0.73 area contraction ratio. In two-phase flow the uncertainty is about 13% ($\sigma = 0.54$, $D = 0.04$, 0.06 m), 14% ($\sigma = 0.73$, $D = 0.04$ m) and 18% ($\sigma = 0.73$, $D = 0.06$ m). As a consequence the local two-phase multiplier is affected by overall uncertainty of about 13% ($\sigma = 0.54$), 17% ($\sigma = 0.73$, $D = 0.04$ m) and 20% ($\sigma = 0.73$, $D = 0.06$ m). It is worthwhile noticing that with $\sigma = 0.73$ the uncertainty should be increased by 3%–5% when the liquid velocity is low (0.6 m/s) and the gas velocity is high (more than 2.5 m/s).

Finally, the uncertainty estimation analysis on void fraction values was carried out in [15] and it resulted about 4%.

3. Theoretical background

3.1. Single-phase flow

The theoretical analysis to evaluate the pressure drop caused by abrupt contraction of the flow area is carried out using a one-dimensional approach (see Fig. 2). If the flow occurs through a sharp edge "thin" orifice, the flow contracts, with negligible losses of mechanical energy, to a vena contracta of area A_c that forms outside the restriction. Downstream of the vena contracta the flow expands in an irreversible process to the pipe wall of flow area A. If the orifice is "thick", downstream of the vena contracta the flow reattaches to the wall within the length of the geometrical contraction and can even develop a boundary layer flow until it finally expands back into the pipe wall. According to Chisholm [3], the thick orifice behavior takes place when the dimensionless orifice thickness s/d (i.e. referred to restriction diameter d) is greater than 0.5. According to the above described model and based on the assumption that each expansion occurs irreversibly and the fluid is incompressible, the single-phase pressure drop Δp_{sp} in a thin orifice can be expressed as a function of the flow area ratio $\sigma = (d/D)^2$ and the contraction coefficient $\sigma_c = A_c/(A\sigma)$ as:

$$\Delta p_{sp} = \frac{\rho V^2}{2}\left[\left(\frac{1}{\sigma\sigma_c} - 1\right)\right]^2, \quad (1)$$

where ρ is the fluid density and V its mean velocity.

If the constriction behaves as a thick orifice, the loss of mechanical energy is due to the double expansion above described. For these conditions the single-phase overall pressure drop can be expressed as:

$$\Delta p_{sp} = \frac{\rho V^2}{2}\left[\left(\frac{1}{\sigma\sigma_c}\right)^2 - 1 - \frac{2}{\sigma^2}\left(\frac{1}{\sigma_c} - 1\right) - 2\left(\frac{1}{\sigma} - 1\right)\right]. \quad (2)$$

The local pressure drop can also be expressed as a function of other parameters than the area flow ratio.

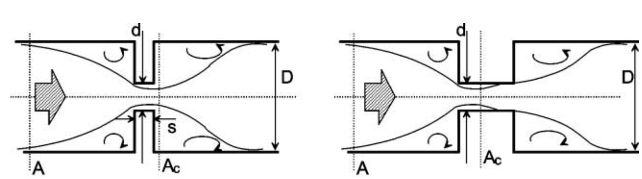

Fig. 2. Single-phase flow across thin (a) and thick (b) orifices.

One of these parameters is the orifice discharge coefficient C_{d} that can be defined (cf. Lin [7], Grace and Lapple, [17], Smith and Van Winkle [18]) according to the following expression:

$$\Delta p_{\mathrm{sp}} = \frac{\rho V^2}{2}\left[\left(\frac{1}{\sigma}\right)^2 - 1\right]\frac{1}{C_{\mathrm{d}}^2}. \tag{3}$$

Starting from Eqs. (1)–(3) a relationship between C_{d} and σ_{c} can be found with reference to thin and thick orifices respectively:

$$\sigma_{\mathrm{c,thin}} = \frac{1}{\sigma + \sqrt{(1-\sigma^2)}/C_{\mathrm{d}}}, \tag{4}$$

$$\sigma_{\mathrm{c,thick}} = \frac{1}{1 + \sqrt{[(1-\sigma^2)/C_{\mathrm{d}}^2] - 1 + 2\sigma - \sigma^2}}. \tag{5}$$

According to the above equations, the local pressure drop Δp_{sp} can be predicted provided that a relationship among σ_{c} and known geometrical parameters is available. Such relationships, experimentally obtained, usually require only the knowledge of the area flow ratio [3,19,20], as in the well known Chisholm expression:

$$\sigma_{\mathrm{c}} = \frac{1}{\left[0.639(1-\sigma)^{0.5} + 1\right]}. \tag{6}$$

3.2. Two-phase flow

Available models for contraction and expansion in two-phase flows follow the scheme adopted in single-phase flows. Such models (based on incompressible flow assumption) allow the existence of a vena contracta even if the experimental observations give no assurance that a non-homogeneous two-phase flow follows exactly the one-dimensional behavior of single-phase flows. In the literature the main studies are those by Janssen [6], Chisholm [3], Simpson et al. [2], Morris [4], Kojasoy et al. [9]. As Friedel pointed out in his review paper [5], all the pressure drop models based on non-homogeneous flow conditions are not independent calculations methods since they need an empirical correlation for the slip S (or mean void fraction α) and some assumptions about the slip ratio variation across the singularity with respect to the unrestricted flow. The accuracy of prediction is thus directly linked up with the proper selection of the void fraction correlation which is the key parameter for pressure drop evaluation.

According to Chisholm and Morris, the slip ratio S is a function of the quality x and fluid density. When the Lockart–Martinelli χ parameter is greater than unity (typical of low quality mixtures such as those obtained in the present investigation, $x < 0.005$) the slip ratio can be expressed as:

$$S = \left[1 + x\left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{g}}} - 1\right)\right]^{0.5}. \tag{7}$$

The above correlation provides slip predictions in good agreement with Armand and Threschev correlation [21] for fully developed flow in the same flow conditions. This correlation, near atmospheric pressure, can be expressed in terms of the gas volume fraction $x_{\mathrm{v}} = V_{\mathrm{sg}}/(V_{\mathrm{sg}} + V_{\mathrm{sl}})$:

$$S = \frac{1 - 0.833x_{\mathrm{v}}}{0.833(1 - x_{\mathrm{v}})}. \tag{8}$$

Kojasoy et al. adopt the Chisholm expression for slip ratio S but they suggest a correction to account for the effect of flow restriction on slip ratio as compared with the case of unrestricted flow:

$$S = \left\{\left[1 + x\left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{g}}} - 1\right)\right]^{0.5}\right\}^{n}. \tag{9}$$

The exponent n is zero at the vena contracta and downstream of it (i.e. the slip ratio is expected to be one) while n is equal to 0.4 and 0.15 in the upstream region of thin and thick orifices respectively.

Finally, in their model, Simpson et al. [2] adopted a different correlation for slip evaluation that does not account for the quality of the mixture:

$$S = \left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{g}}}\right)^{1/6}. \tag{10}$$

The prediction of the two-phase multiplier ϕ_{lo}^2 of the local pressure losses that would occur if the liquid phase were flowing alone through the singularity, can be calculated using different models.

The following is a short review of available relationships.

If the mixture can be considered homogeneous ($S = 1$ all over the test pipe), the expression below can be obtained:

$$\phi_{\mathrm{lo}}^2 = \frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{g}}}x + (1 - x). \tag{11}$$

Chisholm [3], adopting a description of the two-phase flow across the constriction which is based on a single-phase like behavior with vena contracta, developed the following expression:

$$\phi_{\mathrm{lo}}^2 = 1 + \left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{g}}} - 1\right)\left[Bx(1-x) + x^2\right]. \tag{12}$$

Parameter B is a function of the area flow ratio σ, of the single-phase contraction coefficient σ_{c}, of the slip ratio S (as expressed in Eq. (7)) and has different expressions for thin and thick orifices. As Chisholm himself suggests, parameter B can be assumed equal to 0.5 for thin orifices and equal to 1.5 for thick ones.

The approach adopted by Kojasoy et al. [9] is very similar to that of Chisholm and the same expression (Eq. (11)) is proposed for the pressure multiplier evaluation. Some differences exist in the definition of the B parameter related to thin and thick orifices which is expressed in terms of local slip ratio in three different locations (just upstream of the geometrical restriction, at the vena contracta, downstream of it, Eq. (9)).

Morris relationship [4] refers to thin orifices and gate valves and has the following expression:

$$\phi_{\mathrm{lo}}^2 = \left[x\frac{\rho_\mathrm{l}}{\rho_\mathrm{g}} + S(1-x)\right] \times \left[x + \left(\frac{1-x}{S}\right)\left(1 + \frac{(S-1)^2}{(\rho_\mathrm{l}/\rho_\mathrm{g})^{0.5}-1}\right)\right], \quad (13)$$

where the slip ratio is expressed according to Eq. (7), without any limitation on flow conditions.

Simpson et al. [2] proposed the following relationship based on slip predictions by means of Eq. (10):

$$\phi_{\mathrm{lo}}^2 = [1 + x(S-1)]\left[1 + x\left(S^5 - 1\right)\right]. \quad (14)$$

Simpson model is based on data collected with large diameter pipes (up to 127 mm) at mixture qualities generally higher than those obtained in this work ($x < 0.005$).

Finally the latest correlation of Saadawi et al. [8], based on experiments carried out at near atmospheric pressure with a very large diameter pipe (203 mm), has the simple form:

$$\phi_{\mathrm{lo}}^2 = 1 + 184x - 7293x^2. \quad (15)$$

4. Experimental results

4.1. Single-phase flow

From the measurements of the pressure profiles upstream and downstream of the constriction and the measurements of the liquid flow rate, the local pressure drop has been evaluated in terms of orifice discharge coefficient C_d from which the contraction coefficient σ_c has been obtained by means of Eqs. (4) or (5) (for $s/d = 0.59$). Figs. 3 and 4, which refer to either the 60 mm i.d. pipe or the 40 mm i.d. one, show the σ_c values as a function of restriction Reynolds number Re_d for different values of the flow area ratio. As can be observed, the contraction coefficient turns out to be independent of the Reynolds number for values above 5×10^4. For lower values of Reynolds number, the contraction coefficient generally increases with it. Finally

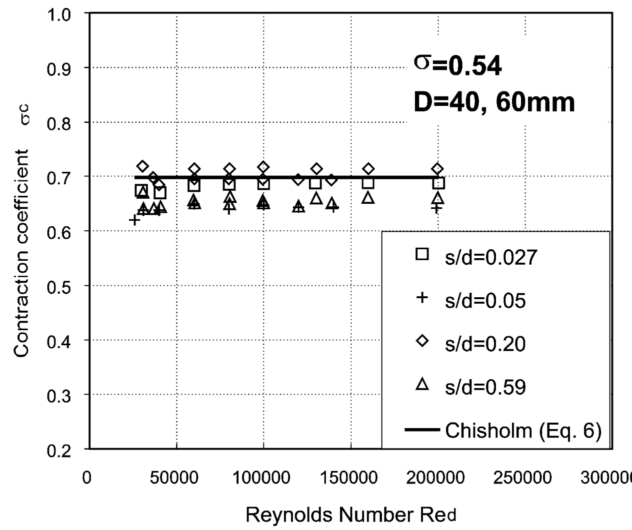

Fig. 3. Contraction coefficient as a function of local Reynolds number ($\sigma = 0.54$).

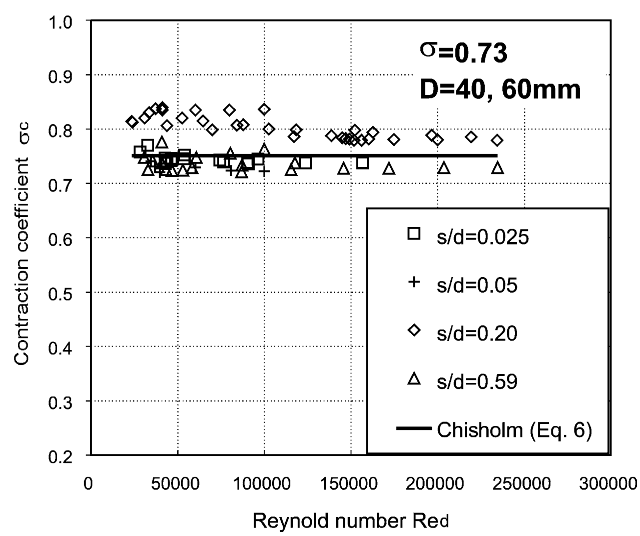

Fig. 4. Contraction coefficient as a function of local Reynolds number ($\sigma = 0.73$).

it can be noticed that the contraction coefficient data from experiments are in good agreement with Chisholm formula predictions (Eq. (6)), sketched as continuous lines in Figs. 3 and 4. Fig. 5 shows the effect of orifice thickness on the local pressure drop during the single-phase flow. As can be observed, the pressure drop across the $s/d = 0.20$ orifice is slightly smaller than that obtained with the $s/d = 0.027$ orifice, even if both contractions can be classified as thin orifices. As a consequence, the contraction coefficient calculated by means of Eq. (4) for the $s/d = 0.20$ orifice is greater than that calculated for the thinner orifices ($s/d \leqslant 0.05$).

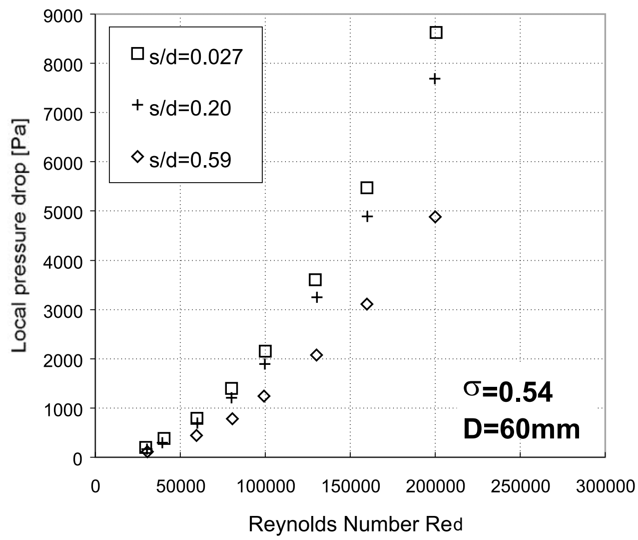

Fig. 5. Single-phase pressure drop as a function of local Reynolds number ($\sigma = 0.54$).

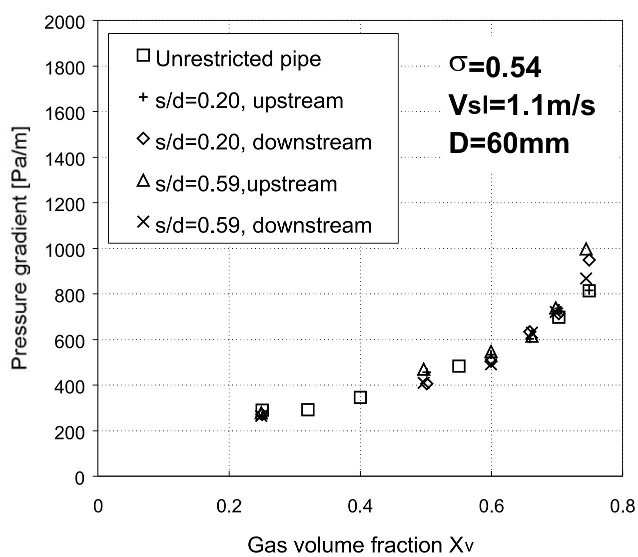

Fig. 6. Pressure gradient as a function of gas volume fraction ($\sigma = 0.54$).

4.2. Two-phase flow

The pressure loss, which can be ascribed to the contraction occurring during the two-phase flow, is calculated from known upstream and downstream pressure gradients. The procedure is based on the assumption that the singularity does not affect the pressure profiles with respect to the unrestricted flow. The analysis of experimental results and the comparison with data pertaining to the straight pipe flow, show that the assumption is generally satisfied, as can be noticed from Fig. 6 which refers to the experiments with the orifices having $\sigma = 0.54$. This evidence is confirmed for all the tested restrictions, even if the flow in the 60 mm i.d. pipe across the $\sigma = 0.73$ constriction showed upstream gradients higher than either the downstream ones or those pertaining to the unrestricted pipe for thicker orifices and higher values of gas volume fraction.

Typical pressure drop values as a function of gas and liquid superficial velocities are shown in Fig. 7a and b. It has been observed that the effect of the orifice thickness is stronger with the restrictions of the area flow ratio $\sigma = 0.73$, while the pressure drops across the $\sigma = 0.54$ orifices are always comparable, with deviations less than 15%.

The singular two-phase multiplier $\phi^2_{\rm lo}$ has been obtained by comparison with single phase measured pressure drops. The results are shown in Fig. 8a and b with reference to the restrictions having $\sigma = 0.54$ and in Fig. 9a and b that refer to the larger area flow ratio constrictions.

All these figures contain either the 60 mm i.d. pipe data (empty symbols) or the 40 mm i.d. pipe ones (filled symbols). The experimental data are compared with the predictions of the homogeneous model (Eq. (11)), and with the values calculated by the relationships of Chisholm for thick orifices (Eq. (12) with $B = 1.5$), Morris (Eqs. (7) and (13)) and Simpson et al. (Eqs. (10) and (14)). The Saadawi et al. relationship (Eq. (15)) has been discarded from the present comparisons due to the fact it underpredicts the experimental values with differences even greater than 100%. It can be observed that, in agreement with Simpson et al. experimental data, their model underpredicts the multiplier at low qualities typical of intermittents flows.

The main evidence from pressure multiplier analysis is that the influence of liquid flow rate is weak. Furthermore, it can be observed that the dimensionless pressure drops obtained for $s/d \leqslant 0.20$ (thin orifices) result in a narrow range of values. The thicker orifices ($s/d = 0.59$) are characterised by higher pressure multipliers, which can show values higher than those predicted by the homogeneous model (Eq. (11)). This occurrence can be mainly ascribed to the fact that as the restriction thickness increases (up to "thick orifice" values), the single-phase pressure drops decrease much more than the two-phase losses increase at the same liquid flow rate (cf. Figs. 5, 7a and b). Nevertheless the experimental values pertinent to thick orifices are quite well fitted by Chisholm formula (Eq. (12) with $B = 1.5$), the only one (together with Kojasoy et al. expression) able to account for orifice thickness.

A few comments can be made about the area flow ratio effect. As can be observed in Figs. 8a–9b, the pressure multipliers pertinent to the $\sigma = 0.73$ singularities show values close to the unity (or even lower) when the gas volume fraction is less than about 0.5. No available relationships can account for this effect, which seems to be peculiar to these moderate flow area restrictions. Since to the authors' knowledge, the experi-

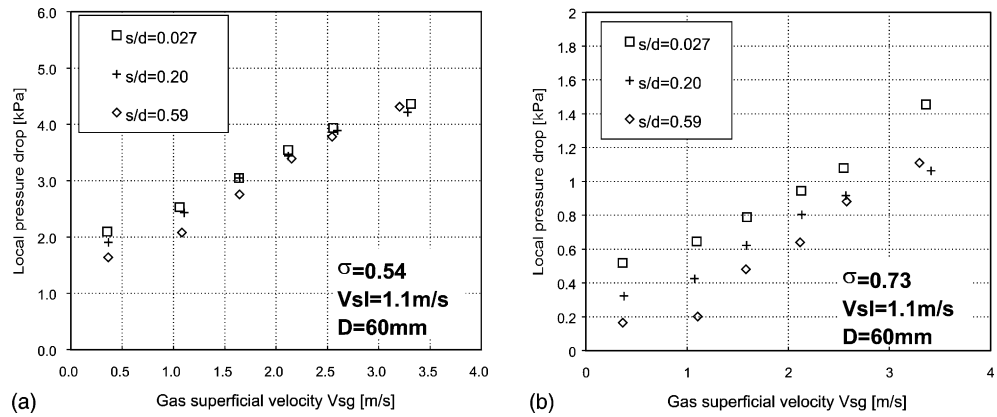

Fig. 7. (a) Local pressure drop as a function of gas volume fraction. Orifice thickness as parameter ($\sigma = 0.54$). (b) Local pressure drop as a function of gas volume fraction. Orifice thickness as parameter ($\sigma = 0.73$).

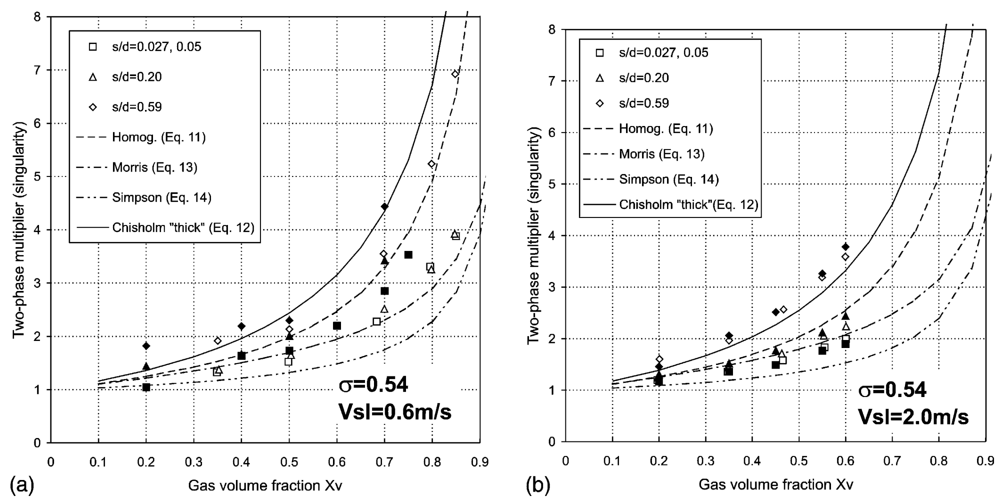

Fig. 8. (a) Pressure multiplier versus gas volume fraction. Orifice thickness as parameter, $V_{sl} = 0.6$ m/s ($\sigma = 0.54$, filled symbols $D = 40$, empty symbols $D = 60$ mm). (b) Pressure multiplier versus gas volume fraction. Orifice thickness as parameter, $V_{sl} = 2.0$ m/s ($\sigma = 0.54$, filled symbols $D = 40$, empty symbols $D = 60$ mm).

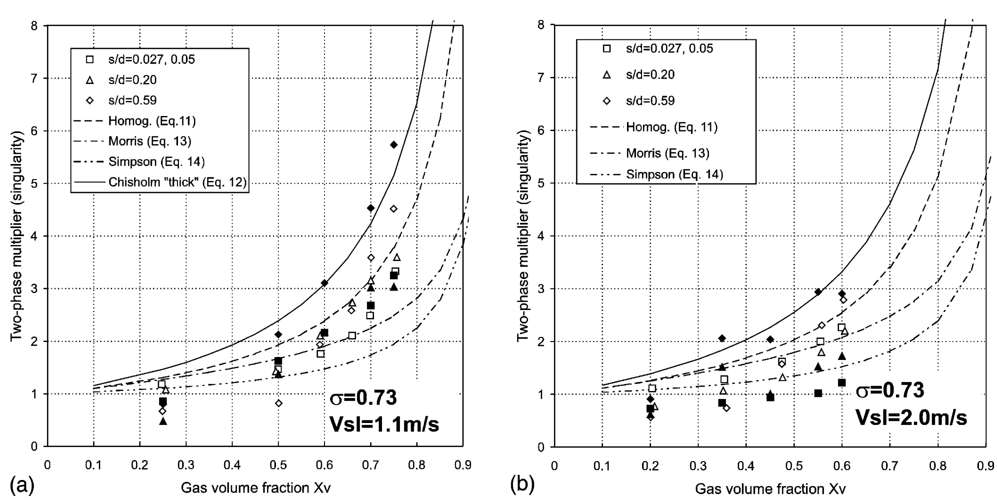

Fig. 9. (a) Pressure multiplier versus gas volume fraction. Orifice thickness as parameter, $V_{sl} = 1.1$ m/s ($\sigma = 0.73$, filled symbols $D = 40$, empty symbols $D = 60$ mm). (b) Pressure multiplier versus gas volume fraction. Orifice thickness as parameter, $V_{sl} = 2.0$ m/s ($\sigma = 0.73$, filled symbols $D = 40$, empty symbols $D = 60$ mm).

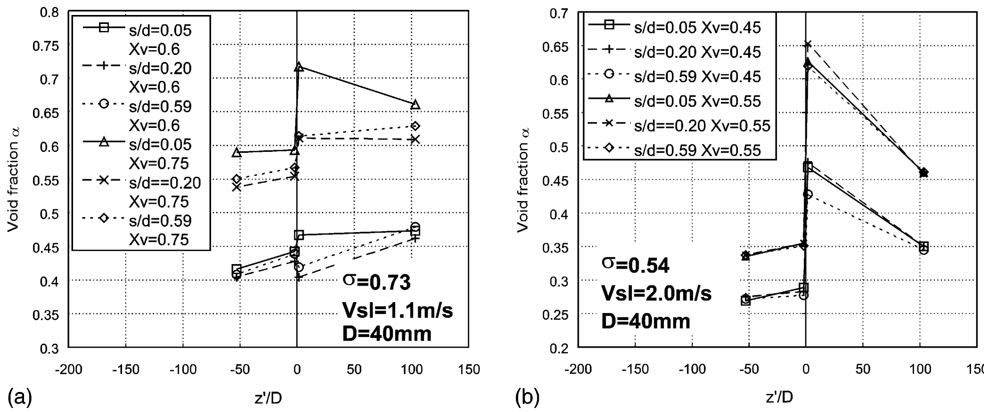

Fig. 10. (a) Area average void fraction at different locations along the pipe. Gas volume fraction as parameter, $V_{sl} = 1.1$ m/s ($\sigma = 0.73$, $D = 40$ mm). (b) Area average void fraction at different locations along the pipe. Gas volume fraction as parameter, $V_{sl} = 2.0$ m/s ($\sigma = 0.73$, $D = 40$ mm).

mental data available in the literature refer to values of $\sigma < 0.5$ and most of them refer to restrictions with $\sigma < 0.3$, further investigations are needed to clarify the behavior of two-phase mixtures across restrictions characterised by high values of the area flow ratio. Finally it should be noted that no strong effects can be ascribed to the pipe diameter, since generally the differences in the results are within the experimental uncertainty.

4.3. Void fraction profiles

Data on the time average void fraction α have been obtained by integration of the time series recorded by the impedance probes located upstream and downstream the pipe discontinuity. As it is well known, the knowledge of the average void fraction allows the slip ratio S to be evaluated, which is important, for intermittent flows, since it allows the velocity of gas pockets V_b (or slug translational velocity V_t) to be estimated. For the sake of briefness, the discussion on statistical indicators such as the probability density function of void fluctuations is omitted in the present paper.

Fig. 10a and b show typical void fraction profiles along the test pipe upstream and downstream of the different orifices. The analysis of the measurements revealed that the void fraction generally undergoes a step change across the singularity with a sharp increase just downstream of the discontinuity ($z'/D = 1$). In that location the void fraction usually attains the maximum measured value along the pipe. This behavior has been observed irrespective of the orifice thickness for the higher values of the liquid flow rate ($V_{sl} = 1.1$, 2.0 mm). At $V_{sl} = 0.6$ m/s the void fraction profiles exhibit a different pattern with slight changes across the restriction and even, in some operating conditions, a reduction of the void fraction at $z'/D = 1$ with respect to the preceding measuring location ($z'/D = -2$). Fig. 11 shows the overall results obtained with the 40 mm pipe in terms

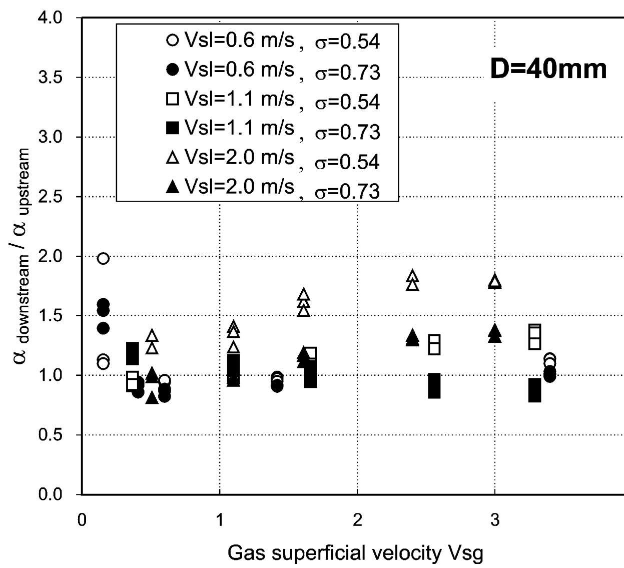

Fig. 11. Ratio of void fraction values downstream and upstream the restriction.

of the ratio between downstream and upstream void fraction values as a function of the gas superficial velocity. As can be observed, when the area ratio is low ($\sigma = 0.54$), the void fraction generally increases through the restriction. Finally, the void fraction values far from the restriction ($z'/D = 61$ for the $D = 60$ mm pipe, $z'/D = 105$ for the $D = 40$ mm pipe) are in good agreement with those predicted by Armand and Treschev correlation (Eq. (8)).

4.4. Slip ratio

From void fraction values, the slip ratio profiles were obtained as a function of gas and liquid flow rates. The values obtained from measurements were compared with some available correlations, namely Armand and Treschev (Eq. (8)), Chisholm (Eq. (7)) and Simpson

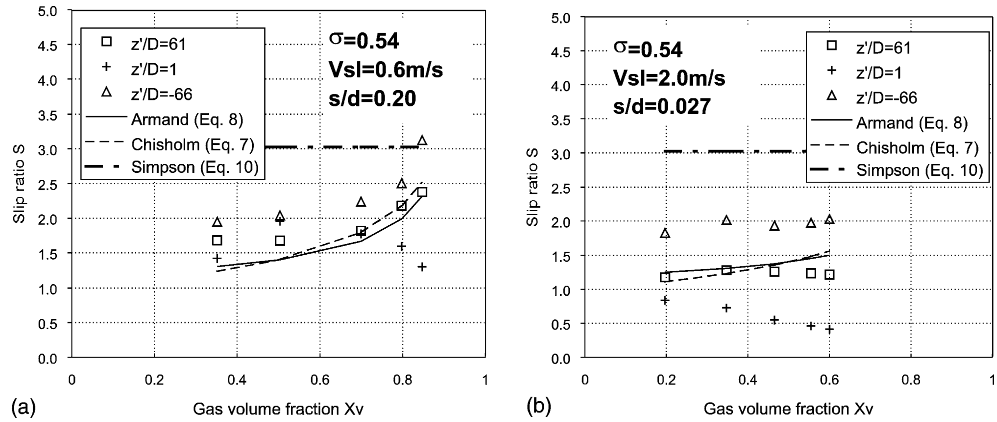

Fig. 12. (a) Slip ratio as a function of gas volume fraction. Measuring location as parameter, $V_{sl} = 0.6$ m/s ($\sigma = 0.54$, $D = 60$ mm). (b) Slip ratio as a function of gas volume fraction. Measuring location as parameter, $V_{sl} = 2.0$ m/s ($\sigma = 0.54$, $D = 60$ mm).

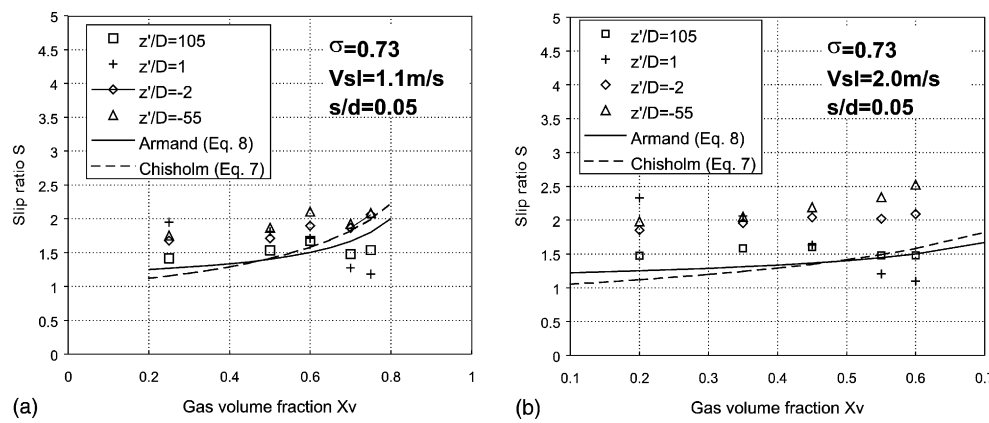

Fig. 13. (a) Slip ratio as a function of gas volume fraction. Measuring location as parameter, $V_{sl} = 1.1$ m/s ($\sigma = 0.73$, $D = 40$ mm). (b) Slip ratio as a function of gas volume fraction. Measuring location as parameter, $V_{sl} = 2.0$ m/s ($\sigma = 0.73$, $D = 40$ mm).

(Eq. (10)). It is worthwhile noticing that Eq. (7) provided very good agreement with the experimental slip ratio values obtained by the authors in the downstream region of the unrestricted pipes [13].

Fig. 12a and b show some results obtained with restrictions having $\sigma = 0.54$. The data refer to the larger pipe ($D = 60$ mm), but the experiments carried out with the smaller pipe are very similar. The figures indicate that the slip ratio generally attains its minimum values just downstream of the restriction. In such location, the slip ratio can even be less than homogeneous flow values. Far from the restriction ($z'/D = 61$, 105), the experimental data are well fitted by both Chisholm and Armand and Treschev correlations. Finally, it can be noticed that Simpson et al. correlation always overpredicts the experimental data, which may explain the poor reliability of the pressure multiplier correlation proposed by the same authors.

Fig. 13a and b refer to the 40 mm i.d. pipe and also show slip ratio values just upstream of the discontinuity. As already discussed with reference to void fraction values, at $z'/D = -2$ the slip ratio is greater than in the immediately downstream measuring location ($z'/D = 1$). Moreover the effect of gas flow rate can be observed: the increase in the gas volume fraction x_v enhances the phase interactions across the restriction resulting in a slip ratio decrease just downstream of the restriction. The influence of the orifice thickness on S appears to be weak especially far from the restriction. Only at $z'/D = 1$ some differences were found in void fraction values and hence in slip ratio values: the slip generally slightly increases when the thickness is augmented.

5. Practical significance

The investigation was motivated by the lack of information regarding the effects of orifice thickness on two-phase pressure losses. The experimental results presented in this study provide a better understanding of the phenomenon (especially with reference to void fraction distribution) and useful information on the reliability of available models and correlations when applied to intermittent flows through orifices having high values of the area contraction ratio.

6. Conclusions

The pressure profiles along horizontal pipes with a sudden contraction constituted by orifices of different thickness and area flow ratio allowed the local pressure drop to be evaluated during single and two-phase flows. Furthermore the impedance method was adopted to measure the area void fraction in different locations upstream and downstream of the singularity and to infer the corresponding slip ratios. The experimental pressure drops due to the restrictions were compared with available relationship predictions. Similar comparisons were performed with reference to slip ratio values.

The main results are the following:

- In single-phase flow, the contraction coefficient data from experiments are in good agreement with Chisholm formula predictions. It has been observed that the pressure drop across the $s/d = 0.20$ orifice is slightly less than that experimented with the $s/d = 0.025$, and $s/d = 0.05$ orifices, even though all restrictions can be classified as thin orifices.
- The pressure multiplier analysis revealed that the data obtained with thin orifices result in a narrow range of values quite well correlated by Morris equation. Thicker orifices ($s/d = 0.59$) are characterised by higher pressure multipliers whose values are quite well fitted by the proper Chisholm formula. Finally, the pressure multipliers pertinent to the $\sigma = 0.73$ singularities show values close to unity (or even lower) when the gas volume fraction is less than about 0.5. No available relationships can account for this effect, which seems to be peculiar of these moderate flow area restrictions.
- The time average void fraction generally increases across the singularity and just downstream of the restriction, the void fraction usually attains the maximum measured value along the pipe. This behavior has been observed irrespective of the orifice thickness for the higher values of the liquid flow rate ($V_{sl} = 1.1$, 2.0 m/s) and it is more evident when the area ratio is low ($\sigma = 0.54$).
- The slip ratios were calculated from void fraction values and were compared with available relationships. Just downstream the restriction ($z'/D = 1$) the measured slip ratio turned out to be even less than the homogeneous flow predictions. Far from the restriction ($z'/D = 61$, 105), the experimental data are well fitted by both Chisholm and the Armand and Threschev correlations. The Simpson et al. correlation always overpredicts the experimental data, which may explain the poor reliability of the pressure multiplier correlation proposed by the same authors.

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