Measurement of the oil holdup for a two-phase oil-water flow through a sudden contraction in a horizontal pipe

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Abstract. Oil-water two-phase flow experiments were conducted in a horizontal duct made of Plexiglas® to determine the holdup of oil by means of the quick closing valves technique, using mineral oil (viscosity: 0.838 Pa s at 20 °C; density: 890 kg m^{-3}) and tap water. The duct presents a sudden contraction, with contraction ratio of 0.64. About 200 tests were performed by varying the flow rates of the phases. Flow patterns were investigated for both the up- and downstream pipe. Due to the relatively high value of the contraction ratio, it was not observed any relevant variation of the flow patterns across the sudden contraction. Data were then compared with predictions of a specific correlation for oil-water flow and some correlations for gas-water flow. A drift-flux model was also applied to determine the distribution parameter. The results agree quite well with flow pattern visualization.

1. Introduction

This work is framed in the research activity on multiphase flows by now well-established at the Department of Energy, Politecnico di Milano [1-3]. The main subject concerns the measurement of the oil holdup by means of the quick closing valves technique for a two-phase oil-water flow downstream a sudden contraction in a horizontal pipe.

This matter has been deeply investigated in the literature especially for gas-liquid flows and a very comprehensive review can be found in [4]. Nevertheless, for liquid-liquid flows the information, mainly related to the pressure drop, is still lacking: concerning oil-water flows across a sudden contraction, the authors were able to find in the literature only two contributions, namely the work by Wang and Pal [5], dealing with emulsions, and the more recent one by Balakhrisna et al. [6], which considers both the phase distribution and the pressure drop for small diameter tubes (0.0254 m and 0.012 m). On the other hand, the applications of such kind of two-phase flow is very relevant in many technical 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 the pipeline design.

The holdup, i.e. the “in situ” volume fraction of a phase, plays a 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 [7], suitable for steady-state measurements on non-intermittent streams; the probe method, based on resistance or capacitance sensors [8] 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) [9]. 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 probe is directly wetted by the mixture, the oil tends to adhere permanently, preventing a correct detection. On the other hand, nuclear techniques are very expensive and require special care for a 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 figure 1. More details can be found in [1-3]. Oil (Milpar 220, μ_o=890 kg/m^3, μ_o=0.9 Pa·s at 20 °C) and water (tap water, μ_w=1.026×10^{-3} Pa·s at 20 °C) are pumped separately from their storage tanks. The water flow rate is measured 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. Plexiglas® pipes are used to allow flow visualization.

The test section consists in a 11 m long circular pipe: the sudden contraction is realized joining tubes, respectively 50 mm and 40 mm inner diameter: hence the contraction area ratio is 0.64. Downstream, at a distance of 2.5 m from the contraction, two manually operated valves are inserted enclosing a volume of about 1.4 dm^3. A drainage cock is mounted at the bottom.

Image recordings are taken by video/photo cameras.

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

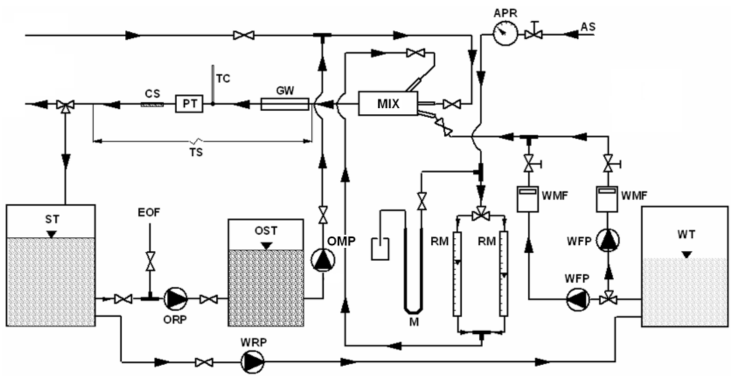


Figure 1. Schematic representation of the oil-water loop. APR air pressure regulation, AS air supplying line, CS capacitance sensor, EOF external oil feeding, GW glass window, M manometer, MIX phase inlet mixer, OMP oil metering pump, ORP oil recovering pump, OST oil supply tank (0.5 m^3), PT pressure 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).

3. Governing parameters

The *superficial velocity or volumetric flux J* (m/s) 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 *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

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

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 following quantities, referred to the downstream pipe, in their proper ranges.

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
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
0.70	0.56	0.56		0.89	0.48
	0.67	0.51		1.00	0.45
	0.78	0.47		1.11	0.43
	0.89	0.44		1.22	0.40
	1.33	0.35		1.33	0.38

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, being chaotic flow regimes, they have not been considered except for defining the bounds of the present investigation, which is devoted to flows with the water adjoining the wall. Furthermore, a finest 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 figure 2.

4. Experimental procedure

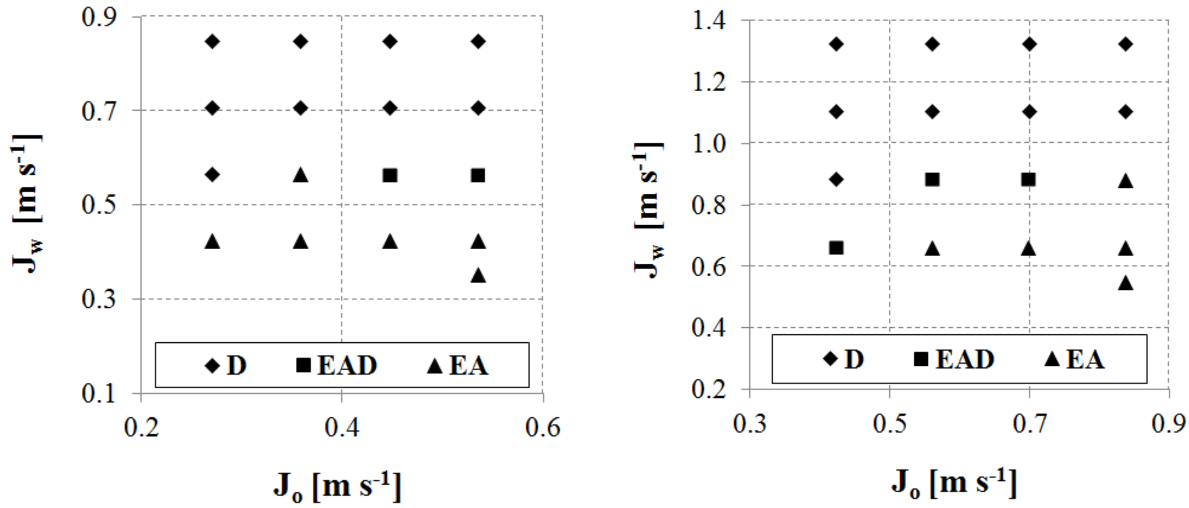
Tests were run by introducing in the test section the water starting from the maximum value of the superficial velocity $J_{w,max}$. Then, oil was added at the selected superficial velocity J_o. At each run J_w was decreased until its minimum value was reached. The value of J_o was then changed and the sequence was 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. At least ten measurements of the holdup have been repeated for each experimental condition.

	J_o (ms^{-1})	J_w (ms^{-1})	Classification
	0.70	1.33	Dispersed (D)
	0.83	0.38	Eccentric annular with big drops (EA-D)
	0.83	0.44	Eccentric Annular (EA)
	0.43	0.34	Stratified (oil at the wall) with big drops (S-D)

Figure 2. Example of the observed flow patterns.

5. Results and discussion

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



(a) (b)

Figure 3. Flow pattern map for the upstream (a) and the downstream pipe (b). EA eccentric annular, EA-D eccentric annular with drops, D dispersed.

Figure 4 (a) shows the oil holdup versus the oil input volume fraction for the whole data set. The superficial velocity varies between 0.34 and 1.33 m s^{-1} for the water and from 0.43 to 0.83 m s^{-1} for the oil. A different marker has been used to identify each flow pattern. 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 and Oliemans [4]. Actually, most of the data refer to such flow regime. On the other hand, the same behaviour is also shown by the data related to the dispersed flow regime where a closer similarity with the homogeneous flow might be expected. Nevertheless, it must be noticed that, according to the flow visualisations, the dispersed 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.

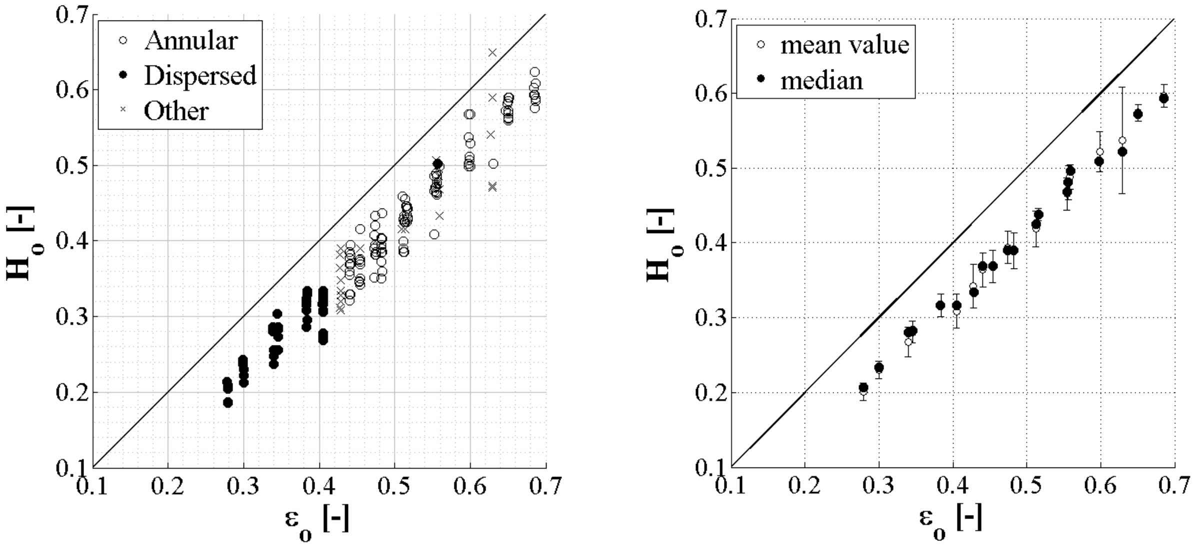


Figure 4. Oil holdup versus oil input volume fraction. Whole data (a) and statistics (b).

Figure 4 (b) shows the statistics for the whole data set. It can be seen that in all the cases but three the mean and the median have the same value. The three conditions for which the mean and the median are different are also characterised by the highest standard deviation. Still relying on visual observations, it can be inferred that the best repeatability has been attained for the conditions corresponding to well-defined flow regimes (either annular or dispersed), whereas the 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 [10]. In particular, the experimental data are reported on the oil velocity (U_o) – volumetric flux (J_{w-o}) plane as depicted in figure 5. 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, meaning that the oil distribution 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 characterised 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 alone are considered: in this case, the slope of the straight line is reduced to about 1.1, but is still greater than unity.

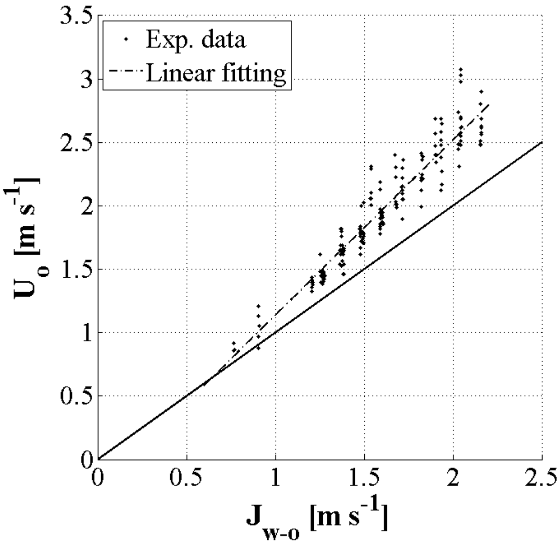


Figure 5. Mean velocity – flux density plane for the oil phase.

The measurements have been compared with the prediction of the empirical correlation developed by Arney et al. [11] 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:

$$H_w = \varepsilon_w \left[1 + 0.35\left(1 - \varepsilon_w\right)\right] \tag{4}$$

Hence, the oil holdup is computed as $H_o = 1 - H_w$. The result is reported in figure 6 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%, whereas from the parity plot shown in figure 7 it is evident that most of the data fall within ±15% relative error. On the other hand, the deviation itself seems to be independent of the flow pattern, even though the correlation has been formulated with data from annular flows only.

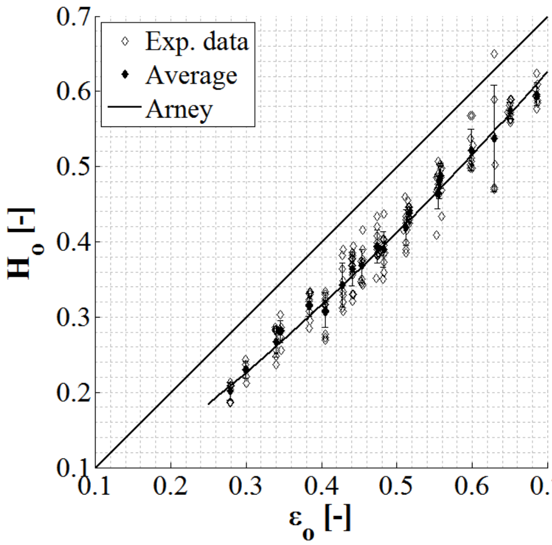


Figure 6. Comparison between the data and the prediction by Arney et al. [8]

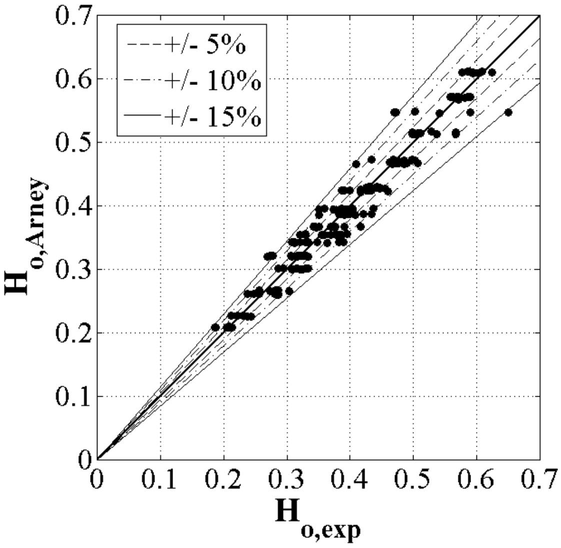


Figure 7. Parity plot for the correlation of Arney et al. [8]

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 [1] a selection of these models has been considered 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 were simply replaced in the correlations with the ones of the oil. Five models, listed in table 2, returned a very good agreement with the data, showing average relative errors lower than 10 %.

Table 2. Relative errors for some gas-liquid prediction models.

Correlation	Average error (%)	Maximum Error (%)
Armand [12]	5.73	25.26
Rouhani [13]	6.52	29.18
Chisholm [14]	7.30	33.02
Dix [15]	9.91	37.44

6. Conclusions

The shut-in method was successfully applied to the measurement of the oil holdup downstream a sudden contraction with 0.64 area ratio. The operating conditions was set such that the majority of the flow regimes was 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.*, originally developed for annular oil-water flow in horizontal straight pipes. On the other hand, 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 towards an increase of oil dispersion. Thus, further investigation on contractions with more severe area ratios can be useful to clarify the influence on the flow pattern.

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