Influence of sudden contractions on in situ volume fractions for oil–water flows in horizontal pipes

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1. Introduction

This work reports the results of an experimental investigation about the oil holdup for two-phase oil–water flow downstream a sudden contraction in a horizontal pipe, by means of the quick closing valves technique. In fact, oil holdup is a fundamental information for the design and operation of systems based on oil–water two-phase flows, but very few information can be found in the literature for liquid–liquid liquid flows in ducts including section changes. More specifically, this matter has been deeply investigated in the literature for gas–liquid flows and a very comprehensive review for uniform diameter ducts can be found in (Woldesemayat and Ghajar, 2007). For liquid–liquid flows, information, mainly related to the pressure drop, is still lacking: concerning oil–water flows across sudden variations of the pipe cross-section, the authors were able to find in the literature only three contributions, briefly summarized in the following.

The work by Hwang and Pal (1997) deals with oil/water and water/oil emulsions flowing in stainless steel pipes with a sudden contraction from 41.24 mm to 20.37 mm i.d. The volume concentration of oil (Bayol 35, viscosity: 2.72 mPa s, density: 780 kg m^{-3}) ranges between 0 and 0.973. Concentrated pressure drops were measured and reported as a function of the mixture kinetic energy showing a good linearity. Hence, emulsions turned out to behave like an equivalent single-phase fluid owing to their nearly homogeneous structure.

Balakhrisna et al. (2010) measured the pressure drop for both contraction and expansion with 0.223 area ratio in small diameter tubes (respectively, 12 mm and 25.4 mm i.d.), considering two different liquid–liquid mixtures: medium viscosity oil–water (oil viscosity: 0.2 mPa s, oil density: 960 kg m^{-3}) and kerosene–water (kerosene viscosity: 12 mPa s, kerosene density: 787 kg m^{-3}). Oil and water volume flow rates were experimented up to 0.0013 m^3 s^{-1}, corresponding to a superficial velocity of 2.5 m s^{-1} in the larger pipe. Flow regimes were detected by means of a high speed camera. The visualization section was enclosed in a box with flat parallel walls and filled with water to reduce optical distor-tions. The viscosity difference makes the comparison interesting as core annular flow regimes are only observed provided that the oil viscosity is sufficiently high as reported also in Angeli and Hewitt (1998). Among the various flow patterns, three kinds of core annular flows were observed and classified as “thick core annular”, “thin core annular” and “sinuous core annular”. An important feature is the robust stability of this flow regime despite the strong perturbation induced by the sudden change in cross-section. In particular, only changes from thick to thin core annular flow were observed for the contraction and the opposite for the expansion. Concentrated pressure drops were measured and reported as a function of the mixture kinetic energy as in Hwang and Pal (1997) through a loss coefficient. Comparisons were made between single-phase water, oil–water and kerosene–water flows, showing an increasing loss coefficient.

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Kaushik et al. (2012) performed a CFD simulation of the same flow conditions experimented by Balakhrisna et al. (2010) which gives satisfactory prediction of hydrodynamic characteristics of core annular flow. On the other hand, problematic agreement with experimental data is shown increasing phase velocities especially as the structure of the oil–water interface is concerned.

The works by Ahmed et al. (2007) and Ahmed et al. (2008) may also be cited, considering oil–air flows in a 25.4 mm i.d. pipe undergoing sudden expansions with three area ratios, namely 0.0625, 0.25 and 0.444. Superficial velocities of oil and air ranged, respectively within the intervals $0.02 < J_o < 0.756$ m s^{-1} and $0.136 < J_g < 3.75$ m s^{-1}. The investigation included: pressure gradi-ent lines up- and downstream the singularity; flow pattern detec-tion by means of a high speed video camera; measurement of the cross-sectional void fraction by means of double ring capacitance meters; measurement of the local void fraction, liquid velocity and turbulence intensity by means of a hot film anemometer. Unfortunately, the values of rheological properties of the oil were not specified.

Despite this relative scarcity of information, the applications of such kind of two-phase flow is very important in many techni-cal fields. In particular, for petroleum engineering applications, the knowledge of the effect of singularities both in terms of flow pattern and pressure drop variation is important in pipeline design.

The "in situ" volume fraction of a phase, also called holdup, plays a role of considerable importance to understand the flow distribution and is used in mechanistic models to predict both the flow pattern and the pressure drop. There are three major techniques to measure the holdup: the shut-in method, usually involving quick closing valves (Oddie et al., 2003), suitable for steady-state measurements on non-intermittent streams; the probe method, based on resistance or capacitance sensors (Du et al., 2012) able to detect instantaneous fractions and to provide even local information, according to the features of the probe itself; the nuclear method (γ-ray or X-ray densitometer) (Rodriguez and Oliemans, 2006). Nevertheless, for oil–water flows difficulties arise with impedance probes because the difference in the permittivity of the two phases is not marked and, furthermore, if the mixture directly wets the probe, the oil tends to adhere permanently, preventing a correct detection. On the other hand, nuclear techniques are very expensive and require special care for safe operation. For these reasons, the shut-in method has been applied in this work due to its relative simplicity and reliability compared to the other techniques.

2. Experimental setup

The liquid–liquid flow facility available in the Multiphase Thermo-Fluid Dynamics Laboratory at the Department of Energy, Politecnico di Milano is sketched in Fig. 1, where the abbreviations mean respectively: APR air pressure regulation, AS air supplying line, CS capacitance sensor, EOF external oil feeding, GW glass window, M manometer, MIX phase inlet mixer, OMP oil metering pump, ORP oil recovering pump, OST oil supply tank (0.5 m^3), PT pressure transducer, RM rotameter, ST phase collector/separator tank (1.0 m^3), TC thermocouple (K type), TS test section, WFP water feeding pump, WMF water magnetic flow meter, WRP water recovering pump, WT water supply tank (5 m^3). More details can be found in Sotgia et al. (2008), Poesio et al. (2009) and Colombo et al. (2012). Oil (Milpar 220, $\rho_o = 890$ kg m^{-3}, $\mu_o = 0.838$ Pa s, $\sigma_o = 0.035$ N m^{-1} at 20 °C) and water (tap water, $\rho_w = 999$ kg m^{-3}, $\mu_w = 1.026 \times 10^{-3}$ Pa s, $\sigma_{o-w} = 0.02$ N m^{-1} at 20 °C) are pumped separately from their storage tanks. The water flow rate is mea-sured by a magnetic flowmeter (accuracy ± 0.5% of the reading), while a calibrated metering pump is used for the oil.

The two liquids pass through a coaxial mixer, where oil flows parallel to the pipe axis while water is injected through an annulus into the oil stream, then the mixture enters the test section. The mixer design (Sotgia et al., 2008) is aimed at favouring the onset of annular flow, which is the most promising flow pattern for pressure drop reduction and thus the most interesting for investigation.

Plexiglas® pipes are used to allow flow visualization.

The test section consists of a 12 m long circular pipe: two sudden contractions are realized joining tubes of different inner diameter, respectively 50/40 mm (contraction area ratio $\varsigma = 0.64$) and 50/30 mm (contraction area ratio $\varsigma = 0.36$). The section change is localized 7.80 m from the mixing section.

The pressure transducer and the thermocouple and positioned 0.15 upstream the singularity.

Downstream, at a distance of 2.5 m from the contraction, it is inserted the shut-in system constituted by two ball valves (FIP VKD-PVC-U DualBlock®) similar to the benchmark equipment adopted in (Strazza et al., 2011). Their distance along the duct axis is 1.03 m for the 50/30 mm case, enclosing a volume of 7.29×10^{-4} m^3, and 1.11 m for the 50/40 mm case, enclosing a volume of 1.4×10^{-3} m^3. As the valves are manually operated, video acquisitions of the valve closure were taken, to verify the closing time and the synchronism between the hands of the operator. For ten valve closures, the measured mean closing time was 208 ms, with a standard deviation of 43 ms. With respect to the

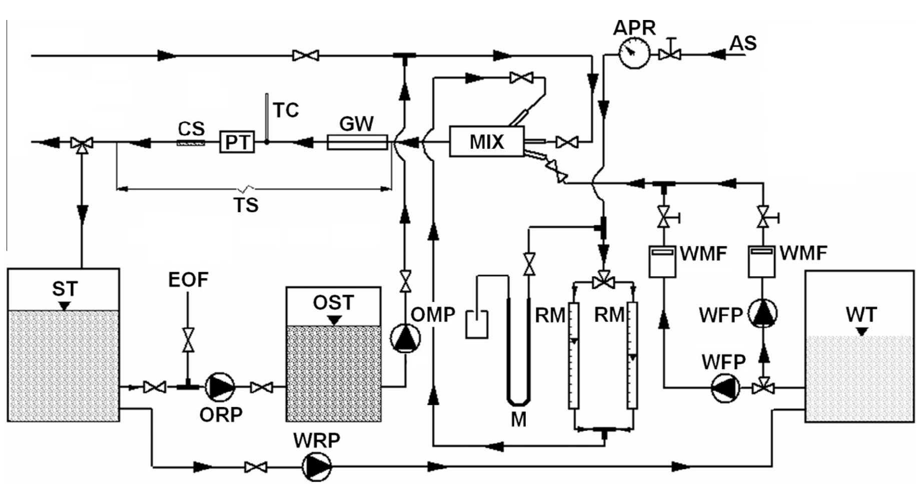


Fig. 1. Schematic representation of the oil–water loop.

time scales of the investigated phenomenon, such times are small enough to consider the valves as quick closing (as they will be named in the following). A drainage cock is mounted on the bottom of the duct enclosed between the valves.

Image and video recordings are taken by a Nikon D90 reflex camera (shutter time 1/4000 s, aperture f/8) and a Canon XM2 video camera (25 fps, shutter time 1/8000 s).

After the test section, the mixture flows into a tank where effective separation of the two liquids is obtained due to gravity.

3. Governing parameters and investigated conditions

Among the main governing parameters of oil–water flows, the more strictly related to the present investigation are reported in the following.

The superficial velocity or volumetric flux J (m s^{-1}) is defined as the ratio between the volume flow rate of each single phase and the area of the pipe cross-section. The mixture superficial velocity or total volumetric flux, is defined as

$$J_{w-o} = J_w + J_o \tag{1}$$

The oil input volume fraction ε_o is defined as

$$\varepsilon_o = \frac{J_o}{J_{w-o}} \tag{2}$$

The water input volume fraction is simply given by $\varepsilon_w = 1 - \varepsilon_o$.

The volume-averaged oil holdup H_o is defined as

$$H_o = \frac{V_o}{V_{tot}} \tag{3}$$

where V_{tot} and V_o (m^3) represent respectively the volume enclosed within the two valves and the portion occupied by the oil. The *water holdup* is simply given by $H_w = 1 - H_o$.

The *oil slip velocity ratio* is the ratio between the oil velocity U_o and the water velocity U_w

Table 1
Summary of the experimental conditions.

J_o (ms^{-1})	J_w (ms^{-1})	ε_o	J_o (ms^{-1})	J_w (ms^{-1})	ε_o
ς = 0.64					
0.43	0.34	0.56	0.83	0.38	0.69
	1.11	0.28		0.44	0.65
0.57	0.34	0.63		0.56	0.60
	1.11	0.34		0.67	0.55
	1.33	0.30		0.78	0.52
				0.89	0.48
0.70	0.56	0.56		1.00	0.45
	0.67	0.51		1.11	0.43
	0.78	0.47		1.22	0.40
	0.89	0.44		1.33	0.38
	1.33	0.35			
ς = 0.36					
0.75			1.24	0.60	0.67
	0.79	0.48		0.69	0.64
	0.99	0.43		0.79	0.61
	1.19	0.39		1.07	0.54
	1.58	0.32		1.19	0.52
	1.97	0.27		1.58	0.45
	2.37	0.24		1.97	0.40
				2.37	0.35
0.99			1.48	0.60	0.71
	0.79	0.56		0.82	0.64
	0.99	0.50		0.99	0.60
	1.19	0.45		1.19	0.55
	1.58	0.39		1.58	0.48
	1.97	0.33		1.98	0.43
	2.37	0.29		2.36	0.38

$$s_o = \frac{U_o}{U_w} \tag{4}$$

where for the generic i-th phase $U_i = J_i/H_i$.

The experimental conditions, summarized in Table 1, are set by varying the superficial velocities of the phases, referred to the downstream pipe, in their ranges.

The reported conditions correspond to different flow regimes mainly classified as annular and dispersed. Stratified flow patterns with oil in contact to the wall have also been observed, but they are not considered except for defining the bounds of the present investigation, which is devoted to flows with the water adjoining the wall. Furthermore, a finer distinction can be made for annular flow patterns according to either the eccentricity or the presence of drops at the oil–water interface. Examples covering the widest range of observations are reported in Fig. 2.

The duct wall and the water annulus are not visible in the pictures due to optical refraction caused by the different refraction indices of water, Plexiglas® and air; nevertheless, annular flows can be recognized by the presence of waves on the upper part of the oil core.

4. Experimental procedure

Tests are run by introducing in the test section the water starting from the maximum value of the superficial velocity $J_{w,max}$. Then, oil is added at the selected superficial velocity J_o. At each run J_w is decreased until its minimum value is reached. The value of J_o is then changed and the sequence is repeated. Concerning the measurement of the oil holdup, once steady-state conditions are achieved, both the valves are closed and simultaneously the pumps are switched off in order to avoid water hammer. After a few minutes the oil and the water trapped within the two valves are separated by gravity. Then, opening the drainage cock, the water is collected in a graduated tank previously calibrated to give the water holdup within 0.3% accuracy. Drainage is continued until oil only flows into the tank, thus granting that all water has been removed from the test section. Due to the design of the valves, a completely negligible quantity of water might be trapped in the fittings. At least ten measurements of the holdup have been repeated for each experimental condition. The overall standard deviation is 5.6% for the 40 mm i.d. pipe and 3.8% for the 30 mm i.d. pipe, showing good repeatability of the measurements.

5. The drift-flux model

Experimental data are conveniently interpreted by means of the approach introduced by Zuber and Findlay (1965) known as the drift-flux model, briefly recalled in the following.

The local ad instantaneous difference between the velocity of one phase and the superficial velocity of the mixture is called drift velocity and writes

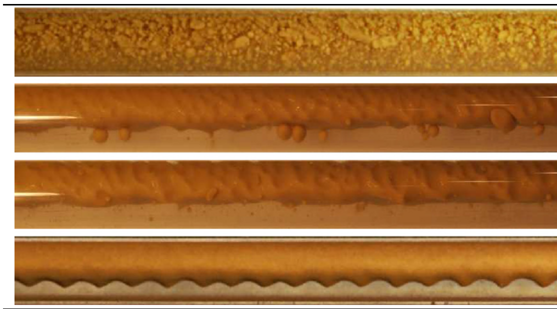
$$\begin{aligned} V_{w-J} &= U_w - J_{w-o} \\ V_{o-J} &= U_o - J_{w-o} \end{aligned} \tag{5}$$

for water and oil, respectively. To avoid redundancy, only oil will be considered since the same considerations also apply for water with obvious modifications of the notation.

Oil velocity is then expressed as

$$U_o = J_{w-o} + V_{o-J} \tag{6}$$

Since the local and instantaneous values of the quantities in Eq. (6) are usually unknown, and data on average values are available from most experimental works, the equation is rewritten introducing the weighted mean value of the quantities, generally defined as



J_o (ms^{-1})	J_w (ms^{-1})	Classification
0.70	1.33	Dispersed (D)
0.83	0.38	Eccentric annular with big drops (EAD)
0.83	0.44	Eccentric Annular (EA)
0.50	0.41	Stratified (oil at the wall) (S)

Fig. 2. Examples of the observed flow patterns (flow direction is from left to right).

$$\bar{F} = \frac{\int_A HFdA}{\int_A HdA} = \frac{\langle HF \rangle}{\langle H \rangle} \tag{7}$$

where F is a generic quantity and H is the holdup (i.e. volumetric concentration).

Eq. (6) then becomes

$$\bar{U}_o = \frac{\langle H_o J_{w-o} \rangle}{\langle H_o \rangle} + \frac{\langle H_o V_{o-J} \rangle}{\langle H_o \rangle} \tag{8}$$

The first term in the sum is reformulated as

$$\frac{\langle H_o J_{w-o} \rangle}{\langle H_o \rangle} = \frac{\langle H_o J_{w-o} \rangle}{\langle H_o \rangle \langle J_{w-o} \rangle} \langle J_{w-o} \rangle = C_0 \langle J_{w-o} \rangle \tag{9}$$

where C_0 is referred to as the distribution parameter, since it takes into account the effect of non-uniform flow and concentration profiles. Actually, for uniform profiles $C_0 = 1$; if the concentration at the pipe axis is larger than that near the wall, $C_0 > 1$; conversely, $C_0 < 1$.

On the other hand, the second term in the sum is the weighted mean drift velocity

$$\bar{V}_{o-J} = \frac{\langle H_o V_{o-J} \rangle}{\langle H_o \rangle} \tag{10}$$

accounting for the effect of the local relative velocity between the oil phase and the mixture.

Eq. (8) then becomes

$$\bar{U}_o = C_0 \langle J_{w-o} \rangle + \bar{V}_{o-J} \tag{11}$$

which is put in dimensionless form as follows

$$\frac{\bar{U}_o}{\langle J_{w-o} \rangle} = C_0 + \frac{\bar{V}_{o-J}}{\langle J_{w-o} \rangle} \tag{12}$$

Since $\bar{U}_o = \langle J_o \rangle / \langle H_o \rangle$ and $\langle \varepsilon_o \rangle = \langle J_o \rangle / \langle J_{w-o} \rangle$, it follows

$$\frac{\langle \varepsilon_o \rangle}{\langle H_o \rangle} = C_0 + \frac{\langle H_o V_{o-J} \rangle}{\langle H_o \rangle \langle J_{w-o} \rangle} \tag{13}$$

Eventually, the relation between the average holdup and the average input volume fraction is then

$$\langle H_o \rangle = \frac{\langle \varepsilon_o \rangle}{C_0 + \frac{\langle H_o V_{o-J} \rangle}{\langle H_o \rangle \langle J_{w-o} \rangle}} \tag{14}$$

As only average values are determined from experiments, to simplify the notation, brackets will be omitted in the following.

6. Results and discussion

The effect of the sudden contraction on the flow regime has been investigated by comparing the flow pattern maps down-stream and upstream the contraction. A significant selection of the data is shown in Fig. 3(a) and (b) where it is seen that the flow patterns do not change dramatically. Nevertheless, it is observed a tendency toward an increase of oil dispersion.

Figs. 4(a) and 5(a) show the oil holdup versus the oil input volume fraction for ς = 0.64 and ς = 0.36 respectively. In the former case, in the downstream pipe the superficial velocity varies between 0.34 and 1.33 m s^{-1} for water and from 0.43 to 0.83 m s^{-1} for oil; in the latter the superficial velocity varies between 0.60 and 2.37 m s^{-1} for water and from 0.75 to 1.48 m s^{-1} for oil. Similar comments hold for the two cases. It can be seen at first that all the data but one fall below the bisector, i.e. the two phase flow cannot be considered as equivalent to a pseudo-homogeneous one. Besides, the oil holdup is lower than the oil input volume fraction suggesting that the effective average velocity is greater for oil than for water or, equivalently, the slip ratio is larger than unity. This result is not surprising for the conditions corresponding to the annular flow regime, where it is expected that the oil in the central core runs faster than the water in the annulus adjoining the pipe wall. Similar findings have been reported by Arney et al. (1993) and Oliemans et al. (1987). Actually, most of the data refer to such flow regime. On the other hand, the same behavior is also shown by the data related to the dispersed flow regime where a closer simi-larity with the homogeneous flow might be expected. Nevertheless, it must be noticed that, according to the flow visualisations, the dis-persed flows have an inhomogeneous appearance with most of the drops crowding in the upper part of the pipe while the water keeps wetting the pipe wall.

Figs. 4(b) and 5(b) show the statistics for the whole data sets. It can be seen that in all the cases the mean and the median have practically the same value apart from very few conditions that are also characterized by the highest standard deviation. Moreover, relying on visual observations, it can be inferred that the best repeatability is attained for conditions corresponding to well-defined flow regimes (either annular or dispersed), whereas data dispersion increases for strongly eccentric annular flows, for annular flows with drops or near to a transition (annular-stratified, annular-dispersed). A deeper analysis of the measurements can be made according to the approach of Zuber and Findlay (1965). In particular, the experimental data are reported on the oil velocity (U_o) – volumetric flux (J_{w-o}) plane as depicted in Fig. 6. It is recalled that data falling on the bisector would represent a homogeneous flow with slip velocity ratio equal to unity. In this case, the measurements lie above the bisector, thus indicating a slip velocity ratio greater than unity, i.e. the oil velocity is higher than the water velocity as previously observed. Additional information arises from the linear regression of the data: the slope of the straight line is 1.38 for ς = 0.64 and 1.36 for ς = 0.36, meaning that the oil dis-tribution is not uniform, being the wall always wetted by water.

Actually, this is verified for the annular flow regime, which is observed in most of the experimental conditions; on the other hand, it can be inferred that the dispersed flow regimes are not

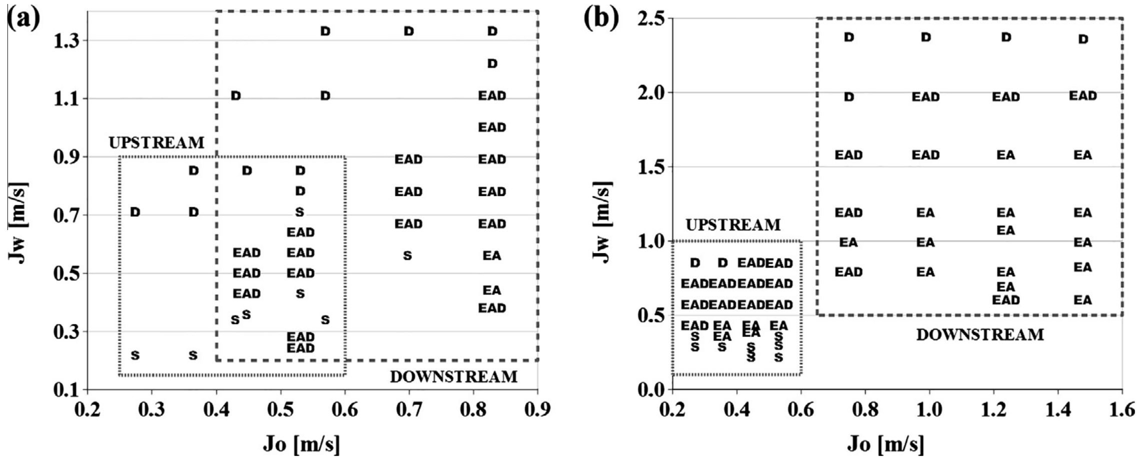


Fig. 3. Flow pattern map for the upstream and downstream pipes: (a) $\varsigma = 0.64$, (b) $\varsigma = 0.36$. EA eccentric annular, EAD eccentric annular with drops, D dispersed, S stratified.

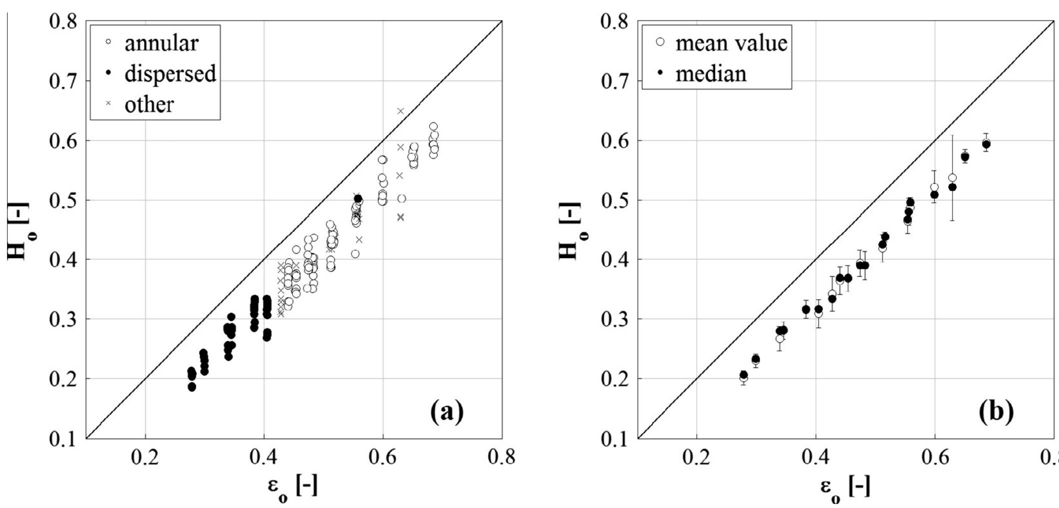


Fig. 4. Oil holdup versus oil input volume fraction for case $\varsigma = 0.64$. Whole data (a) and statistics (b).

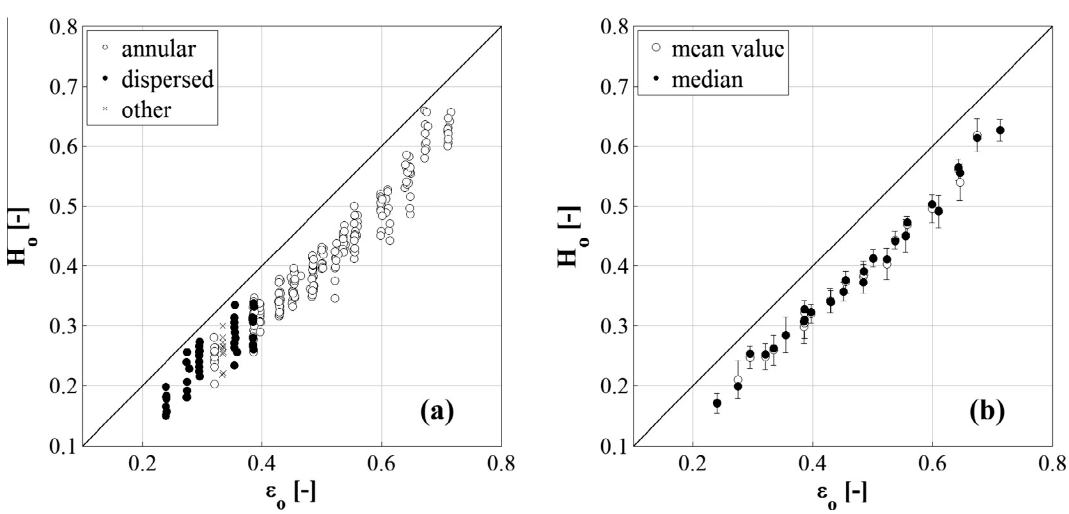


Fig. 5. Oil holdup versus oil input volume fraction for case $\varsigma = 0.36$. Whole data (a) and statistics (b).

characterized by a homogeneous mixing of the two phases, and the pipe wall is mainly adjoined by water, in agreement with the visual observations. This is confirmed also when the data corresponding to dispersed flows are considered alone: in this case, the slope of the straight line is reduced to about 1.1 for $\varsigma = 0.64$ and 1.07 for $\varsigma = 0.36$, but it is still greater than unity.

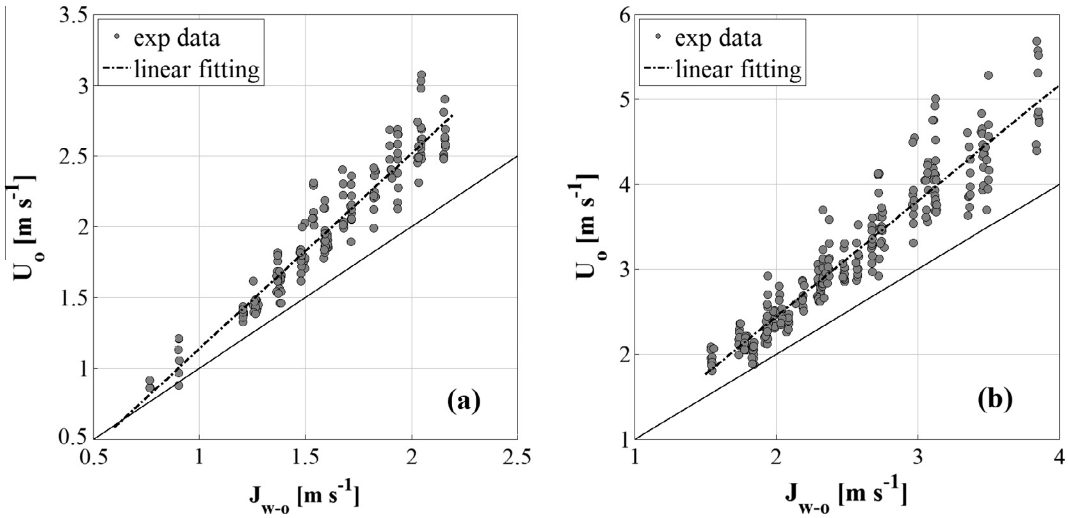


Fig. 6. Mean velocity – flux density plane, according to the drift-flux model by Zuber and Findlay (1965), for the oil phase: (a) $\varsigma = 0.64$, (b) $\varsigma = 0.36$.

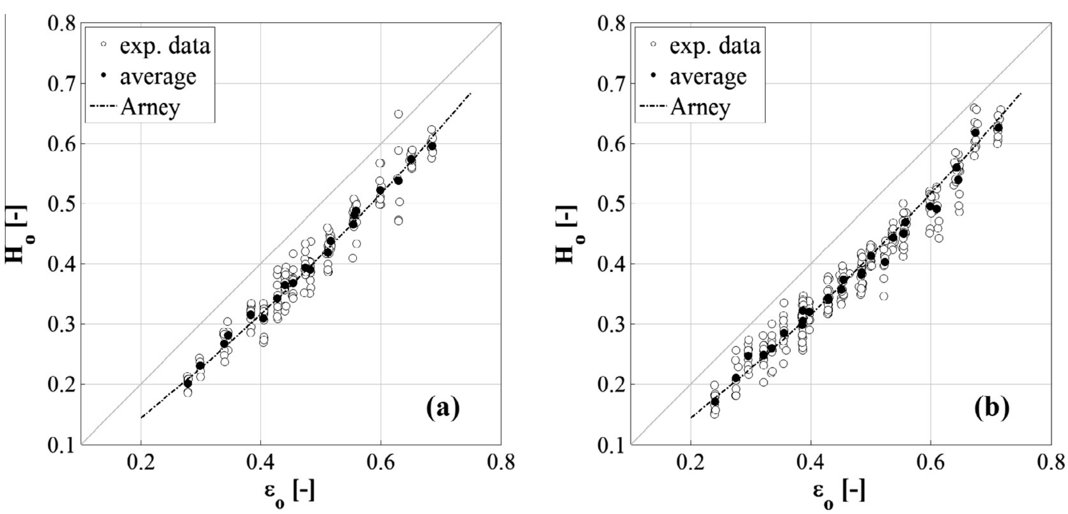


Fig. 7. Comparison between the data and the prediction by Arney et al. (1993) for $\varsigma = 0.64$ (a) and $\varsigma = 0.36$ (b).

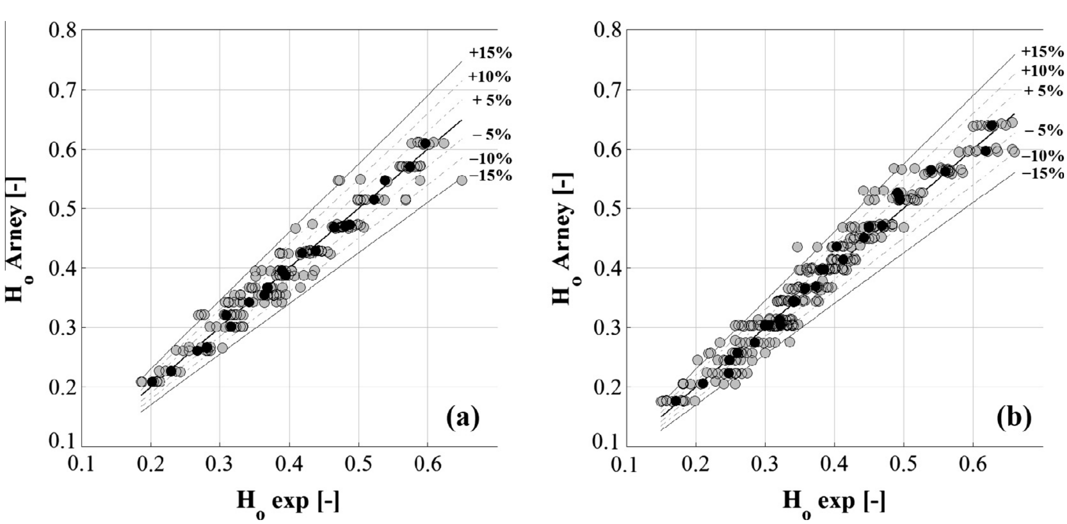


Fig. 8. Parity plot for the correlation of Arney et al. (1993) for $\varsigma = 0.64$ (a) and $\varsigma = 0.36$ (b). Lines represent ±5, 10, 15% from the bisector.

Table 2
Liquid holdup relative errors for some gas–liquid prediction models.

Correlation	ς = 0.64		ς = 0.36	
	Avg. error (%)	Max. error (%)	Avg. error (%)	Max. error (%)
Armand (1946)	5.73	25.26	6.96	33.56
Rouhani and Axelsson (1970)	6.52	29.18	9.33	35.65
Chisholm (1973)	7.30	33.02	8.45	44.23
Dix (as reported in Coddington and Macian (2002))	9.91	37.44	15.30	52.23

The measurements have been compared with the prediction of the empirical correlation developed by Arney et al. (1993) who performed quite similar experiments for straight tubes using quick closing valves as in the present work. Nevertheless, it has to be remarked that the considered flow patterns were always annular. In the original formulation, the water hold up can be estimated as:

$$H_w = \varepsilon_w[1 + 0.35(1 - \varepsilon_w)] \quad (5)$$

Hence, the oil holdup is computed as $H_o = 1 - H_w$. The result is reported in Fig. 7 where it is compared with the experimental data, showing a very good agreement. In particular, considering the maximum relative error between the prediction and the average measurements is 5.15% for ς = 0.64 and 5.88% for ς = 0.36 whereas from the parity plot shown in Fig. 8 it is evident that most of the data fall within ±15% relative error for both contraction ratios. The higher deviation in the latter case suggests a stronger influence of the sudden contraction on the downstream flow. On the other hand, the absolute deviation itself seems to be independent of the flow pattern (while the relative deviation depends also on the holdup values, and consequently on the flow pattern), even though the correlation has been formulated with data from annular flows only.

As observed in the Introduction, a large number of experimental correlations to predict the holdup in gas–liquid flows are available in the literature. Taking into account the wide survey presented in (Woldesemayat and Ghajar, 2007) a selection of these models has been used to check the possibility to extend their application to oil–water flows. Considering that the experimental data refer to annular or dispersed flow regimes, which are also met in gas–liquid flows, with the oil phase playing the role of the gas phase, the rheological properties of the gas are simply replaced in the correlations with the ones of the oil. The results are listed in Table 2, where it is seen that most of the models return very good agreement with the data, showing average relative errors lower than 10%.

7. Conclusions

The shut-in method was successfully applied to the measurement of the oil holdup downstream sudden contractions with 0.64 and 0.36 area ratio, respectively. The operating conditions were set such that the majority of the flow regimes were eccentric annular since this flow pattern is the most convenient for pumping. On the other hand, dispersed flow regimes were observed at the highest values of the input water superficial velocity. Regardless of the flow pattern, the results can be predicted quite well by the correlation of Arney et al. (1993), originally developed for annular oil–water flow in horizontal straight pipes. Nevertheless, some correlations originally developed for gas–liquid flows are able to provide predictions within 10% relative error. The flow visualisations show that the contraction does not modify significantly the flow pattern, even though it is observed a tendency toward an increase of oil dispersion.

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