A detailed characterization of viscous oil-water flows downward sudden contractions in horizontal pipes

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Abstract. Two-phase flows of viscous oil and water through singularities such as sudden area contractions/expansions have been taken into limited consideration in the relevant scientific literature. Nevertheless, they play a role of primary importance in industrial systems, for instance, but not only, in the exploitation of oil wells and pipelines. The proposed work is based on the comparison of photographic images of the flow patterns taken from three points of view, i.e. upper, lower and frontal, thanks to a couple of mirrors $\pm 45^\circ$ inclined with respect to the horizontal plane. Oil-water flow regimes have been observed both upward and downward of five horizontal test sections with diameter ratios $d/D = 40/50$, $30/50$, $30/40$, respectively. The observed structures of the oil-water interface, especially for core-annular flows, has suggested also detecting flow patterns in a 30 mm straight pipe for sake of comparison. Actually, the shape of the oil-core interface appears significantly influenced by the sharp-edged area change as well as by the expected momentum variation.

1. Introduction

Geometrical singularities like sudden contractions and expansions, elbows, valves, T-junctions are often present in industrial duct systems. Two-phase flows of liquid (water) – gas (air, vapour, steam) through such singularities have been widely investigated both by experimental and theoretical approaches. In particular, flow patterns and pressure drop have been studied for sudden contractions [1-4], expansions [5-8], valves and orifices [9-12]. Some studies have been also dedicated to the flow distribution and stability in systems with junctions, parallel channels and manifold collectors [13-16].

On the contrary, there are few works on liquid-liquid flows especially if one liquid phase shows medium-high viscosity such as heavy hydrocarbons, which play a non-negligible industrial interest. Actually, though very low viscosity oils, e.g. kerosene [17] can be assumed to behave almost like water, in contrast, heavy oils in mixture with water (and/or gas) show different flow patterns such as the typical core annular flow (CAF) and a variety of wavy stratified flows (WSF).

The main question is: how much does a geometrical singularity influence the flow characteristics in the downward pipe, i.e. flow patterns, pressure gradients and holdup, resulting in the concentrated pressure drop? In fact, researches on water-air flows through sudden contractions of several area ratios and diameters [3] have shown that the method of pressure gradients, usually adopted to measure the concentrated pressure drop across the singularity for single phase flows, cannot be trivially extended to two-phase flows because it may lead to absurd trends of the concentrated pressure drop. The reason is found in the flow pattern change downstream the contraction due to the influence of the upstream one. Furthermore, the results for gas-liquid flows are hardly extended to liquid-liquid flows even for
straight pipes, confirming the G. Hewitt dilemma: “From gas-liquid to liquid-liquid flow: a difficult journey?”

The experience gained by the authors suggests that it is worth paying attention to the effects of singularities on the structure of the oil-water interface indicating the perturbation of the flow regime, which in turn affects the concentrated pressure drop.

In particular, the proposed work is based on the comparison of photographic images of the flow patterns taken from three points of view, i.e. upper, lower and frontal, thanks to a couple of mirrors ±45° inclined with respect to the horizontal plane. Oil-water flow regimes have been observed both upward and downward of five horizontal test sections with diameter ratios \(d/D = 40/50, 30/50, 30/40\), respectively. The observed structures of the oil-water interface, especially for core-annular flows, has suggested also detecting flow patterns in a 30 mm straight pipe for sake of comparison. Actually, the shape of the oil-core interface appears significantly influenced by the sharp edged area change as well as by the expected momentum variation.

2. Test facility

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.

![Figure 1](image-url)

**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 m³), PT pressure transducer, RM rotameter, ST phase collector/separator tank (1.0 m³), 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 m³).

Oil (Milpar 220, \(\mu_o = 890 \text{ kg/m}^3\), \(\mu_w = 0.9 \text{ Pa·s at 20 °C, } \sigma_o = 0.035 \text{ N/m}\)) and water (tap water, \(\mu_w = 1.026 \times 10^{-3} \text{ Pa·s at 20 °C, } \sigma_w = 0.070 \text{ N/m}\)) 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 of a 12 m long horizontal duct made of two circular pipes: a 7 m long upstream pipe, \(D = 50 \text{ mm or 40 mm inner diameter, and a 5 m long downstream pipe of lower inner diameter, namely } d = 30 \text{ mm. According to the definition of contraction area ratio}

\[
\zeta = \left(\frac{d}{D}\right)^2
\]
three configurations with $\zeta = 0.64$ (D = 50 mm, d = 40 mm), $\zeta = 0.56$ (D = 40 mm, d = 30 mm) and $\zeta = 0.36$ (D = 50 mm, d = 30 mm) have been investigated.

Flow patterns have been detected by photographic and video recordings of all the upstream and downstream pipes and of a straight tube 30 mm i.d. for comparison.

3. 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. Table 1 reports the ranges of the oil and water superficial velocities.

| D [mm] | $J_o$ [m/s] | $J_w$ [m/s] |
|--------|-------------|-------------|
| 50     | 0.27 – 0.54 | 0.42 – 0.85 |
| 40     | 0.56 – 0.84 | 0.66 – 1.33 |
| 30     | 0.75 – 1.49 | 1.18 – 2.36 |

Table 1. Superficial velocities of oil and water in the investigated ducts.

Another parameter useful to characterize the operating conditions is the water input volume fraction, defined as

$$\varepsilon_w = \frac{J_w}{J_w + J_o} \quad (2)$$

These operating conditions correspond to flow regimes with water wetting the wall, both annular and dispersed, in order to avoid stratified flows with oil adjoining the upper wall that are characterized by poor repeatability. Such flow regimes are not suitable for pumping due to their increased pressure drop. The stability of the core annular flow has been investigated by the authors in [18].

Referring to figure 2 the photographs were taken by means of a photo camera Nikon D90 with an AF-S Nikkor 60 mm macro lens, mounted on a suitable tripod. Exposure time was 1/4000 s and the necessary lighting was provided by two 800 W halogen lamps. Two mirrors lying parallel to the pipe and ±45° inclined with respect to the horizontal plane provide top and bottom views in addition to the frontal one. The optical path followed by the light in the frontal view is only 5-6% lower than the others; moreover, the images were used for a qualitative analysis; therefore, no correction was performed to equalize the dimensions of the images relative to the different views. This simultaneous triple view, not reported in the literature where only frontal and top views are available [19], allows a complete observation of the oil-water interface.

Figure 2. Setup of the triple view imaging system.
4. Results and discussion
The investigation has aimed at detecting differences in the flow structure downstream the sudden area contraction due to both the sharp-edged change in diameter and the increase in momentum flux.

In the conditions reported in table 1, the flow regime is mainly core annular, more or less eccentric, and gradually evolving to disperse patterns of oil drops as the water superficial velocity is increased.

**Figure 3-1.** Flow patterns for the D50 duct, $J_0 = 0.27$ m/s, $J_w = 0.42$ (a), 0.57 (b), 0.71 (c), 0.85 (d) m/s

**Figure 3-2.** Flow patterns for the D50 duct, $J_0 = 0.54$ m/s, $J_w = 0.42$ (a), 0.57 (b), 0.71 (c), 0.85 (d) m/s
As a principal observation, eccentricity of the downstream flow patterns is reduced compared to the upstream ones for both core annular and dispersed regimes, whereas transitions between different regimes have not been observed. Moreover, the developing length downward the contraction appears to be about 10 diameters. Actually, pressure drop measurements taken in a parallel test campaign have shown a constant pressure gradient along the downstream pipe with regression coefficients very close to unity. Along the upstream pipe 50 mm i.d., the flow patterns at the minimum and maximum value of $J_o$ (see table 1) are depicted in figures 3-1 (a), (b), (c), (d) and 3-2 (a), (b), (c), (d), respectively, in order to show the flow evolution. In particular, at the lowest $\varepsilon_w$ and the highest $J_o$, a strongly eccentric oil core flow takes place, as it is seen in figures 3-1 (a) and 3-2 (a).

The presence of oil drops in the lower side of the duct increases with $\varepsilon_w$, figure 3-2 (b), with the flow evolving toward dispersion, figure 3-2 (d). Therefore, in our opinion, this kind of regime cannot be labelled as “core annular” but “eccentric core flow” because the oil occupies less than the upper half of the pipe and presents its lower interface almost flat, figure 3-2 (a).

At the highest $\varepsilon_w$, regimes of oil dispersed drops in water have been observed showing more or less pronounced eccentricity according to $J_o$, figures 3-1 (d) and 3-2 (a).

In figures 3-1 (c) and 3-2 (d) the regimes of transition from the eccentric core with oil drop to the dispersed flow are depicted. Note that in the figure 3-2 (d) the dispersed flow is not completely established. In the intermediate regimes – figures 3-1 (b), (c) and 3-2 (b), (c) – oil cores of lower size with several oil drops also present more irregular interfaces.

Along the upstream pipe of 40 mm i.d., the flow patterns at the minimum and maximum value of $J_o$, table 1, are shown in figures 3-3 (a), (b), (c) and 3-4 (a), (b), (c), respectively. The figures with the label (b) correspond to the transition from core to dispersed flow.

**Figure 3-3.** Flow patterns for the D40 duct, $J_o = 0.42$ m/s, $J_w = 0.66$ (a), 1.22 (b), 1.33 (c) m/s

**Figure 3-4.** Flow patterns for the D40 duct, $J_o = 0.84$ m/s, $J_w = 0.66$ (a), 1.11 (b), 1.33 (c) m/s
In figure 3-3 (a) the oil core appears eccentric, though with larger holdup than for the 50 mm pipe even by increasing \( \varepsilon_w \), figure 3-3 (b). In contrast, the dispersed flow at the maximum \( \varepsilon_w \) appears practically axisymmetric, figure 3-3 (c).

The mixture at the highest \( J_o \) shows a nearly centered core for the lowest \( \varepsilon_w \), figure 3-4 (a), eccentric core increasing \( \varepsilon_w \), figure 3-4 (b), towards a complete dispersion, figure 3-4 (c).

Flow patterns in the 30 mm i.d. pipe, downstream the 50 mm i.d. one, appear strongly influenced by the singularity, not only by the increased momentum flux, but also by the sharp-edged change in diameter. The flow patterns at the minimum and maximum value of \( J_o \) (see table 1) are depicted in figures 3-5 (a), (b), (c), (d) and 3-6 (a), (b), (c), (d), respectively, in order to show the flow evolution.

In particular, it is seen that increasing \( \varepsilon_w \) at the maximum \( J_o \) eccentricity disappears (figures 4.6 all). On the contrary, at the minimum \( J_o \) eccentricity is still shown though at a lower extent in comparison with the 50 mm upstream tube. Dispersed flow patterns, however, appear in any case axisymmetric. Moreover, the oil-water interface for any regime with oil core, with or without drops, is extremely uneven, likely due to the effect of the sharp change in the cross-section diameter.

![Figure 3-5](image1.png)

*Figure 3-5.* Flow patterns for the D30 duct downstream the D50 duct, \( J_o = 0.75 \) m/s, \( J_w = 1.18 \) (a), 1.57 (b), 1.97 (c), 2.36 (d) m/s

![Figure 3-6](image2.png)

*Figure 3-6.* Flow patterns for the D30 duct downstream the D50 duct, \( J_o = 1.49 \) m/s, \( J_w = 1.18 \) (a), 1.57 (b), 1.97 (c), 2.36 (d) m/s

Flow patterns in the pipe of 30 mm i.d., downstream the 40 mm one, are reported in figures 3-7 (a), (b), (c) and 3-8 (a), (b), (c) for the minimum and maximum \( J_o \), respectively.

Core flow patterns still appear strongly influenced by the geometrical singularity, in spite of both the lower variation in the momentum flux and the reduced upstream eccentricity. Consequently, the
sharp-edged change in diameter appears the most important factor affecting flow patterns as it is also inferred by the comparison between figures 3-5 (a) and 3-7 (b).

These observations are strengthened in considering the flow evolution along the constant 30 mm diameter pipe is shown in the figures 3-9 (a), (b), (c), (d) and 3-10 (a), (b), (c), (d) for the minimum and maximum $J_o$, respectively. It is clearly seen that the core interface appears more regular than in the pipes downstream the contraction, as described above, whereas it is not possible to observe significant differences in the dispersed regimes.

The changes in the flow patterns produced by the sudden contraction have also a quantitative impact. In fact, the couples $(\varepsilon_w, J_o)$ corresponding to the transition between core and dispersed pattern are plotted in figure 4 for both the downstream and the upstream flows, as well as for the flow in the straight pipe. $J_o$ has been normalized ($J_o,n = J_o/J_{o,max}$) to make the comparison easier. It is evident that the contraction promotes the transition that takes place at lower $J_o$.

![Figure 3-7. Flow patterns for the D30 duct downstream the D40 duct, $J_o=0.75$ m/s, $J_w=1.18$ (a), 1.57 (b), 2.36 (c) m/s](image1)

![Figure 3-8. Flow patterns for the D30 duct downstream the D40 duct, $J_o=1.49$ m/s, $J_w=1.18$ (a), 1.38 (b), 2.36 (c) m/s](image2)

5. Conclusions

Detecting the flow patterns from a threefold view, i.e. frontal, top and bottom, turns out to be a very useful tool to characterize the structure of the oil-water interface without lack of information. In particular, the top view allows verifying whether oil is sticking the wall, and detecting the transition toward dispersed flow as the elongated oil drops, resulting from breaking the core, disappear. The more usual front view adopted to classify the flow regimes highlights the eccentricity in horizontal streams for both core and dispersed patterns. The bottom view, never reported in the literature to the best knowledge of the authors, is useful to study the shape of the lower interface in core flows and, in particular, the formation and the motion of oil drops.
Figure 3-9. Flow patterns for the D30 duct, $J_o = 0.75$ m/s, $J_w = 1.18$ (a), 1.57 (b), 1.97 (c), 2.36 (d) m/s

Figure 3-10. Flow patterns for the D30 duct, $J_o = 1.49$ m/s, $J_w = 1.18$ (a), 1.57 (b), 1.97 (c), 2.36 (d) m/s

Figure 4. Water input volume fraction versus normalized oil superficial velocity. Comparison between downward and upward/straight pipe flows.
With reference to the specific subject of this work, the complete inspection of the oil-water interface is important to put in evidence the influence of sharp-edged contractions compared with the same flow conditions in constant diameter pipes.

In fact the qualitative changes in the flow patterns are connected with important quantitative findings that need further investigation: in particular, the transition between core bubbly and dispersed flow occurs at a lower value of the water superficial velocity at constant oil superficial velocity.

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