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Upward and downward inclination oil–water flows

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This paper is dedicated to the memory of Jason Y.-L. Lum

Abstract

The effect of upward (+5°, +10°) and downward (−5°) pipe inclinations on the flow patterns, hold up and pressure gradient during two-liquid phase flows was investigated experimentally for mixture velocities between 0.7 and 2.5 m/s and phase fractions between 10% and 90%. The investigations were performed in a 38 mm ID stainless steel test pipe with water and oil as test fluids. High-speed video recording and local impedance and conductivity probes were used to precisely identify the different flow patterns. In both positive and negative inclinations the *dispersed oil-in-water* regime extended to lower mixture velocities and higher oil fractions compared to horizontal flow. A new flow pattern, *oil plug* flow, appeared at both +5° and +10° inclination while the *stratified wavy* pattern disappeared at −5° inclination. The oil to water velocity ratio was higher for the upward than for the downward flows but in the majority of cases and all inclinations oil was flowing faster than water. At low mixture velocities the velocity ratio increased with oil fraction while it decreased at high velocities. The increase became more significant as the degree of inclination increased. The frictional pressure gradient in both upward and downward flows was in general lower than in horizontal flows while a minimum occurred at all inclinations at high mixture velocities during the transition from *dispersed water-in-oil* to *dual continuous* flow.

Keywords: Liquid–liquid flow; Pressure gradient; Hold up; Phase distribution; Upward flow; Downward flow

1. Literature review

Two-phase liquid flows are a common occurrence in the oil and process industries. In the oil industry, in particular, oil and water are often produced and transported together in pipelines that have various degrees of inclination from the horizontal. Depending on the properties of the fluids, fluid flow rates and pipe inclination and diameter, a number of different flow patterns occur, which can generally be classified into the following two categories (Lum et al., 2004):

Separated flow: where both phases retain their continuity; the two phases can be either completely separate, occupying the top and bottom of the pipe respectively (*stratified* flow), or there may be interdispersion of one

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phase into the other (*dual continuous* flow) i.e. oil drops are present in the water-continuous layer and water drops are present in the oil-continuous layer. At certain conditions, one phase can occupy the core of the pipe with the other flowing in the annulus around it (*annular* flow). This pattern usually appears with high viscosity oils in which case the oil flows in the core.

Dispersed flow: where one phase is continuous and the other is in the form of dispersed drops; the drops can either occupy a limited section of the pipe, leaving a clear layer of the continuous phase (*stratified mixed* flow), or all of it, resulting in an almost uniform cross-sectional distribution (*fully dispersed* flow) at the higher velocities.

The introduction of a small inclination in the pipeline, as well as the size of the inclination, will affect the boundaries between the flow patterns observed in horizontal flows. In addition in deviated flows the gravitational force has components both normal and parallel to the pipe axis. The normal component promotes segregation of the phases as in horizontal flow, while the parallel one can act either in the direction of the flow (downward flow) or in the opposite direction (upward flow). Therefore, a declination in the pipe causes higher in situ water velocity than in the corresponding horizontal case; conversely, the in situ water velocity in an inclined pipe is lower than in a horizontal. These differences in flow patterns, in situ velocity and phase hold up will also cause changes to the frictional pressure drop measured in inclined pipes compared to horizontal ones.

Investigators in this area have studied a range of deviation angles. In general, they are concerned with the effect of pipe deviation from either the true vertical or the true horizontal position. The traits of flows deviating from the horizontal (0–30°) differ from those deviating from the vertical (30–90°), for example, in flow pattern types. The present work is concerned with flow phenomena in small deviations from the horizontal, both in inclined and declined directions. The relevant literature is summarised below (for a detailed review see Lum et al., 2004).

1.1. Flow patterns

1.1.1. Upward inclined flow

At low mixture velocities, where the transition from *stratified* (*S*) to *dual continuous* (*DC*) flow occurs, a general agreement exists that in upward inclined flows dispersion appears at lower velocities than in the horizontal case (Oddie et al., 2003; Lum et al., 2004). The magnitude of the shift in this transition boundary has been observed to increase with inclination (Alkaya, 2000). There is no consensus on the effect of inclination at higher velocities, namely on the boundary of the *dual continuous* and *fully dispersed* flows (Lum et al., 2004); mixing could be generally enhanced (Vedapuri et al., 1997), or either enhanced or retarded according to input composition and velocity (Scott, 1985; Lum et al., 2004). Alkaya (2000) observed that this transition boundary was not affected by slight inclination but that a new *dispersed* flow pattern, *dispersed water-in-oil under an oil layer*, appeared at ±5° at high oil fractions and low velocities. The data points of Oddie et al. (2003), while sparse, do indicate enhancement of mixing with increased inclination; interestingly, this transition was evident from 0° to +2°, and from +10° to +20°, but not from +2° to +10°. Abduvayt et al. (2004) observed *stratified* and *dual continuous* flows while *dispersed* flow did not appear for the conditions investigated at +0.5° and +3°. They also reported an enhancement of the *stratified* region with inclination.

In terms of the interface shape of *stratified* flow, Alkaya (2000) reported a very smooth interface between +1° and +5°. In contrast Scott (1985) at +15° and +30° and Abduvayt et al. (2004) at +3° noted that the smooth interface of horizontal flow was completely replaced by large amplitude waves. Kurban's (1997) experimental work revealed that both smooth and wavy interfaces still exist when the pipe is inclined at +1°.

1.1.2. Downward inclined flow

The number of investigations on slightly declined oil–water flows is smaller than on slightly inclined ones. The works of interest are those of Cox (1985) at −15° and −30°, which is complementary to that of Scott (1985) above, Vedapuri et al. (1997) at −2°, Alkaya (2000) at −0.5°, −1°, −2° and −5°, Oddie et al. (2003) at −2° and Abduvayt et al. (2004) at −0.5° and −3°. Cox (1985) and Alkaya (2000) observed that the transition from *separated* to *dispersed* flow occurs at lower velocities in downward inclined than in horizontal flow, but Oddie et al. (2003) observed a lesser degree of dispersion at −2°, such that the flow was less homogeneous than at 0°. The data of Cox (1985) reveal relatively little change from horizontal to −15°, but a more significant shift from −15° to −30°: *dual continuous* flow appears at a lower mixture velocity at −30° than at 0° and −15°. For Alkaya (2000), downward inclination enhanced the *dispersed water-in-oil* pattern slightly so that it appears at lower mixture velocities at −5°, but not at −1°. There was little effect of downward inclination on the boundaries of the other patterns by Alkaya (2000) otherwise. According to Abduvayt et al. (2004) at −3° the *stratified smooth* pattern disappears and is replaced by *stratified wavy* flow, which at low water fractions extends to a higher mixture velocity compared to horizontal flow. In addition they also found that at this inclination the *dual continuous* pattern diminishes and occurs only at intermediate and high input water fractions.

1.2. Hold up

The ratio between the average in situ velocities of the two-phases is often given in terms of the *velocity ratio*, S, defined as the ratio of in situ oil to water velocity, which can be calculated as follows:

$$S = \frac{\beta_o/\beta_w}{\varepsilon_o/\varepsilon_w} \tag{1}$$

where β_o and β_w are the input volume fractions of oil and water respectively, and ε_o and ε_w are the in situ volume fractions of oil and water respectively, averaged over the pipe cross-section. $S > 1$ means that the oil travels faster in the pipe while $S < 1$ indicates that water is the faster phase.

1.2.1. Upward inclined flow

Previous investigations indicate that low upward inclination generally results in higher water holdup than in horizontal flow. Relevant systems are those described by Scott (1985) at +15° and +30°, Alkaya (2000) at +1° and +5°, Lum et al. (2002) at +5° and Abduvayt et al. (2004) at +0.5° and +3°. Of the reported S values, all the data by Scott (1985) and most of those by Lum et al. (2002) and Abduvayt et al. (2004) are in general above one, while the data by Alkaya (2000) is mixed.

1.2.2. Downward inclined flow

The available data are by Cox (1985) at −15° and −30°, Alkaya (2000) at −1° and −5° and Abduvayt et al. (2004) at −0.5° and −3°. Abduvayt et al. (2004) showed velocity ratios always less or equal to one, Cox (1985) found generally low velocity ratios, although not always below one, while Alkaya (2000) reported mixed velocity ratios either above or below one, as for upward flow.

1.3. Pressure gradient

The effect of inclination causes the total ΔP to be a function of elevation as well as friction and acceleration. The acceleration component has a negligible magnitude in oil–water flow systems (Flores et al., 1998) and the frictional component can be determined by subtracting the elevation component from experimentally measured total pressure gradients.

The behaviour of the frictional pressure drop (ΔP_f) with varying input velocities and compositions at low inclinations is not well documented. Alkaya (2000) reported pressure gradient data and compared it against various models available. In general, the total two-phase pressure gradient could be either higher or lower than the single-phase values, depending on mixture velocity and input composition, while with increasing input oil fraction pressure gradient generally increased to a maximum before decreasing to the value of single-phase oil. The data of Alkaya (2000) in horizontal and inclined flow appeared similar, with the peaks and troughs in the inclined case being the lesser of the two. Lum et al. (2004) provides data on frictional pressure gradient at 0° and +5°. It was seen that the two-phase ΔP_f values generally decreased to a minimum at intermediate oil volume fractions for each mixture velocity. In terms of the values obtained, there is a marginal difference in the ΔP_f between 0° and +5°. The results of Abduvayt et al. (2004) showed an increase in the total pressure drop with inclination.

2. Experimental set-up

The experimental set-up used in this work for the observation of flow patterns in oil–water flows has been previously described in detail in Lum et al. (2004). The test fluids were oil, Exxsol D140, supplied by Exxon Chemicals and tap water (oil and water properties are shown in Table 1). The test pipe consists of two parallel 8-meter long sections made of stainless steel with 38 mm ID, joined by a U-bend. When an inclination is imposed, both upward and downward measurements can be taken simultaneously, in the first and second sections respectively. The liquid storage and distribution sections consist of two 880-litre oil and water tanks, with corresponding centrifugal pumps (Ingersoll-Dresser). The oil and water flow rates are measured separately with variable area flow meters that have a range of 0–240 l/min, with an accuracy of 1% full scale (ABB Instrumentation). The two fluids join at the beginning of the test section via a modified T-junction, which ensures minimum mixing. The mixture is recovered at the outlet of the test section in a separator vessel with a Knit-Mesh™ coalescer within, to enhance separation.

Experiments are conducted at +10° and −5° from the horizontal. Visual observation with a video camera and local electrical probes are the main methods used to identify the flow patterns.

The flow is recorded through a transparent acrylic pipe located 7 m from the test tube entrance for the upward inclination and 7 m from the U-bend (15 m from the entrance) for the downward inclination using two high-speed video cameras, a Kodak Ektapro EM and a Kodak 4540MX. The recording speed used is 1000 frames per second for the Ektapro EM and 1125 frames per second for the 4540MX. The images taken are full size and have a definition of 240 pixels horizontal by 200 pixels vertical by 625 grey levels.

At high mixture velocities, where the delineation of the flow pattern boundaries only by video recording is not possible, impedance and conductivity local probes are also used. The impedance probe is used to determine the time-averaged phase distribution in the pipe cross section. It consists of a coaxial wire with a 1.4 mm diameter outer conductor and a 0.2 mm diameter inner conductor, separated by an insulator (see Lovick and Angeli (2001) for detailed description). The alternating current used has a frequency of up to 7 kHz for flows up to 1.5 m/s and up to 70 kHz for flows up to 2.5 m/s. The sampling time at each point is over 2.8 s up to 1.5 m/s mixture velocities and about 1.7 s for velocities up to 2.5 m/s. Phase distribution is found by sampling 80 points along the vertical, horizontal and diagonal axes in the pipe cross section. Phase fraction at each sampling point is determined from the contact time of each phase with the probe tip. From the phase distribution diagrams, the average in situ volume fraction of each phase can also be estimated. The conductivity probe can identify the continuous phase and indicate whether one (*dispersed* flow) or both (*dual continuous* and *stratified* flows) of the phases are continuous as well as the position of the oil–water interface in the separated (*stratified* and *dual continuous*) patterns. The operating principle is the same as that of the impedance probe. The only differences are that two separate thin wires are used as electrodes instead of a single coaxial wire and the separation distance of the two conducting electrodes, 10 mm, is set to be greater than the diameter of the largest expected drop. The local probes are located in the upward and downward inclined pipes just before the transparent sections.

Average in situ composition of the flow was mainly measured using Quick Closing Valves (QCV). The two pairs of valves are placed at the ends of each transparent pipe, 73 cm apart, with an 800 ml trapped mixture volume between them. The QCV produced a narrow spread of data points with an average standard deviation of 5.3% for all measurements. Fluctuation in values was greatest at the lower mixture velocities and least at the higher ones. Based on this and the accuracy of the flowmeters the experimental uncertainty of the slip ratio at +10° is estimated at ±15% at lower mixture velocities and about ±8% at higher mixture velocities. At −5° the uncertainty in the slip ratio is estimated at ±13% for the lower mixture velocities and ±9% for the higher ones.

Table 1
Properties of the liquids at 25 °C

Liquid	Oil Exxsol D140 (Exxon Chemicals)	Water
Density (kg/m^3)	828	998
Viscosity (m Pa s)	5.5	0.993
Surface tension (mN/m^2)	20	72
Interfacial tension (mN/m^2)	40	

Differential pressure gradient was measured through two pairs of pressure tapping ports located 1.5 m apart just before the transparent pipes for upward and downward flows, using a Validyne DP103 differential pressure transducer that has a maximum pressure rating of 22 kPa and an accuracy of 0.25% full scale. The average standard deviation of these measurements was 4.8%. From the measured pressure gradient the frictional one can be estimated using the in situ hold up. The experimental uncertainty of frictional pressure gradient taking into account the accuracy of the pressure transducer and the uncertainty of the hold up measurements is estimated to be within ±10% for both +10° and −5°.

The mixture velocities examined are from 0.7 m/s to 2.5 m/s and input oil volume fractions are from 10% to 90%. The phase distribution experiments are for fewer conditions, i.e. between 20% and 84% input oil fraction with more points at the higher oil fractions. The pipe is always pre-wetted with oil before each two-phase run.

3. Results and discussion

3.1. Flow patterns

Refined versions of the flow pattern maps from the same experimental facility previously presented at 0° and +5° (Lum et al., 2002, 2004) are shown in Fig. 1, for an increased range of conditions. In horizontal flow, the main difference with the previous map occurs at the higher mixture velocities of 2.0 and 2.5 m/s, where the *dual continuous* (*DC*) pattern appears at lower input oil fractions and persists to slightly higher ones. In the +5° inclined flow, a significant change to the previously published map is that a new flow pattern, *plug flow* (*PG*), appears at 0.7 m/s, at the lowest input oil fraction of 10%. The *PG* flow at +5°, which was identified with the use of the high speed cameras, consists of a break in the continuous oil flow at the top of the pipe. The behaviour of *PG* flow is discussed in more detail below, as its characteristics are clearer at +10°.

Comparing inclined to horizontal data, it is clear that *dispersed oil-in-water* (*Do/w*) flow appears at lower mixture velocities and over a wider range of conditions at inclined than in horizontal flow (Fig. 1). The *dispersed water-in-oil* (*Dw/o*) pattern, on the other hand, is confined at the higher input oil fractions and high mixture velocities. The transition from *stratified wavy* (*SW*) to *dual continuous* (*DC*) flow is also seen to appear at lower mixture velocities in inclined flow.

3.1.1. +10°

At +10° from the horizontal, the following flow patterns were identified: *stratified wavy*, *dual continuous*, *plug* and *dispersed* flow. *Plug flow* (*PG*) only appeared during inclined flow and at low input oil fractions (oil plugs in water). *Dispersed* flow appeared in the form of both *dispersion of oil-in-water* (*Do/w*) and *dispersion of water-in-oil* (*Dw/o*). The corresponding flow pattern map is shown in Fig. 2, together with the pattern boundaries at +5° inclination and horizontal flows.

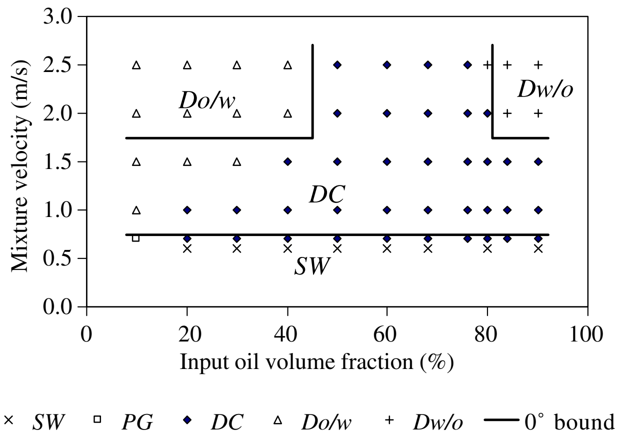

Fig. 1. Comparison of flow patterns at +5° inclination with the flow pattern boundaries at 0°.

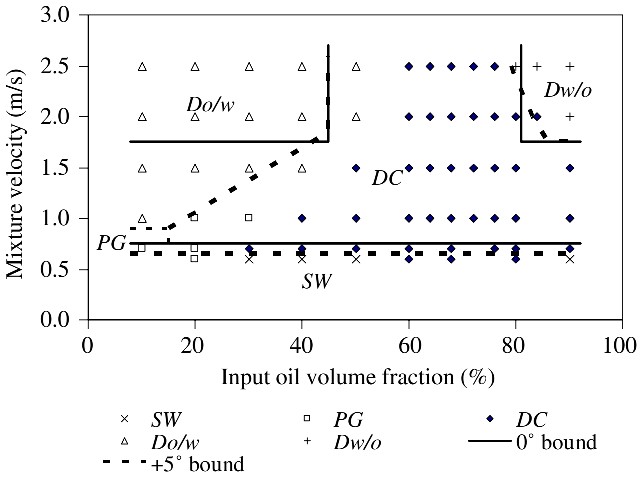

Fig. 2. Comparison of flow patterns at +10° inclination with the flow pattern boundaries at 0° and +5°.

In general, an increase in inclination from +5° to +10° further extends the region of *Do*/*w* flow to higher input oil fractions. Further, the *PG* flow region is enlarged to higher input oil fractions and mixture velocities. The boundaries between *SW* and *DC* flow, and between *DC* and *Dw*/*o* flow, are slightly affected by inclination. In particular:

(a) *Stratified flow*. The interface in the *stratified wavy* (*SW*) pattern is noticeably wavier and more irregular at +10° than at +5°; in contrast, an almost smooth interface was observed in horizontal flow for similar conditions (Fig. 3).
(b) *Plug flow*. The *plug flow* (*PG*) regime occurs at +10°, from 0.6 m/s to 1.0 m/s, and from 10% to 30% input oil fraction. This marks the appearance of a time-dependent flow pattern, characterised by a thick plug of oil flowing at the top of the pipe for several pipe diameters. This plug becomes gradually thinner until it is replaced by either oil drops or virtually single-phase water. The oil plug then re-appears, reinstating the oil–water mixture. The sequence of events is shown in Fig. 4. The range of conditions at which *PG* flow occurs increases significantly with a slight increase in the inclination, i.e. from +5° and +10° (Fig. 2). There is a difference in the clarity of the plug between +5° and +10°: the break in the oil plug is barely visible at +5° (Fig. 5).
(c) *Dual continuous flow*. At +10°, the *dual continuous* (*DC*) regime begins to appear at 0.6 m/s, from 60% to 80% input oil fraction, lower than at +5° where it appears at 0.7 m/s (Fig. 2). A comparison of the *DC* pattern between +5° and +10° inclinations at 1.0 m/s is shown in Fig. 6: the flow is more dispersed at +10° than +5°. The drops are concentrated at the interface, and are tightly clustered together. As the

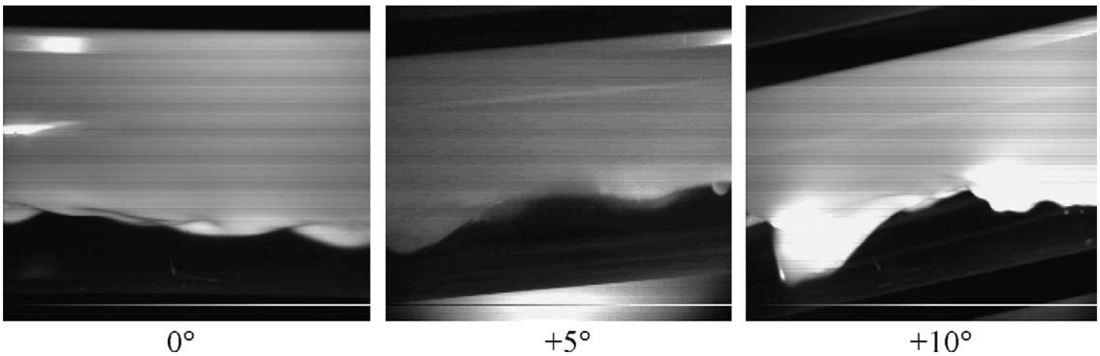

Fig. 3. *Stratified wavy* (*SW*) flow at 0.7 m/s mixture velocity and 68% input oil fraction at different inclinations.

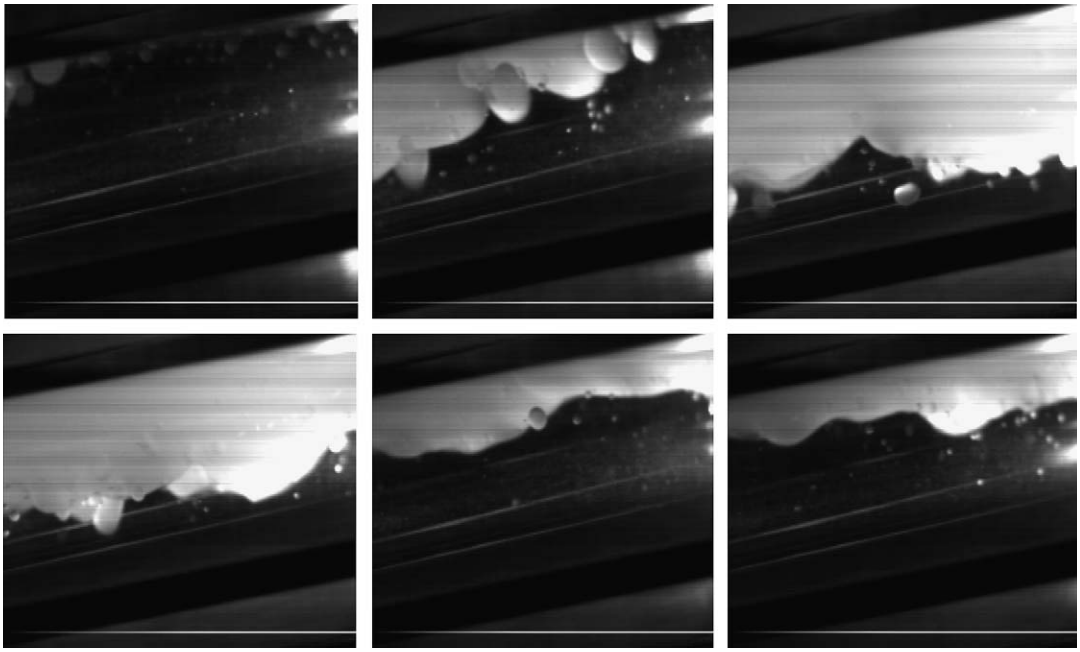

Fig. 4. *Plug flow* (*PG*) at +10° inclination, 0.7 m/s mixture velocity and 20% input oil fraction.

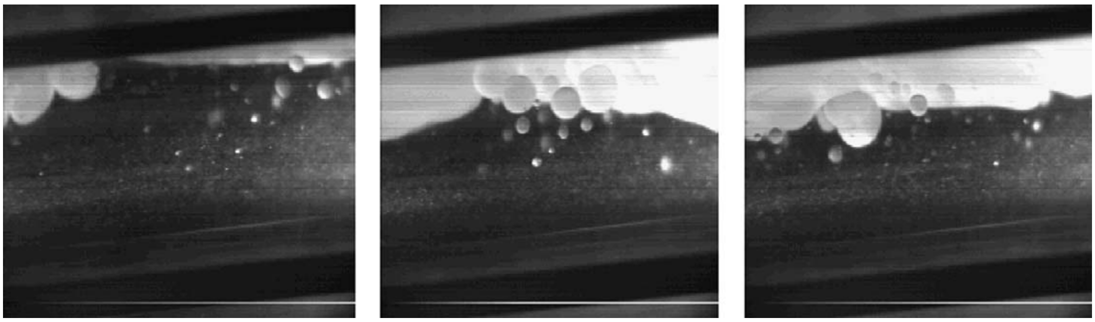

Fig. 5. *Plug flow* (*PG*) at +5° inclination, 0.7 m/s mixture velocity and 10% input oil fraction.

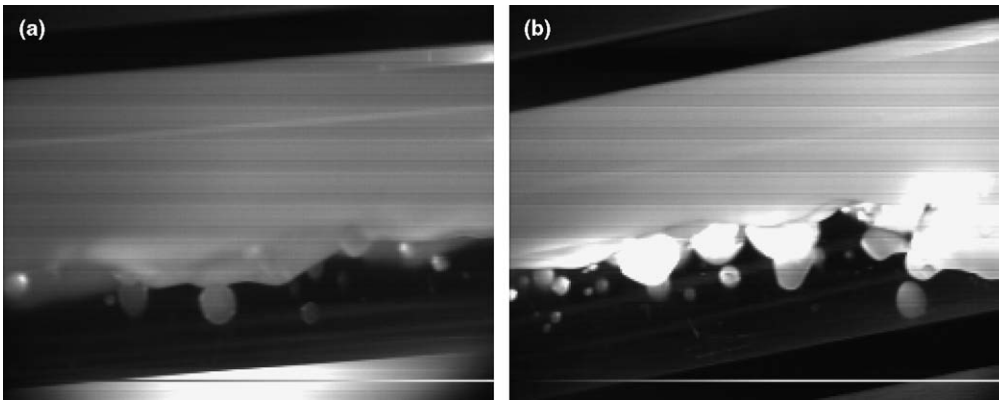

Fig. 6. *Dual continuous* (*DC*) flow at 1.0 m/s mixture velocity, 68% input oil fraction at (a) +5° and (b) +10° inclination.

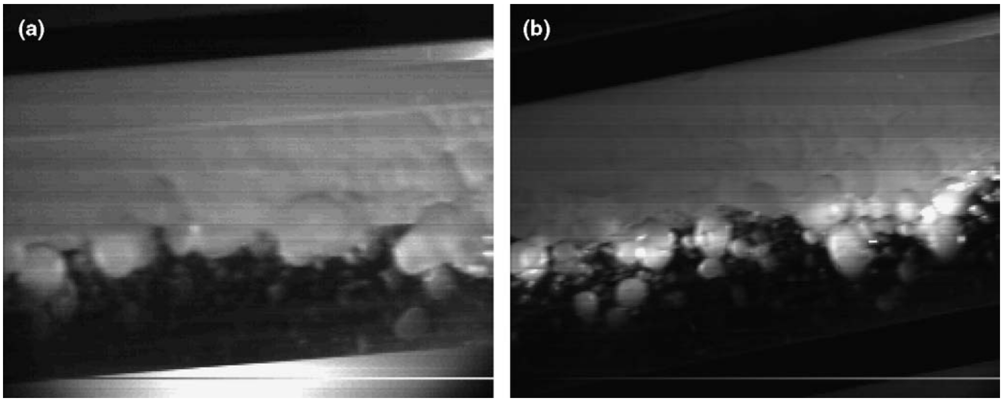

Fig. 7. *Dual continuous* (*DC*) flow at 1.5 m/s mixture velocity, 50% input oil fraction at (a) +5° and (b) +10° inclination.

velocity is increased the level of dispersion at the two inclinations becomes more similar (Fig. 7). As also seen in the *stratified* pattern, the introduction of an inclination causes the flow to be wavier in the *DC* pattern. The degree of waviness correspondingly increased with inclination so that the flow at +10° is wavier than at +5°.

(d) *Fully dispersed flow*. The range of the *dispersed oil-in-water* (*Do*/*w*) regime increases as the inclination is increased from +5° to +10°: it appears up to 50% input oil fraction at +10° instead of up to 40% at +5° (Fig. 2). This is related to the higher in situ water content associated with increased upward inclination. It may also be related to the fact that the component of gravity perpendicular to the pipe axis (which is the force that drives drops together and would cause their coalescence to a separate layer) becomes weaker at increasing inclination. Although the oil is fully dispersed, the concentration gradient of the oil drops is clearly evident, even at 2.0 m/s (Fig. 8). At 2.5 m/s, the video images are not clear and the flow pattern can only be identified with the use of local probes.

The boundary between *dual continuous* (*DC*) and *dispersed water-in-oil* (*Dw*/*o*) flow shifts slightly to the right when the inclination changes from +5° to +10° (Fig. 2). This again is associated with the higher in situ water fraction expected at higher inclinations, although (as the data in Fig. 13 also show) the change is not very significant and as a result the shift in the pattern boundary is only small.

In comparing the current results with those of previous investigators there is little consensus on the flow behaviour at this range of conditions. It should be noted that the conditions used by the other investigators either cover much lower velocities (Scott, 1985) or lower inclinations (Kurban, 1997; Vedapuri et al., 1997;

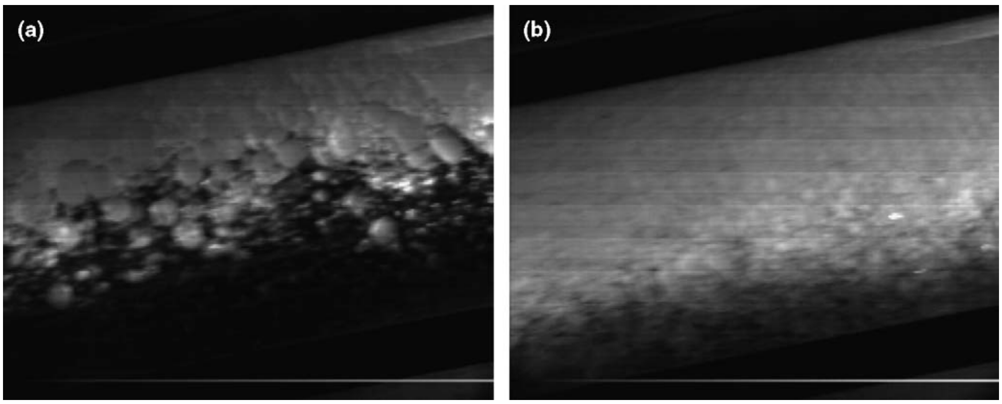

Fig. 8. *Oil-in-water dispersed* flow (*Do*/*w*) at +10° inclination, 20% input oil fraction and mixture velocity (a) 1.5 m/s and (b) 2.0 m/s.

Alkaya, 2000; Abduvayt et al., 2004). However, some general observations can be made. It appears that the increase in inclination from +5° to +10° causes fewer changes in the pattern boundaries after the initial effect of introducing an inclination to horizontal flow. This is in agreement with the results of Oddie et al. (2003), who found no change between +2° and +10° and of Alkaya (2000) who found that at high mixture velocities there was no significant effect of inclination on boundaries. The slight decrease of the *Dw/o* regime in the current work with increased inclination (see Fig. 2) is in contrast to the results by Vedapuri et al. (1997). The new pattern identified by Alkaya, *Dw/o&o*, between *DC* to *Dw/o* flow is also found in this work at both +5° (at 2 m/s at 84% input oil and at 2.5 m/s at 80% and 84% input oil) and at +10° (at 2.5 m/s at 80% and 84% input oil). However, this pattern is treated as part of the *Dw/o* as it would be difficult to ascertain in all cases whether a clear layer of oil with no water drops in it exists or there are some water drops reaching the top of the pipe. In contrast to the current study, Abduvayt et al. (2004) reported an increase in the region of *stratified* flow with inclination (the *stratified smooth* pattern disappeared and was replaced by *stratified wavy* flow) which extended to higher mixture velocities at intermediate and high input water fractions. The area occupied in the map by the *dual continuous* flow on the other hand diminished with a trend similar to what was found in this study.

The time-dependent flow, *plug flow* (*PG*), shown here is similar to results obtained at higher inclinations, i.e. at least above +25° (Vigneaux et al., 1988; Ding et al., 1994; Flores et al., 1997). A key difference between the present work and that of Flores et al. (1997) is that a counter-current element seen by Flores et al. (1997) could not be seen in the current study. Another difference between low and high inclinations is that the low inclination *PG* flow can take a number of forms (i.e. virtually no drops, dense drops at tail end of plug only, dense drops throughout), but *PG* flow at high inclinations seems to consist of packs of drops alone, probably due to the increased effect of the gravity component and the correspondingly greater degree of mixing.

3.1.2. −5°

At −5°, the mixing of the two phases is enhanced, and only *dual continuous* (*DC*) and *dispersed* flows (both *Do/w* and *Dw/o*) appear. Their boundaries are shown in Fig. 9, together with the flow pattern boundaries of horizontal and +5° flows. The extent to which the dispersion is enhanced by the downward inclination can be seen in Fig. 10: there are many more drops at −5° than at +5° for the same phase flowrates. This early introduction of dispersion could be driven by the more disturbed interface found in downward inclined flow (Cox, 1985; Alkaya, 2000).

(a) *Dual continuous flow*. At −5°, the *DC* pattern appears at velocities as low as 0.5 m/s, the lowest velocity measured. At higher mixture velocities, the boundary between *DC* and *Do/w* is shifted to higher input oil fractions such that the area occupied by the *DC* pattern becomes significantly smaller than for 0° and +5° (Fig. 9).

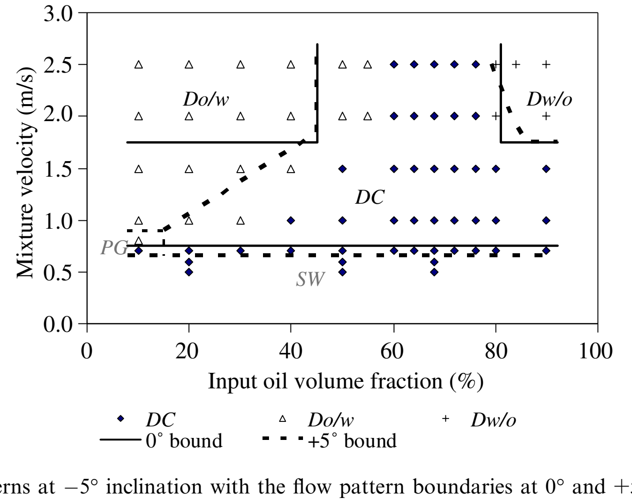

Fig. 9. Comparison of flow patterns at −5° inclination with the flow pattern boundaries at 0° and +5°. The flow patterns that do not appear at −5° inclination, *SW* and *PG*, are written on the map in grey.

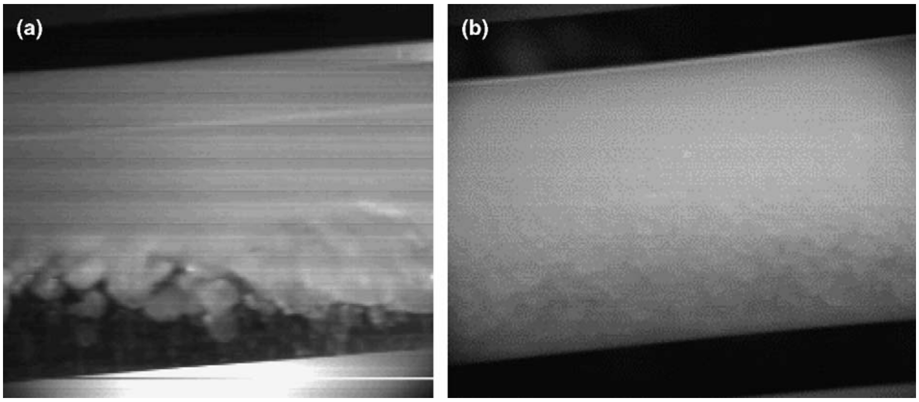

Fig. 10. Level of dispersion at 1.5 m/s mixture velocity, 68% input oil fraction at (a) +5° and (b) −5° inclination.

(b) *Fully dispersed flow*. At −5°, the *Do/w* regime extends to higher input oil fractions, compared to 0° and +5°, while the boundary of *Dw/o* does not change significantly. It is believed that a number of factors contribute to this behaviour such as the higher tendency of water to disperse the oil and the different velocity and thickness of the continuous water layer at the different inclinations. The higher velocity of the water layer at −5° increases the amount of oil dispersed in water and makes the transition from *DC* to *Do/w* to appear at higher oil fractions than at +5°. This is enhanced by the ability of water to disperse oil more easily (oil loses its continuity at about 67% fraction) than oil to disperse water. The boundary between *Dw/o* and *DC* remains at almost similar high oil fractions in all different inclinations. In downward flow the high velocity of the water layer promotes more dispersion of oil in water than the opposite. Oil will therefore only completely disperse the water when the water fraction becomes small. In upward flow, on the other hand, water tends to stay back and retains a relatively large thickness until high oil fraction, which makes it difficult for oil to disperse it all until the water fraction becomes again small. Although the transition from *DC* to *Dw/o* flows was less affected by inclination, the higher in situ water fraction in the upward flows makes the boundary to shift slightly to the right as the inclination increases which makes the area occupied by the *Dw/o* regime to decrease slightly as well.

In contrast to the current work *stratified wavy* (*SW*) flow pattern has been observed in downward flow by other investigators (Cox, 1985; Alkaya, 2000; Oddie et al., 2003; Abduvayt et al., 2004). This could be due to the different ranges of velocities and liquid properties used. In addition *PG* flow did not appear at all, but this is in accordance with previous work where it was also not seen (Cox, 1985; Vedapuri et al., 1997; Alkaya, 2000; Oddie et al., 2003; Abduvayt et al., 2004).

The extensive level of increase in *Do/w* flow seen at −5° has not been reported by other investigators who saw virtually no change when a downward inclination was introduced. This could be due to a number of factors: for example Oddie et al. (2003) investigated relatively small inclinations, at which no great shift could be observed, while Cox (1985) studied relatively few conditions at higher velocities.

3.2. Hold up

3.2.1. +10°

The velocity ratio data at +10° is shown in Table 2. The oil, as the less dense phase, travels at a considerably higher velocity than the water, so that *S* is almost always above one. In general the slip between the phases decreases and *S* tends to 1 with increasing mixture velocity as the degree of mixing is increased. Two distinct trends appear depending on mixture velocity. At low mixture velocities the slip ratio increases with increasing oil fraction while at high velocities the slip ratio is not affected significantly or is slightly decreasing with increasing oil fraction. A considerable decrease with oil fraction is observed at a mixture velocity of 2.5 m/s and oil fraction less than 60%. These trends are demonstrated below for a low and a high mixture velocities respectively and compared with the relevant results at horizontal and at +5° inclined flows.

Table 2
Velocity ratio at +10° pipe inclination

% Input oil	Mixture velocity (m/s)				
	0.7	1	1.5	2	2.5
	Velocity ratio				
10	1.01	0.79	1.07	1.01	1.71
20	1.16	0.91	1.72	1.45	1.41
30	1.30	2.81	1.31	1.38	1.34
40	1.39	1.80	1.46	1.43	1.20
50	2.63	1.71	1.50	1.28	1.19
60	2.04	1.45	1.66	1.51	1.08
64	1.91	1.72	1.52	1.40	1.13
68	2.10	1.90	1.58	1.39	1.25
72	1.95	1.64	1.64	1.44	1.24
76	2.19	1.60	1.51	1.56	1.24
80	2.22	1.75	1.44	1.36	0.85
90	2.38	1.82	0.79	0.86	0.92

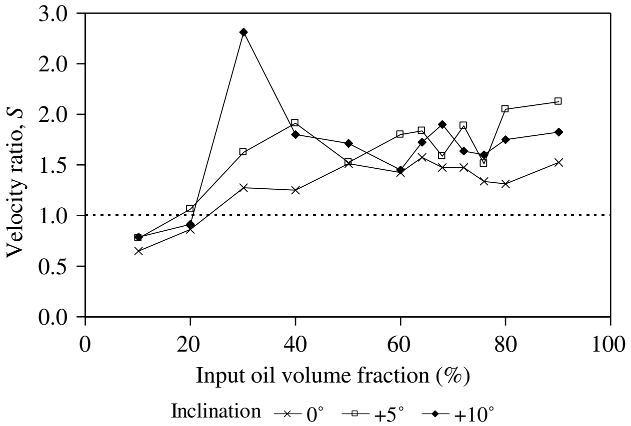

Fig. 11. Velocity ratio at 1.0 m/s mixture velocity for upward inclinations.

3.2.1.1. Comparing slip ratios at +10° with 0° and +5° at low mixture velocities. At the lower mixture velocities and +10° inclination, *S* shows a clear increasing trend with increasing input oil fraction (see Fig. 11 for 1 m/s). As expected for upward inclinations, the oil is flowing faster than water, and *S* is above 1, except at low input oil fractions. At these fractions oil is *dispersed o/w* at the top of the pipe (10% oil fraction) or in the boundary between *plug* and *Do/w* flows (20% oil fraction). The dispersed oil is accumulated at the top of the pipe where water has low velocity. Although oil drops could move somewhat faster than the surrounding water, their average velocity may still be less than the average water velocity, which also takes into account the faster moving water at the centre of the pipe. When *plug* flow establishes at 30% oil fraction a high value of *S* appears.

With further increase of the input oil fraction *S* remains above one, as a result of gravity and interface shape. At these oil fractions the pattern is *DC* and the interface is curved upwards (see Fig. 12). The water phase has now relatively large contact area with the pipe wall which, combined with gravitational effects, favours higher velocity of the oil phase that is concentrated in the faster moving area of the pipe away from the wall.

Comparing the *S* values of 0°, +5° and +10° at low mixture velocities, it is clear that *S* is higher in inclined than in horizontal flow (Fig. 11). The increase from 0° to +5°, however, appears generally greater than from +5° to +10°. This could be due to the increased mixing at the higher inclination: at +10°, high water holdup is still favoured but is tempered slightly by the increased level of mixing.

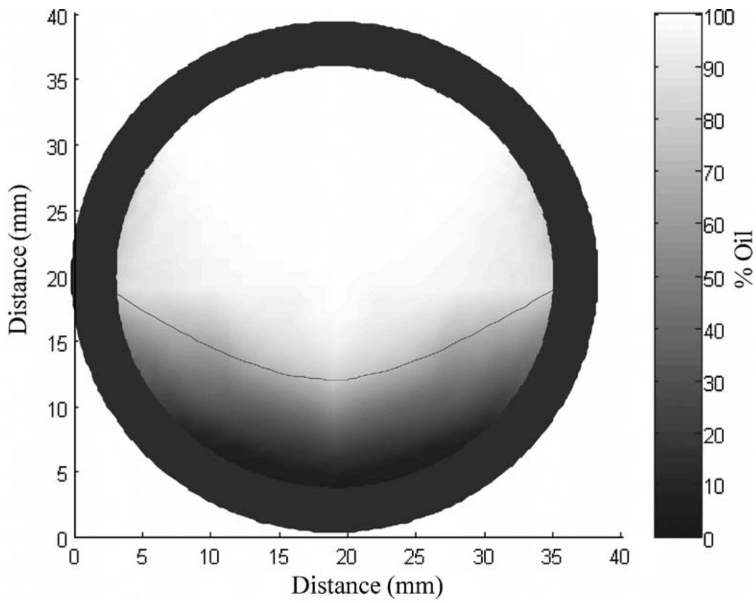

Fig. 12. Phase distribution in a pipe cross section at 1.0 m/s mixture velocity and 80% input oil fraction at +10° inclination. The continuous line indicates oil–water interface.

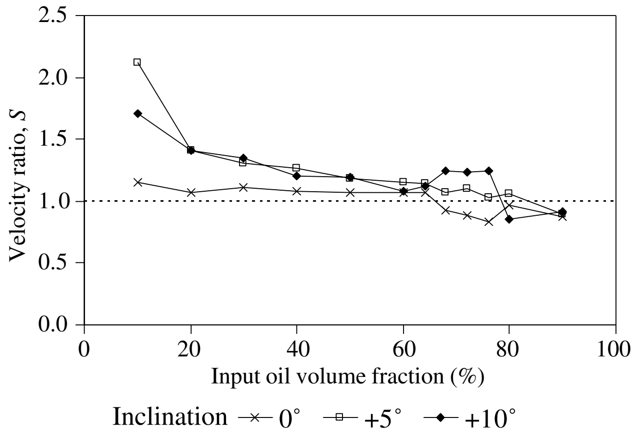

Fig. 13. Velocity ratio at 2.5 m/s mixture velocity for upward inclinations.

3.2.1.2. Comparing slip ratios at +10° with 0° and +5° at high mixture velocities. At the higher mixture velocities and +10° inclination, it appears that S tends to decrease with increasing input oil fraction (see Fig. 13 for 2.5 m/s). At low input oil fractions, the flow is *fully dispersed oil-in-water* (*Do/w*) and quite homogeneously distributed with oil consequently away from the wall, in the faster flowing region of the pipe (Fig. 14). As the input oil fraction increases, the water phase remains continuous, in *dual continuous* (*DC*) flow, and S remains above one (Fig. 13). The high in situ water fraction in the pipe due to the upward inclination could be a reason for the water remaining continuous at such high oil fractions (Fig. 15). The water ceases to be continuous only at the highest input oil fractions (80–84%) where the flow becomes *fully dispersed water-in-oil* (*Dw/o*) and increased mixing reduces the slip between the phases, causing S to approach one. In fact at these oil fractions the S value is just below one indicating that the dispersed water phase flows faster than the oil.

Comparing the S value at 0°, +5° and +10° for high velocities, it can be seen that S and consequently the in situ water fraction generally increase with pipe inclination. The behaviour here is similar to that discussed for low velocity flows with the S value generally closer to one at the high velocities than at the low ones.

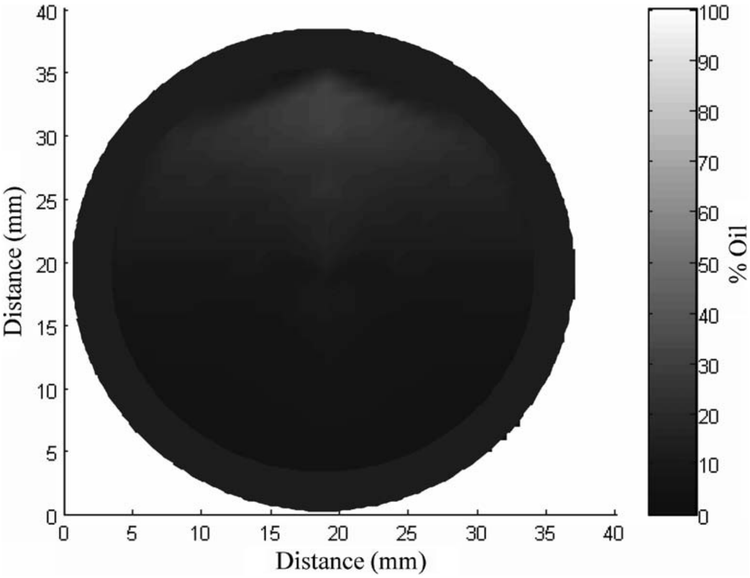

Fig. 14. Phase distribution in a pipe cross section at 2.5 m/s mixture velocity and 20% input oil fraction at +10° inclination.

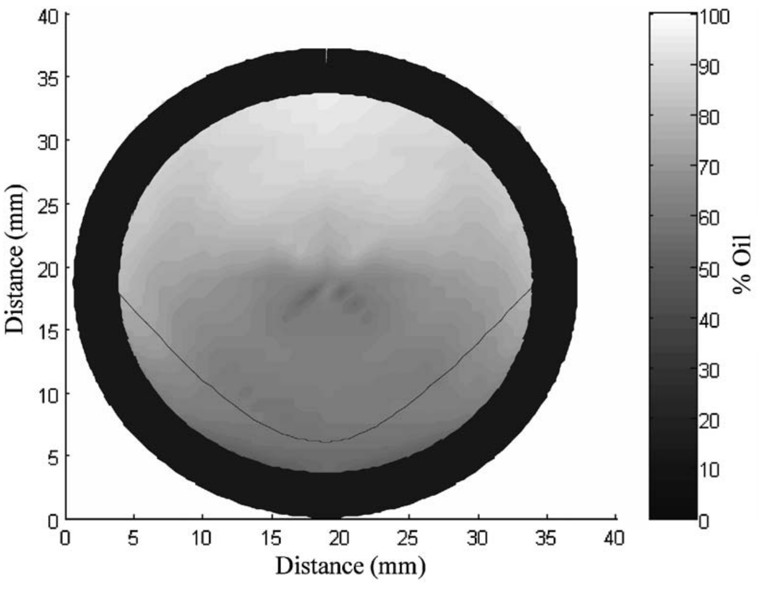

Fig. 15. Phase distribution in a pipe cross section at 2.5 m/s mixture velocity and 76% input oil fraction at +10° inclination. The continuous line indicates oil–water interface.

As data from previous investigations in inclined flows differ from the current work in the inclinations and flow velocities used, only general comparisons can be made. A value of S above one was found by Scott (1985), Flores et al. (1998) and Oddie et al. (2003). Abduvayt et al. (2004) also found values above 1 apart from a few cases at the highest mixture velocities at +0.5°. Based on limited data points, the velocity ratios by Alkaya (2000) are very close to one, either above or below it. Previous work also shows that S approaches one with increasing mixture velocity, due to the higher level of dispersion (Scott, 1985; Flores et al., 1998; Alkaya, 2000; Oddie et al., 2003; Lum et al., 2004; Abduvayt et al., 2004).

3.2.2. −5°

The velocity ratio data at −5° inclination is summarised in Table 3. In downward flow higher degree of mixing between the two phases was observed which results in slip ratios close to one in many cases. Surprisingly the velocity ratio also remains above 1 in the majority of cases as was seen in the upward inclinations as well, indicating that oil is still travelling faster than water. Again two trends can be seen at low and high mixture velocities. These are presented separately below together with the relevant data at 0° and +5° inclination.

3.2.2.1. Comparing slip ratios at −5° with 0° and +5° at low mixture velocities. At the lower mixture velocities, *S* rises from below one at low oil input fractions to above one at slightly higher oil fractions (Fig. 16). With increasing input oil fraction, *S* falls to values close to one with a flat profile and increases again at the highest oil volume fractions. *S* values close to one would be expected as the degree of mixing in downward flow is generally high.

At low input oil fractions, the flow is *dispersed oil-in-water* (*Do/w*). As the dispersed phase oil flows away from the wall (see Fig. 17) it experiences less drag which would allow it to flow faster; on the other hand buoyancy favours the water to flow faster and the overall effect is slip ratio less than one. *S* increases to values close to one and just above it as the oil fraction increases and the pattern becomes *dual continuous*. When this pattern is present the interface is curved upwards resulting in a high water wall contact area (for example

Table 3
Velocity ratio at −5° pipe inclination

% Input oil	Mixture velocity (m/s)				
	0.7	1	1.5	2	2.5
	Velocity ratio				
10	0.52	0.70	1.03	1.05	2.26
20	0.63	0.76	2.02	1.59	1.29
30	0.62	1.43	1.26	1.36	1.22
40	0.95	1.10	1.25	1.24	1.12
50	0.96	1.04	1.22	1.16	1.22
60	0.93	1.09	1.13	1.11	1.05
64	0.81	1.04	1.13	1.09	1.10
68	0.91	1.06	1.15	1.01	1.18
72	0.99	1.01	1.13	1.01	1.21
76	1.05	0.99	1.05	0.96	1.19
80	1.24	1.19	1.02	0.95	0.90
90	1.31	1.42	0.96	0.84	0.97

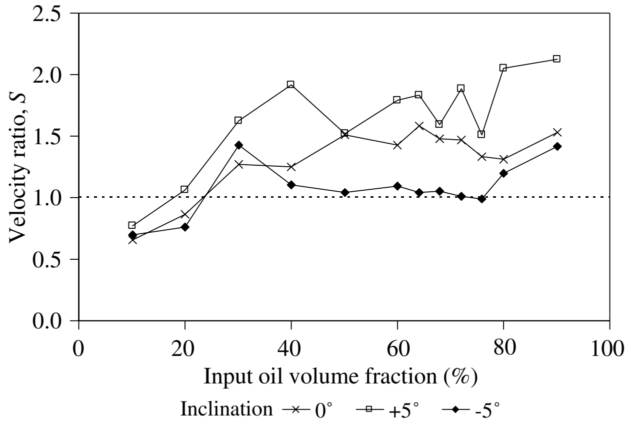

Fig. 16. Velocity ratio at 1.0 m/s mixture velocity for upward and downward inclinations.

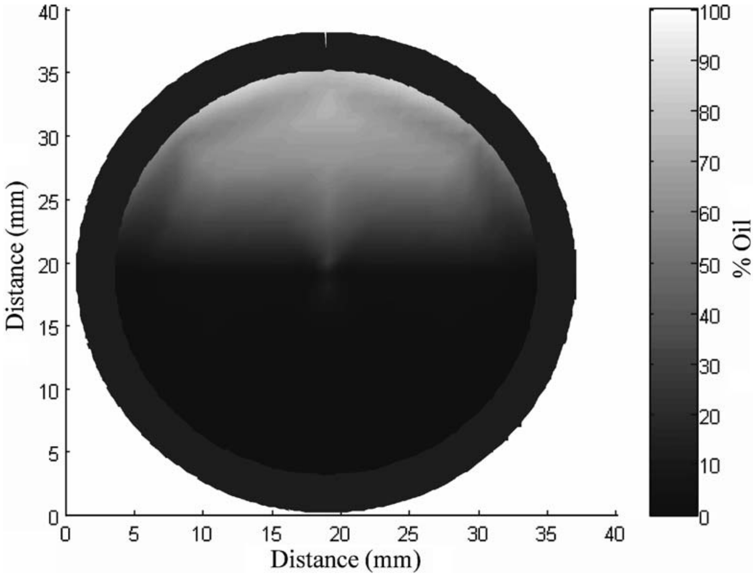

Fig. 17. Phase distribution in a pipe cross section at 1.0 m/s mixture velocity and 20% input oil fraction at −5° inclination.

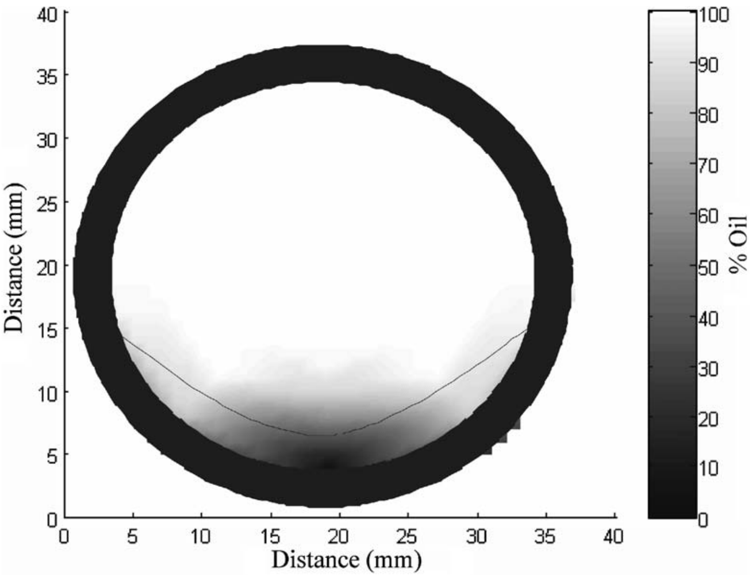

Fig. 18. Phase distribution in a pipe cross section at 1.0 m/s mixture velocity and 80% input oil fraction at −5° inclination. The continuous line indicates oil–water interface.

see Fig. 18) which would slow down the water and explain the S values just above one, against gravity which would favour faster water and S below one. The flow pattern persists as DC to the highest input oil fractions. At these fractions however, the interface, as can be seen from Fig. 18 is very curved forming a semi annulus around the oil and further increasing the water wall contact area relative to its volume. This results in the increase in S shown in Fig. 16.

Comparing the S values at low velocities for 0°, +5° and −5°, it can be seen that S is generally closest to one at −5°, due to both the higher level of dispersion in that inclination and also the effect of gravity. The behaviour and values of velocity ratios at all inclinations are similar from 10% to 30% oil fraction, and differ at higher input oil fractions with the differences between −5° and +5° being the greater.

3.2.2.2. Comparing slip ratios at −5° with 0° and +5° at high mixture velocities. At the higher mixture velocities, S tends to decrease from above one to slightly below it with increasing input oil fraction as the flow changes from *dispersed oil-in-water* (*Do/w*) at low oil fractions, to *dual continuous* (*DC*) at intermediate ones and to *dispersed water-in-oil* (*Dw/o*) at high oil fractions (Fig. 19). At low and high oil fractions the values of slip velocity suggest that the dispersed phases, oil and water respectively, move faster than the continuous ones. This is opposite to what is found for water continuous dispersions at low mixture velocities where the dispersed oil appeared to be slower than the continuous water and could be attributed to the difference in dispersion homogeneity that is improved at the higher velocities (see Fig. 20 compared to Fig. 17). During *dual continuous* flow at the intermediate oil fractions, it appears that oil travels faster but the difference between the oil and water velocities decreases as the oil fraction increases and more water disperses into the oil. Finally at high input oil fractions water disperses completely in the oil (Fig. 21) and S decreases further to values below 1.

Comparing the flows of 0°, +5° and −5°, S at −5° is lower and closer to one than at the other inclinations at the high oil fractions, as would be expected for downward flow. However, at low oil fractions S at −5° is

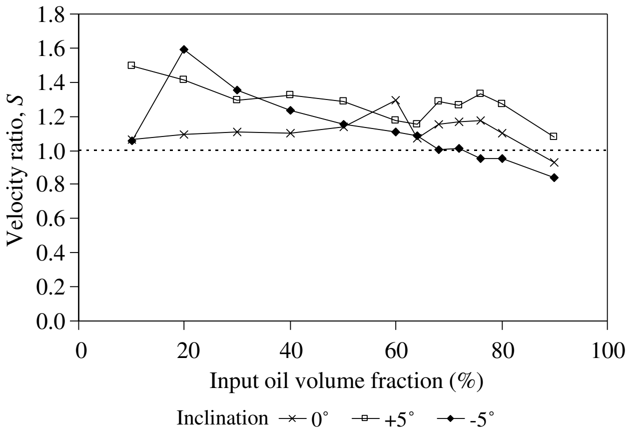

Fig. 19. Velocity ratio at 2.0 m/s mixture velocity for upward and downward inclinations.

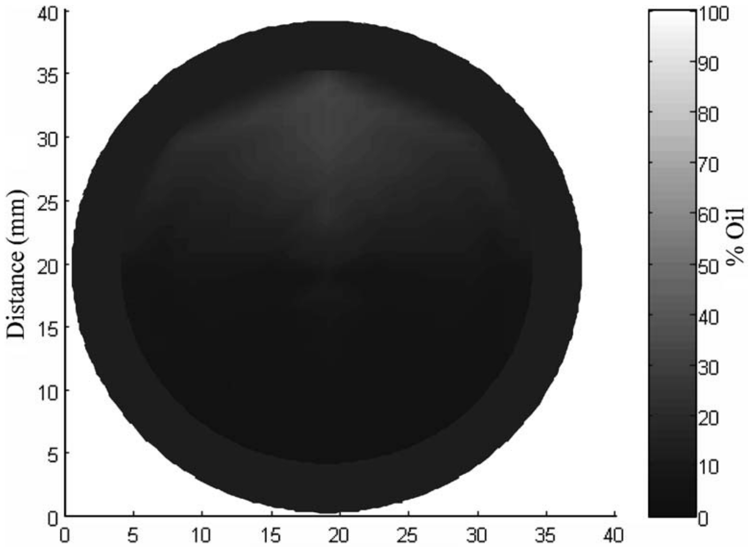

Fig. 20. Phase distribution in a pipe cross section at 2.0 m/s mixture velocity and 20% input oil fraction at −5° inclination.

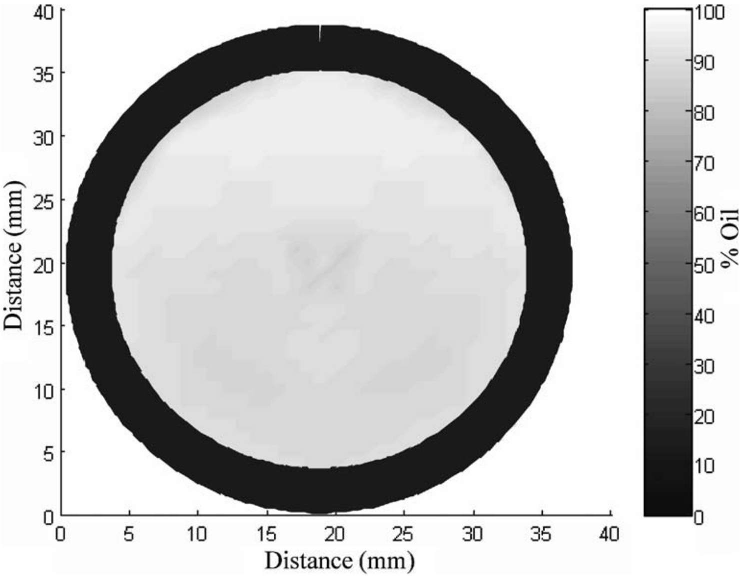

Fig. 21. Phase distribution in a pipe cross section at 2.0 m/s mixture velocity and 84% input oil fraction at −5° inclination.

higher than in horizontal flow and in some cases even higher than in upward flow perhaps indicating that the increased mixing which disperses the oil phase into water counteracts the effect of buoyancy.

In contrast to the above Abduvayt et al. (2004) reported in situ water fractions less than the input ones indicating S values below one for all the conditions investigated at −3°.

3.3. Pressure drop

3.3.1. +10°

The frictional (ΔP_f) and total (ΔP_t) pressure gradient results at +10°, averaged over at least two measurements, are tabulated in Table 4. The frictional pressure gradient is also plotted in Fig. 22. There is little variation of pressure gradient with oil fraction at the lower two velocities. At the higher velocities ΔP_f takes values below the single phase oil ones and a minimum is formed which becomes more distinct as the velocity

Table 4
Total (ΔP_t) and frictional (ΔP_f) pressure gradient at +10° pipe inclination

% Input oil	Mixture velocity (m/s)									
	0.7		1.0		1.5		2.0		2.5	
	Total and frictional pressure drop (kPa/m)									
	ΔP_t	ΔP_f	ΔP_t	ΔP_f	ΔP_t	ΔP_f	ΔP_t	ΔP_f	ΔP_t	ΔP_f
10	1.821	0.150	1.986	0.321	2.301	0.629	2.770	1.099	3.197	1.499
20	1.794	0.145	1.988	0.348	2.236	0.563	2.636	0.979	3.055	1.406
30	1.775	0.146	1.873	0.210	2.206	0.567	2.579	0.947	2.961	1.331
40	1.764	0.159	1.836	0.211	2.094	0.477	2.538	0.933	2.884	1.286
50	1.739	0.118	1.837	0.241	2.010	0.419	2.435	0.863	2.828	1.261
60	1.699	0.122	1.806	0.250	1.953	0.385	2.325	0.769	2.789	1.254
64	1.682	0.121	1.782	0.228	1.953	0.403	2.289	0.750	2.731	1.206
68	1.681	0.123	1.769	0.218	1.940	0.398	2.263	0.738	2.644	1.126
72	1.668	0.134	1.744	0.217	1.957	0.427	2.223	0.708	2.536	1.029
76	1.669	0.141	1.735	0.226	1.988	0.478	2.181	0.674	2.489	0.993
80	1.658	0.144	1.750	0.251	1.968	0.473	2.221	0.739	2.447	0.980
90	1.608	0.133	1.728	0.268	2.013	0.572	2.433	0.995	2.876	1.440

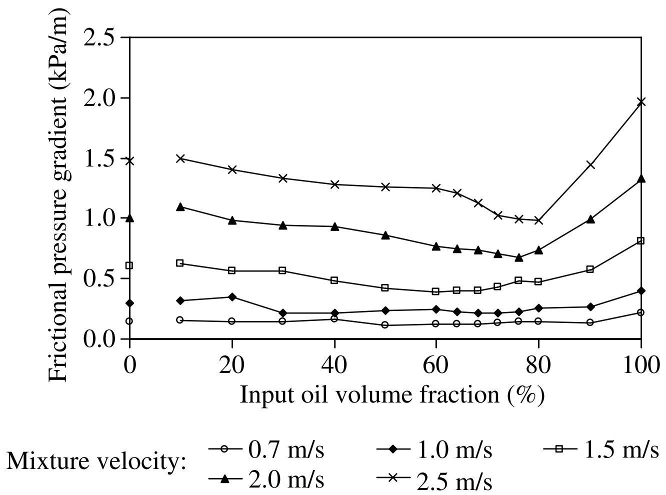

Fig. 22. Frictional pressure gradient at +10° for different mixture velocities.

increases. These decreased pressure gradient values are attributed to drag reduction in liquid–liquid systems when a dispersion is present (either in *dual continuous* or *fully dispersed* flows). In particular, at 2 m/s and 2.5 m/s starting from *dispersed water-in-oil* pattern with decreasing oil (increasing water) fraction the pressure gradient decreases. At about 80% oil fraction after the transition from *dispersed water-in-oil* to *dual continuous* flow, pressure gradient starts increasing again. At the highest velocity 2.5 m/s the initial sharp increase changes at about 60% oil fraction to a more moderate one and ΔP_f slowly increases towards the single phase water value. At 2 m/s the slope of the pressure gradient curve after the minimum does not change very much. The minimum in pressure gradient and the change in slope can be explained with the relative strength of drag reduction in oil and water continuous dispersions. Drag reduction is stronger in oil continuous than in water continuous flows and increases with the dispersed phase fraction (Pal, 1993). The low pressure gradient values at oil fractions above 80% occur therefore when an oil continuous dispersion occupies the whole pipe cross section and has a high concentration of the dispersed water phase. A minimum in pressure gradient can therefore appear just before the transition from *Dw/o* to *DC* flow or just after when a thin water layer has formed with little or no amount of oil dispersed in it. As the water layer will form a semi-annulus (see for example Fig. 15) surrounding the oil, it may decrease further the pressure gradient. With increasing water fraction and thickness of the water layer, the drag reduction effect is reduced as the amount of water dispersed into the oil is less and part of the pipe is now occupied by a water continuous dispersion. At the highest velocity the loss of the oil continuous layer in the transition from *DC* to *Do/w* seems to result to a further decrease of the drag reduction phenomenon.

The input oil composition at which the minimum point occurs appears to fluctuate between 76% and 80% at 2.0 m/s, and between 72% and 80% at 2.5 m/s. However, by averaging the data, the minimum point occurs as shown in Fig. 22 at 76% and 80% for 2.0 m/s and 2.5 m/s respectively. Below frictional pressure gradients at a low and a high mixture velocity are compared with the relevant data at 0° and +5° inclination.

3.3.1.1. Comparing frictional pressure gradient data at +10° with those at 0° and +5°. The ΔP_f results at +5° and +10° are generally very similar, both in terms of trends and of absolute values (Figs. 23 and 24 for low and high mixture velocities respectively) and mostly within the experimental uncertainty of 10%, while they are both in general lower than the horizontal flow values. It appears that any significant effect on pressure gradient of pipe inclination is introduced by changing the position of the pipe from the horizontal while the actual magnitude does not affect pressure gradient significantly at these small inclinations. The reduction of the pressure gradient magnitude compared to horizontal flows could be due to the increase in the amount of water retained or to the increase of dispersion present that favours drag reduction.

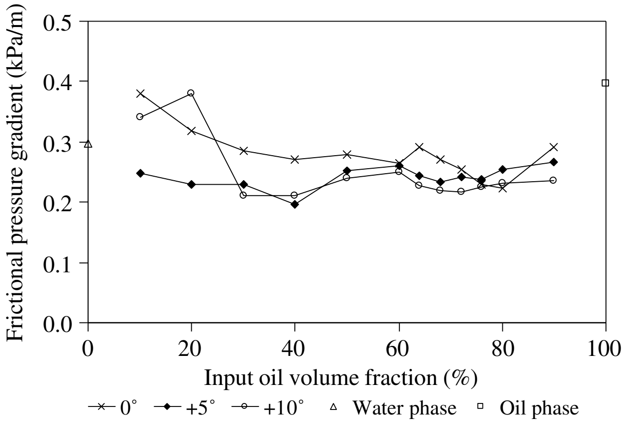

Fig. 23. Frictional pressure gradient at 1.0 m/s mixture velocity for horizontal and upward inclinations.

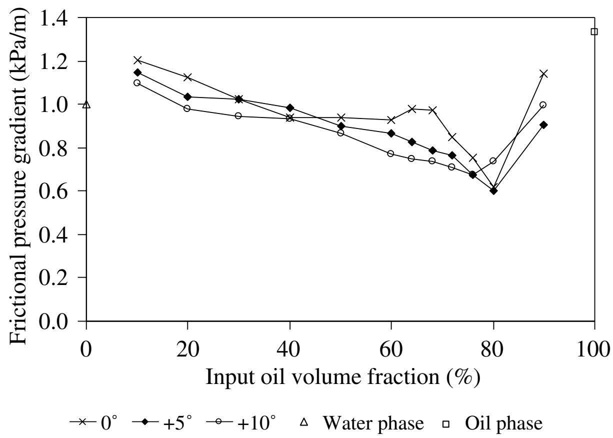

Fig. 24. Frictional pressure gradient at 2.0 m/s mixture velocity for horizontal and upward inclinations.

Table 5
Total (ΔP_t) and frictional (ΔP_f) pressure gradient at −5° pipe inclination

% Input oil	Mixture velocity (m/s)									
	0.7		1.0		1.5		2.0		2.5	
	Total and frictional pressure drop (kPa/m)									
	ΔP_t	ΔP_f	ΔP_t	ΔP_f	ΔP_t	ΔP_f	ΔP_t	ΔP_f	ΔP_t	ΔP_f
10	−0.66	0.168	−0.52	0.314	−0.20	0.638	0.259	1.098	0.666	1.506
20	−0.65	0.161	−0.47	0.345	−0.33	0.510	0.119	0.953	0.684	1.509
30	−0.65	0.148	−0.57	0.241	−0.27	0.550	0.094	0.913	0.606	1.414
40	−0.68	0.110	−0.57	0.229	−0.24	0.563	0.107	0.910	0.623	1.416
50	−0.67	0.106	−0.54	0.234	−0.30	0.492	0.131	0.918	0.630	1.409
60	−0.65	0.111	−0.53	0.240	−0.31	0.465	0.206	0.976	0.694	1.460
64	−0.65	0.098	−0.52	0.241	−0.29	0.479	0.189	0.953	0.790	1.551
68	−0.65	0.105	−0.51	0.239	−0.26	0.497	0.028	0.782	0.622	1.377
72	−0.64	0.114	−0.51	0.232	−0.26	0.488	0.029	0.778	0.564	1.313
76	−0.62	0.129	−0.51	0.234	−0.25	0.495	0.104	0.845	0.359	1.100
80	−0.61	0.131	−0.51	0.228	−0.24	0.495	0.230	0.965	0.583	1.319
90	−0.60	0.126	−0.48	0.248	−0.06	0.661	0.367	1.093	0.890	1.616

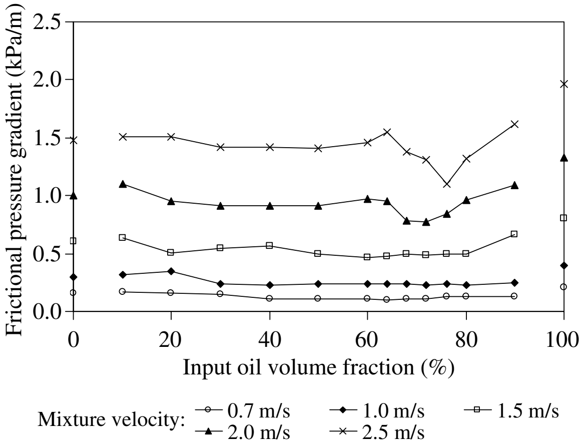

Fig. 25. Frictional pressure gradient at −5° for different mixture velocities.

3.3.2. −5°

Results at −5° are shown in Table 5 for frictional and total pressure gradient and in Fig. 25 for frictional pressure gradient. The trends are similar to those at +10° inclination. At the low velocities, ΔP_f shows relatively little variation with input oil fraction. At high velocities the minima observed in horizontal and upward flows continue to appear in downward flow. The changes in the pressure gradient slope at these velocities are again associated with the boundaries of the *DC* pattern with *Dw/o* flow at the high oil fraction and with the *Do/w* flow at the low oil fraction. Peaks appear at 2.0 m/s and 2.5 m/s. The peak is relatively small at 2.0 m/s and appears between 60% and 64% input oil fraction in the different measurements. At 2.5 m/s, the peak appears between 64% and 72% input oil fraction, with the average being at 64%. It was found that just before the transition from *DC* to *Do/w*, the interface is curved upwards (see Fig. 26 in comparison to Fig. 27) and the oil has a large contact area with the wall which is opposite to the usual finding that water has a large contact area at similar input oil fractions. This increase in oil wall contact area would explain the peak in the frictional pressure gradient.

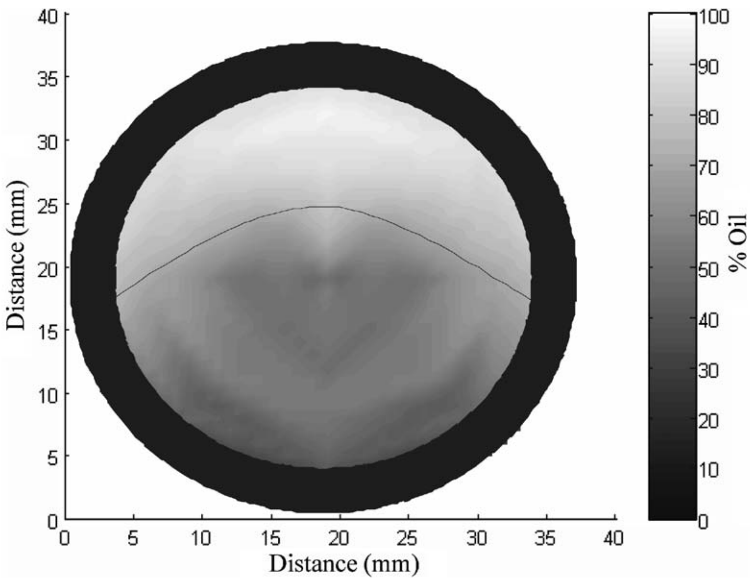

Fig. 26. Phase distribution in a pipe cross section at 2.0 m/s mixture velocity and 68% input oil fraction at −5° inclination. The continuous line indicates oil–water interface.

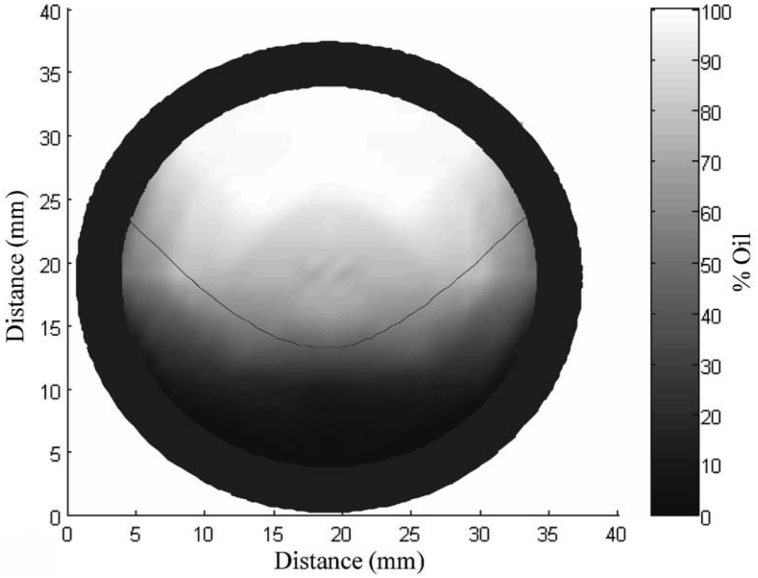

Fig. 27. Phase distribution in a pipe cross section at 2.0 m/s mixture velocity and 68% input oil fraction at +5° inclination. The continuous line indicates oil–water interface.

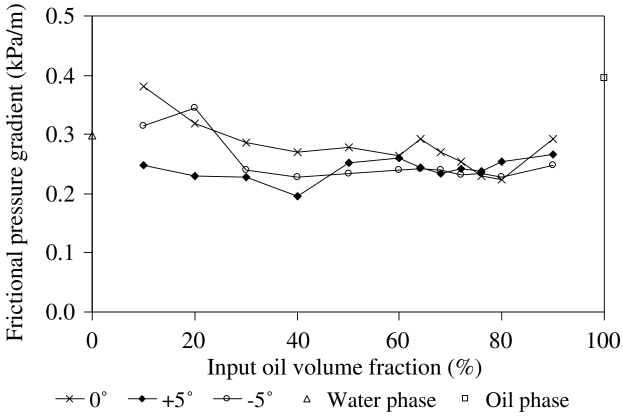

Fig. 28. Frictional pressure gradient at 1.0 m/s mixture velocity for different pipe inclinations.

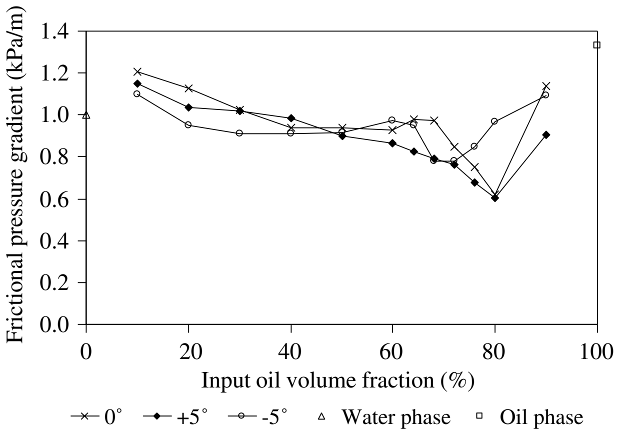

Fig. 29. Frictional pressure gradient at 2.0 m/s mixture velocity for different pipe inclinations.

A comparison of the 0° and ±5° flows is made in Figs. 28 and 29 for low and high mixture velocities respectively. It would be expected that the effect of downward inclination would be opposite to that of upward inclination i.e. that the two-phase ΔP_f would be higher in downward inclination than in horizontal and upward flows. In fact ΔP_f at −5° has very similar values or even slightly lower to those at horizontal and upward inclined flows. As was seen in the flow pattern section the increased mixing seen at downward flows balances buoyancy and the more viscous oil is dispersed in many cases (as *DC* or *Do/w* flow) and not accumulating in the pipe to give higher pressure drop (see Fig. 9).

4. Conclusions

The effect of upward and downward inclination during oil–water flow on flow pattern, hold up and pressure drop were investigated experimentally. The results were also compared with published inclined flow studies. The *dual continuous* regime prevailed at the flow conditions used in all inclinations, but it appeared for a smaller range of conditions at +10° and −5° than at horizontal and +5° inclinations. A new flow pattern, *oil plug flow* was found at both +5° and +10° inclination. With increasing inclination the boundaries of this regime extended to higher oil fractions and mixture velocities.

In *stratified wavy* flow the interface was found to become wavier as the degree of inclination increased from the horizontal. However, this pattern disappeared completely in downward flow. The *Do/w* regime extended to lower mixture velocities and higher oil fractions as the inclination increased, because of increased in situ water fraction with inclination. Interestingly, the area occupied by the *Do/w* regime was also extended to lower mixture velocities and higher oil fractions at −5° compared to horizontal flow probably because of increased water velocity in downward inclinations and tendency of the water to disperse the oil. Finally, the transition from *DC* to *Dw/o* flows was less affected by inclination and shifted slightly to higher oil fractions as the inclination increased from −5° to +10°.

Although, as expected, the velocity of the oil phase increased with pipe inclination, from −5° to +10°, nevertheless oil was found to flow faster than water at most compositions and mixture velocities. In general, and for all inclinations, at low mixture velocities the oil to water velocity ratio, *S*, increased with oil fraction from below to above one. This increase was more prominent in the upward inclinations, while in the downward inclination this increase was more moderate. At high mixture velocities, with increasing input oil fraction *S* decreased and in most cases fell to slightly below one during *Dw/o* flow. The trend of the decrease in *S* is different for the different pipe inclinations investigated in this work. The above description of the behaviour of *S* at low and high velocities is general and not conclusive due to the combined effect of flow patterns formed and interface shape.

Frictional pressure gradient, ΔP_f, was found to be lower in two-phase than in single-phase oil flow at all inclinations investigated. The frictional pressure gradients in both upward and downward flows were lower than in horizontal flow despite the similarity in flow patterns. This could be attributed to the high in situ water fraction in upward flows and to the increased mixing seen in downward flows. At low mixture velocities there was little variation of ΔP_f with oil fraction. Minima appeared at high mixture velocities during the transition from *Dw/o* to *DC* patterns. The phase distribution diagrams provided information on the exact flow pattern and interface shape and helped explain the trends in hold up and pressure gradient.

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