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Flow patterns and pressure drop in oil–air–water three-phase flow through helically coiled tubes

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We are so glad to present this paper to express our congratulations to Professor G. Hetsroni for his achievements in the international academic field of multiphase flow and as a dedication for Professor G. Hetsroni's 65th birthday anniversary.

Abstract

Experimental investigations on oil–air–water three-phase flow were carried out in two helically coiled tubes with inner diameter of 39 mm and coil diameters of 265 and 522.5 mm, respectively. The purpose of this work is to provide a basis for the invention and development of a new kind of separation technology for gas–oil–water mixtures with low oil fraction $\beta \leq 30\%$. The flow patterns of oil–water two-phase flow and oil–air–water three-phase flow were directly observed in test sections made of plexiglass tubes. The flows observed in coiled tubes could be classified into more than four flow patterns and some flow regime maps were generated and delineated for these tubes. The present results were compared with some results in horizontal flow. The phase inversion characteristics in helically coiled tubes were also discussed. The frictional pressure drop of oil–air–water three-phase flow were measured. The effects of flow rates and liquid properties on pressure drop were examined. Based on the experimental data and analysis of the flow mechanism the criteria for the flow pattern transition boundaries between two different flow patterns were proposed in terms of dimensionless parameters. Correlations for the predictions of pressure drop were also obtained. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Oil–air–water three-phase flows; Flow patterns; Frictional pressure drop; Helically coiled tube

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1. Introduction

Gas–oil–water three-phase flow mainly occurs in the petroleum and chemical industries, for example, in both on-shore and offshore hydrocarbon production and in transporting the gas–oil–water mixtures from offshore production. This is because water is often emitted from the wells in addition to the product oil and natural gas streams, which arise both naturally within the reservoir (i.e. connate water) and from water flooding of the reservoir at a later stage in the production (i.e. injected water). It is often economic to operate wells with over 90% water in the output liquid flow. Thus, it is important to have some knowledge on the flow characteristics of the three-components, such as flow patterns, pressure drop and holdup, especially at high pressure, for the proper design and operation of pipelines. Since sand is also produced in a number of cases, a rig was designed to cope with up to four phases. Hence the name OAWS (oil–air–water–sand) was given to the facility at the National Laboratory of Multiphase Flow in Power Engineering in Xi'an Jiaotong University for the study of three- or four-phase flows at pressure up to 8 bar.

Flows of mixtures of two immiscible fluids such as oil and water are also encountered frequently in the design of a variety of industrial processes and equipment. Although there were a number of publications on liquid–liquid two-phase flow in the 1950s and 1960s, the field has been relatively quiescent until recently. However, the interest in pipeline transport of oil–water mixtures has led to a resurgence of work in the area (Hewitt, 1997). In the work of Charles et al. (1961) as reported by Govier and Aziz (1972), four kinds of flow patterns named bubble (oil dispersed), slug (oil dispersed), (both phases dispersed) and mist (water dispersed) flow were defined and delineated in a horizontal pipe with an inner diameter of 26 mm using oil with viscosity of 16.8 mPa s at 20°C and density of 998 kg/m^3. Govier et al. (1961) conducted a study of flow pattern characteristics with a 37 ft long vertical pipe with 1.038 in. i.d. Four different flow patterns were observed, namely bubbles and drops of oil in water, slugs of oil in water, of oil and water and drops of water in oil. They concluded that if the oil phase was taken as a 'gas phase' with high density, the flow patterns of oil–water flow were almost the same as those of gas–liquid two-phase flow.

Arirachakaran et al. (1989) observed Stratified flow, Mixed flow, Annular flow, Intermediate flow and Dispersed flow, five flow patterns of oil–water flow in two horizontal tubes with 38 and 25.1 mm i.d., respectively. In their flow pattern map, Intermediate flow exists under very narrow flow conditions. Nadler and Mewers (1995) conducted similar investigations in a horizontal straight pipe with 59 mm i.d. They distinguished flow patterns and presented a flow pattern map, but did not observe intermediate flow.

Valle and Kvandal (1995) reported their results obtained in a 10 m long 37.5 mm i.d. glass tube. They observed and defined: Stratified Smooth (SS), Stratified Wavy (SW), Stratified Wavy-Entrained (SWE), Stratified wavy flow with a highly dispersed water zone and a moderately dispersed oil zone (SWWD) and Stratified wavy flow with a highly dispersed oil zone and a moderately dispersed water zone (SWOD), five flow patterns. Valle and Utvik (1997) reported of oil–water two-phase flow patterns in a horizontal tube 120 m long, with inner diameter of 77.9 mm. Light crude oil from North Sea was employed, with viscosity of 1 cP and density of 741 kg/m^3. They observed only two flow patterns, namely dispersed and stratified flows, taken after the classification of Trallero (1995) who carried out a comprehensive review of oil–water two-phase flow. Hewitt (1997) pointed out that (a) Stratified flows exist for both types of fluid combination. (b) Slug flow is ubiquitous in gas–liquid flow, but is something of a rarity in liquid–liquid two-phase flow.

Andreini et al. (1997) conducted also an experiment on oil–water two-phase flow patterns in small horizontal tubes with inner diameters of 3 and 6 mm, respectively. The ratio of oil to water viscosity ranged from about 560 to 1300 and different tubes (Glass, Steel, Copper and PVC) were employed. A number of flow patterns were observed and reported in terms of Dispersed, Intermittent and Annular flow. Oil was observed, in most cases, to flow in the core of the tube, while water flowed around the wall perimeter. The tube wall was found to influence the flow patterns for relatively low ratios of flow rates of water to oil (less than 0.12–0.3). The effects of the characteristics of the tube wall on oil–water flows were also investigated and reported by Andreini et al. (1997) in their pressure drop investigations.

As to the theoretical investigations of liquid–liquid two-phase flow pattern transitions, the available literature is very limited. Brauner and Maron (1989, 1992a, 1992b) and Hasson et al. (1970) made some attempts in this subject using a two-phase, two-fluid model with limited success. Hall and Hewitt (1993) carried out investigations of oil–water flow using the two-fluid model that was used by Taitel and Dudler (1976) for gas–liquid flow in its simplest form. The effect of ratio of oil to water viscosity on liquid height was theoretically studied.

Although much work on oil–water two-phase flow was conducted in the past 40 years, there still exist some uncertainties, more data need to be added to the database of this kind of flow.

Generally speaking, gas–liquid–liquid three-phase flows can be regarded as a special kind of gas–liquid two-phase flows. An ordinary gas–liquid two-phase flow is the two-phase flow of a gas and a uniform liquid, while gas-liquid-liquid, three-phase flow may be considered as the two-phase flow of a gas and a liquid mixture. Moreover, three-phase flows are always non-uniform spatially and temporally in the pipe, which refers mainly to the non-uniformity of the liquid properties such as viscosity, density, etc. On one hand the non-uniformity makes the three-component flow considerably different from an ordinary gas–liquid two-phase flow and therefore makes it necessary to investigate it separately as a form of multiphase flow. On the other hand, three-phase flow is strongly related to gas–liquid two-phase flow and therefore the methods, theories, correlation, conclusions, etc., developed for gas–liquid two-phase flow can be used as the basis, reference or standing points in the investigation of three-phase flow.

Compared to numerous investigations of two-phase flow in the literature, there are only limited publications on three-phase flow of gas–liquid–liquid mixtures. According to the review by Hewitt et al. (1995), the first paper on this subject was published 46 years ago. Sobocinski (1953) conducted air–oil–water flow experiments and found that there is a maximum of the pressure gradient at an input water fraction in the liquid of approximately 0.77, this maximum value being even larger than that for air–oil two-phase flow under the same conditions. Malinowsky (1975), Laflin and Oglesby (1976) and Hall (1992) confirmed the above result later but at different values of input water fractions and attributed it to phase inversion, i.e. an inversion in which the continuous phase changes from being oil to being water or vice versa. Sobocinski (1953) also noticed the effect of the oil and water configuration on flow patterns and tried to develop a three-dimensional (i.e. three mapping parameters) flow regime map for three-phase flow, but with limited success. Malinowsky (1975), Laflin and Oglesby (1976) and

Stapelburg and Mewes (1994) extended existing two-phase flow regime maps (2-dimensional) to gas–liquid–liquid flow and claimed good agreement.

Acikgoz et al. (1992) experimentally found new and interesting flow patterns in air–oil–water flow using new technology and offered new three-dimensional maps. Pan et al. (1995) conducted an experiment on air–oil–water flow in a 77.92 mm horizontal pipe at a pressure of 5 bar, classified the observed flows into seven flow patterns and generated and delineated a flow pattern map. They also found a maximum value on the curve of pressure gradient versus the water fraction of the (fixed) total liquid flow which is due to phase inversion and suggested the introduction of a new parameter, called mixing degree coefficient to quantitatively describe the mixing between the two immiscible liquids.

The above investigations are mostly on straight pipes oriented vertically or horizontally; there exists little work on oil/water two-phase flow and air-oil-water three-phase flow in curved tubes. Coils are used in chemical reactors, agitated vessels, storage tanks, and in some nuclear steam generators. Recently, coiled tubes are usually employed as intermediate heater elements in oil transporting systems. Therefore, it is of great interest to conduct research on the flow characteristics in oil–water two-phase flow and oil–air–water three-phase flow through these kinds of tubes. The purpose of the present study is to augment understanding and knowledge of oil/water two-phase flow and air–oil–water three-phase flow in helically coiled tubes. The flow patterns of oil–water two-phase flow were experimentally observed first. Then the flow patterns and pressure drop characteristics of oil–water–air three-phase flow were investigated and flow regime maps were generated and delineated. Correlations for the prediction of pressure drop are also proposed.

2. Experimental facility and instrumentation

2.1. Test loop and test sections

As mentioned above the OAWS facility was designed and built in our lab to cope with up to four phases (i.e. oil, air, water and sand) for the study of three-or four-phase flows in pipelines at a pressure up to 8 bar. Experiments were conducted in this rig, which is schematically illustrated in Fig. 1.

The test sections used in these experiments include two helically coiled tubes oriented horizontally made of 39 mm i.d. plexiglass tube: a coil diameter D of 265 mm, 4320 mm in length L and coil diameter of 522.5 and 6760 mm in length, respectively. The coil pitches of the two test sections are 45 mm. All the test sections are shown in Fig. 2.

2.2. Measurement techniques

The flow rates of oil, gas and water were measured using three orifice meters with different flow ranges, which were calibrated prior to the experiment. The temperature of the working fluids was measured both at the inlet and at the outlet of the test section using thermocouples with an accuracy of 0.2°C. The pressure of the working fluids were also measured both at the inlet and at the outlet of the test section. A 1151-DP differential pressure transducer was used

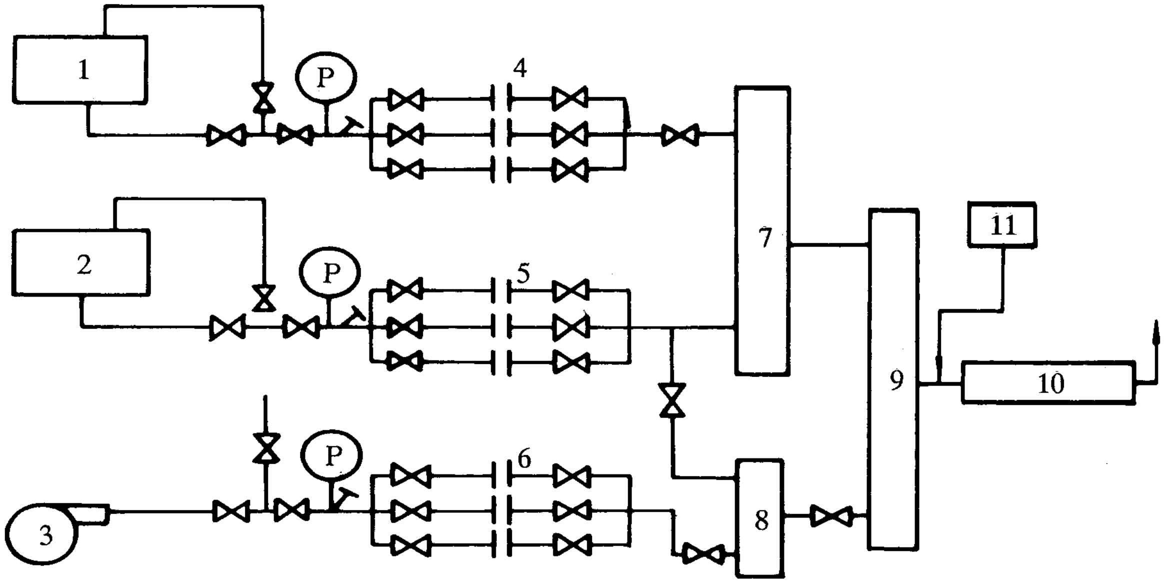


Fig. 1. OAWS test system. 1. Oil tank, 2. Water tank, 3. Compressor, 4. Oil-orifice meters, 5. Water-orifice meters, 6. Gas orifice, 7. Oil–water mixer, 8. Gas–water mixer, 9. Gas–oil–water mixer, 10. Test section, 11. Sand tank. *P*, Pressure meter, *T*, Thermocouple or temperature probe.

to measure the pressure drop over the whole test section. The arrangement and locations of the thermocouples and the pressure transducers can be seen in Fig. 2. The flow pattern was distinguished by visual observation. All the signals representing the flow rates, temperature, pressure and differential pressure were transmitted to an IBM computer and recorded using an IMP acquisition system. The experimental data were saved for further processing.

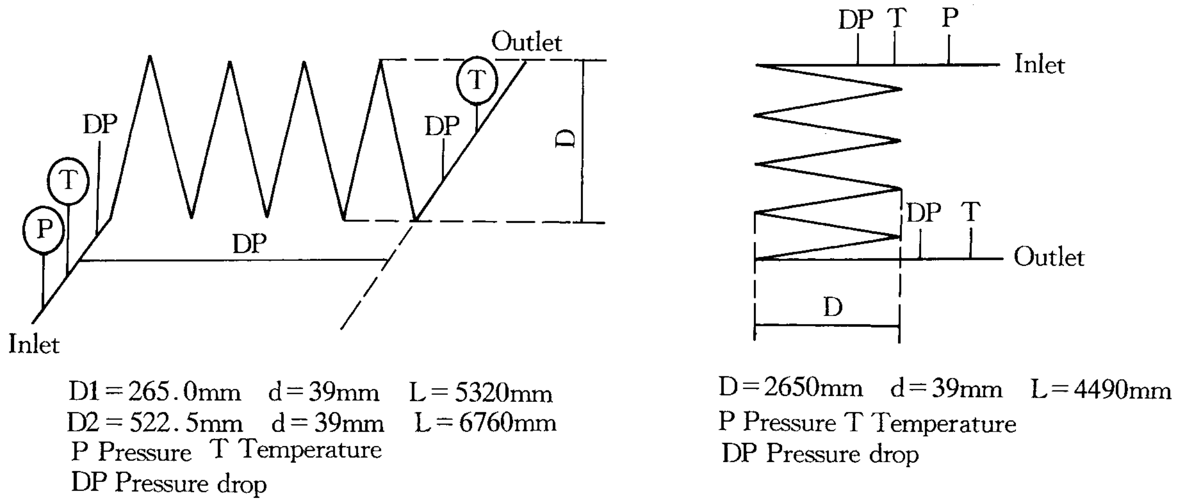


Fig. 2. Schematic diagrams of the test sections.

2.3. Experimental conditions and procedures

In the present experiments, the oil–water liquid–liquid two-phase flow characteristics were researched first. During these oil–water two-phase flow experiments the water flow rate was kept constant and the oil flow rate was increased stepwise. At each oil and water flow rate combination, the flow pattern was carefully observed and recorded and at the same time the other parameters, were also sampled and recorded. In order to minimize the random errors, all the values were averaged using 60 separate samples. The above procedure was repeated until the final oil flow rate value of interest or the maximum oil flow rate was reached. Then a new water flow rate was chosen and the above procedure was repeated. For these oil–water experiments, the oil superficial velocity ranges from 0.0141 to 0.91 m/s and the water superficial velocity from 0.018 to 1.8 m/s. The volume fraction (water-cut) of water in the oil/water mixture changes from 0.02 to 0.976. The system pressure is in the range of 1 to 2 bar (gauge) and the temperature of the working fluids was kept in the range of 15–20°C. No. 46 Mechanical Oil was used. Before the experiment, the oil properties, such as viscosity, density and surface tension with water were measured, and are shown in Table 1. The experimental conditions are given in Table 2.

The experimental procedure for oil–water–air three-phase flow was as follows:

The input oil fraction in the liquid phases was kept constant at 10%, 15%, 20%, and 30%. For every fixed input oil fraction, the water flow rate was kept constant for a few runs and the air flow rate was changed from small to large for each new run. This arrangement aimed at getting a flow pattern map at a specific input oil fraction. After all the flow rates and system pressures were set to the required values, a few minutes were allowed to reach steady flow and then the data acquisition PC was started to collect the data.

3. Results and analysis

3.1. Flow patterns and their transition mechanisms

3.1.1. Oil–water liquid–liquid two phase flow

3.1.1.1. Classifications of flow patterns. The two-phase flow characteristics in helically coiled tubes are very complex and unique due to the combined effects of gravitational and centrifugal forces, especially in horizontal coilded tubes, where the angle between the gravity and centrifu-

Table 1
Properties of the oil used in the present study

Properties	Formula	Unit
Density	$\rho_0 = \frac{871}{1+1.64(t-20)\times 10^{-3}}$	kg/m^3
Viscosity	$\eta_0 = 446.86\mathrm{e}^{-0.06094t}$	cP
Surface tension with water	$\sigma_{0,\mathrm{w}} = (36.97 - 0.38t) \times 10^{-3}$	N/m

Table 2
Experimental conditions and fluid properties

	Name and units	Value
Fluid properties (at 20°C)	ρ_g, air density (kg/m^3)	1.2–7.36
	ρ_w, water density (kg/m^3)	998.3
	η_w, water viscosity (kg/ms)	0.00114
Experimental conditions	J_{sg}, air superficial velocity (m/s)	0.45–19.02
	J_{so}, oil superficial velocity (m/s)	0.0141–.0.91
	J_{sw}, water superficial velocity (m/s)	0.018–1.85
	T or t, average temperature (°C)	15–20
	P or p, system pressure (bar)	1–5

gal forces changes along the axial direction within one turn. Compared to the flow characteristics in horizontal coiled tubes, the flow pattern in vertical coiled tubes changes very little after the mixture passes through the first turn of the test section. In horizontal coiled tubes, the flow pattern may indeed change along the axial direction even under the same flow condition. According to our observations, the flow pattern is almost the same in the same position of the helically tubes after the first turn. In the following section, the flow patterns at the horizontal zone of the tubes are discussed.

Investigations on oil/water two-phase flow were carried out and flow patterns were classified according to previous literature. Some researchers made a very detailed classification for the flow patterns such as Soleimani et al. (1997) and Arirachakaran et al. (1989), while others made a relative coarse classification such as Valle and Utvik (1997). In the present investigation, we give a detailed classification. The flow patterns schematically shown in Fig. 3 were distinguished and observed according to the authors observations and analysis.

1. The stratified flow pattern (ST), occurs within the lower mixture velocity conditions. It is characterized by the existence of a distinct interface between the oil and water phases and a continuous liquid film flowing along the tube wall for each phase. Oil flows at the upper part of the tube, while water flows at the lower part. (a) Since both two-phase velocities are sufficiently low, there exists a distinct interface. No blending of the two phases around the

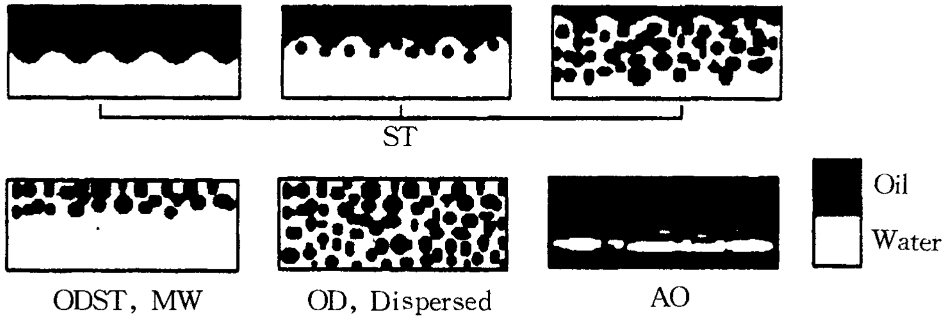


Fig. 3. Classification of oil–water flow patterns in coiled tubes.

oil/water interface was found. In our experiment, waves on the oil/water interface were always observed: these were all long-wavelength waves due to the gravitational force. This kind of flow pattern corresponds to the stratified wavy flow defined by Soleimani et al. (1997). (b) Increasing the velocity of the two-phase mixture, the momentum transferred between the oil and water phases through the interface is increased. At certain condition, some amount of the continuous oil phase becomes dispersed oil droplets near the interface. Further increasing the velocity of the mixture, the amount of the oil droplets increases and the thickness of the continuous oil layer decreases. This kind of flow pattern corresponds to the three-layer flow pattern and stratified mixed/oil layer flow pattern defined by Soleimani et al. (1997).

2. Oil-Droplet Stratified Flow (ODST), which is similar to the mixed flow pattern defined by Arirachakaran et al. (1989), occurs at the higher water fraction conditions. Within this flow pattern, the oil phase, characterized by different size droplets, exists within the continuous water phase. Due to buoyancy, all the oil droplets agglomerate at the upper part of the tube, while the water phase flows at the lower part.
3. Oil-Dispersed Flow (OD), which is similar to the dispersed flow defined by Arirachakaran et al. (1989) and Soleimani et al. (1997) in horizontal flows and to the oil bubble flow observed by Govier et al. (1961) in vertical oil/water flow. According to the experimental observations, all the oil phase is present as oil droplets and distributed homogeneously in the continuous water phase. This flow pattern occurs under higher mixture velocity and higher water cut conditions.
4. Annular Oil Flow (AO), occurs under higher oil flow rate and lower water flow rate. The oil phase flows along the tube wall as a continuous phase, while water flows in the core of the tube as water droplets and water filaments.

It is worthwhile to note that the oil–water flow pattern of annular water flow was not observed in the present experiments; this is mainly due to the low viscosity oil employed. It was concluded that oil of such viscosity cannot sustain the stable oil core in the water annulus (Arirachakaran et al., 1989).

3.1.1.2. Flow pattern maps. The oil/water two-phase flow pattern map in vertical coiled tubes is shown in Fig. 4(a), where the volume fraction of water (water cut) in the oil–water mixture is flotted as the abscissa and the mixture velocity as the ordinate. The curve 1 in the figure is the phase inversion boundary obtained in the present experiments. The dashed lines represent the results obtained by Arirachakaran et al. (1989) in horizontal steel straight tube with 1.5 in. i.d. Curve 2 shows the phase inversion boundary observed in their experiment. The flow regime below the dashed line is a stratified flow pattern. The regions that lie above the dashed line and on the left of curve 2 are water in oil flow patterns (where the oil phase behaves as a continuous phase and the water as dispersed phase). The regions that lie above the dashed line and on the right of curve 2 are oil in water flow patterns (where the water behaves as a continuous phase and the oil as dispersed phase). The flow patterns in horizontal helically coiled tubes may change along the axial length because of the combined effects of the gravitational and centrifugal forces. According to our observations the flow pattern is the same at the same position of each turn of the tube. The whole picture of the flow pattern in one turn is shown in Fig. 5

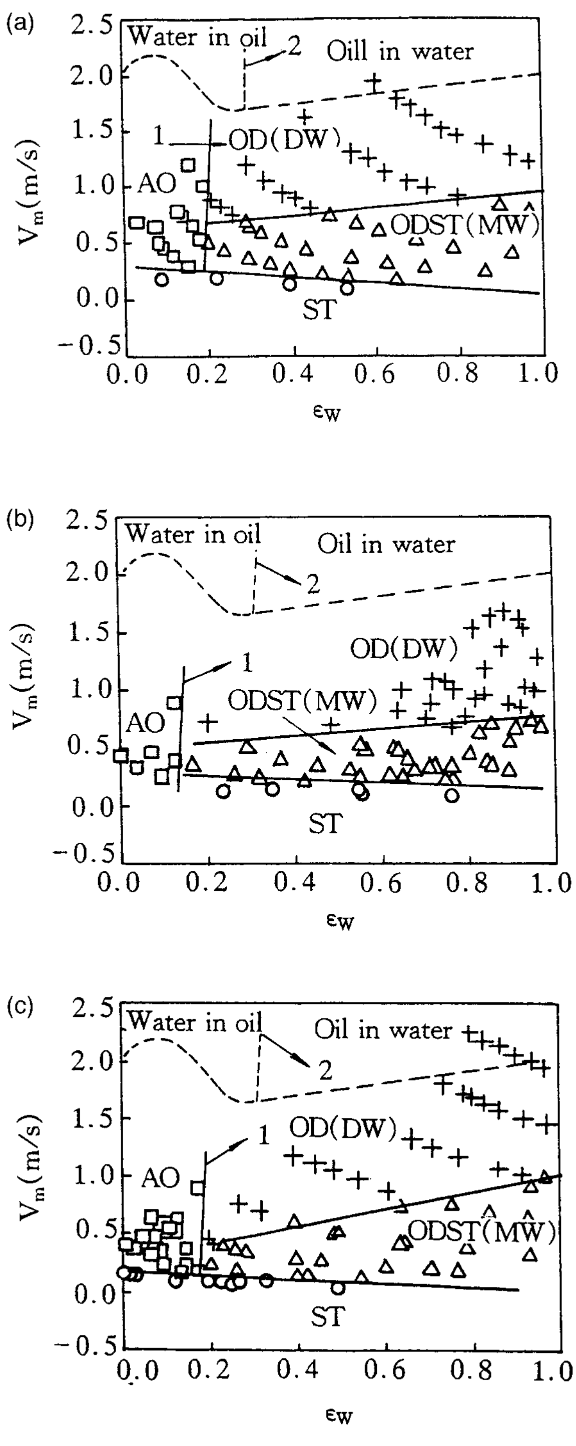


Fig. 4. The flow pattern maps for oil–water two-phase flow in helically coiled tubes.

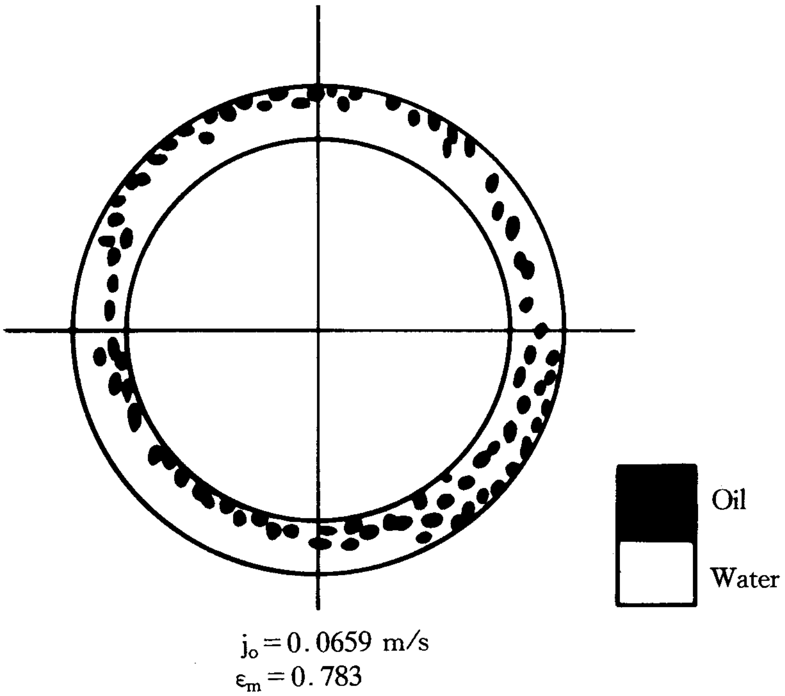


Fig. 5. The picture of flow pattern within one turn in horizontal coiled tube.

for a certain flow condition. In order to compare the results in horizontal helically coiled tubes were with those obtained in vertical coiled tubes and in horizontal straight pipelines, only the flow pattern results at the horizontal exit shown in Fig. 4(b) and (c). Also shown in these two figures are the results of Arirachakaran et al. (1989). The meanings of each line in these two figures are the same as in Fig. 4(a). From these figures some useful results can be obtained.

1. Four different flow patterns, such as ST, AO, ODST and OD, are observed in both horizontally and vertically positioned coiled tubes under the present flow conditions, which are similar to the results obtained by previous researchers (Arirachakaran et al., 1989). However, there exist great differences in the transition boundary conditions between horizontal straight flows and coiled flows. In our experiment, the mixture velocities at which the transitions from ST to ODST, from ODST to ST to AO occur are much lower than those in straight flow: this may be attributed to the existence of the secondary flow caused by the centrifugal force in coiled tubes.
2. The water-cut at which phase inversion (the dispersed phase changes into a continuous phase while the continuous phase into a dispersed one) occurs in coiled tubes is less than 0.2. This value is smaller than the value of about 0.3 obtained by Arirachakaran et al. (1989) in a horizontal straight pipe; this may be due to the following two reasons. Firstly, the oils employed in the two experiments are different. It is found by Arirachakaran et al. (1989) that the oil viscosity has significant effect on the phase inversion water cut. They

provided the following equation to predict the phase inversion water-cut ε_w in the oil–water flow system.

$$\varepsilon_w = 0.5 - 0.1108 \log \eta \tag{1}$$

where η is the dynamic viscosity of the oil in cP.

It is found that the increase in oil viscosity reduces the water-cut for phase inversion. The oil viscosity in our experiment is 149 cP at 18°C, while it is 84 cP at 21°C in their experiment. According to Eq. (1), the water-cut for phase inversion in the present study should be around 0.26, which means that the differences in oil viscosity are not enough to explain such differences in phase inversion water-cut. Secondly, we think that the different flow tubes used in the two experiments would have an effect. Because a secondary flow perpendicular to the bulk flow exists, the mixing between the two phases is much higher in coiled tubes under the same flow conditions. This would better mix separated phase and disperse easier the continuous phase and would lead to the small water cut value for phase inversion. Kinugasa et al's. (1997) work seemed to confirm our above standpoint. They found that for any oil system with increasing stirring speed, the volume fraction of the dispersed phase at phase inversion from W/O to W/O dispersion decreased. However, firm conclusions cannot be drawn since there are only limited data. In order to explain and understand the mechanism, further work should be done.

3. The smaller the coil diameter, the wider the stratified flow regime and the smaller the phase inversion water-cut is. This may be attributed to the larger centrifugal force exerted and the highly intense secondary flow in smaller coil diameter tube under the same flow rate. The positioning of coiled tubes has also an influence on the flow pattern and phase inversion characteristics. Since the mixing of oil and water mixtures in horizontal coiled tubes is higher than that in vertical coiled tubes, the water-cut for phase inversion is a little smaller in horizontal coiled tubes.

3.1.1.3. Discussion. Although there are lots of publications on the flow pattern characteristics of liquid–liquid two-phase flow systems both experimental and theoretical, no general result has been obtained and accepted so far. The reason is that the liquid–liquid two-phase flow pattern depends not only on the working fluid properties, flow conditions and flow channel geometry, but also on the characteristics of the phase inversion, which is unique phenomenon occurring in the liquid–liquid flow systems. However, the results concerning this phenomenon obtained by different investigators sometimes differ greatly, therefore further efforts and investigation should be aimed at.

It is generally accepted that one can obtain an oil–water smooth stratified flow pattern as long as the flow rates of two phases are kept low enough. The interfacial waves with long wavelength would appear with increasing two-phase flow rates within the stratified flow region. Brauner and Maron (1992a, 1992b) define the smooth-stratified flow regime for an oil–water flow system by employing linear stability analysis. The region within the Zero-Neutral Stability Solution, where all disturbances for any wavelength will decay with time and space, will remain smooth-stratified. The region between the Zero-Real-Characteristics (ZRC) line and the Zero-

Neutral Stability Solution, where some disturbances with a certain wavelength will increase with time gradually, would behave as wavy-stratified flow. Beyond the solution of ZRC, flow pattern transitions could occur.

With increasing water flow rate the energy transferred from the water phase into the oil phase through the oil–water interface will increase. The oil phase near the interface is subjected to the higher shear, which would lead to the occurrence of oil droplets separated from the continuous oil phase. More and more continuous oil phase will be dispersed into oil droplets with increasing water-cut. When there is no continuous oil flowing in the system, the oil dispersed stratified pattern is obtained. At this case, all the oil droplets will agglomerate at the upper part of the tube cross-section because of the effect of the buoyancy force. This flow pattern is termed as Oil-Droplet Stratified Flow (ODST). Therefore, the transition from wavy stratified flow to ODST is the result of the combined effects of water phase turbulence, surface tension and buoyancy. Further increasing the water flow rate will result in the oil droplets distributing homogeneously in the cross-section, because the water turbulent force becomes high enough to overcome the buoyancy force under this condition. Thus, the dispersed droplet flow pattern occurs. Brauner and Maron (1992a, 1992b) modelled the fully dispersed pattern boundary. They pointed out, that when the ratio of the maximum dispersed phase diameter (related to the turbulent dissipation scale), to the critical diameter for the oil particles (defined from the balance of buoyancy and surface tension), is less than one, the fully-dispersed pattern will result.

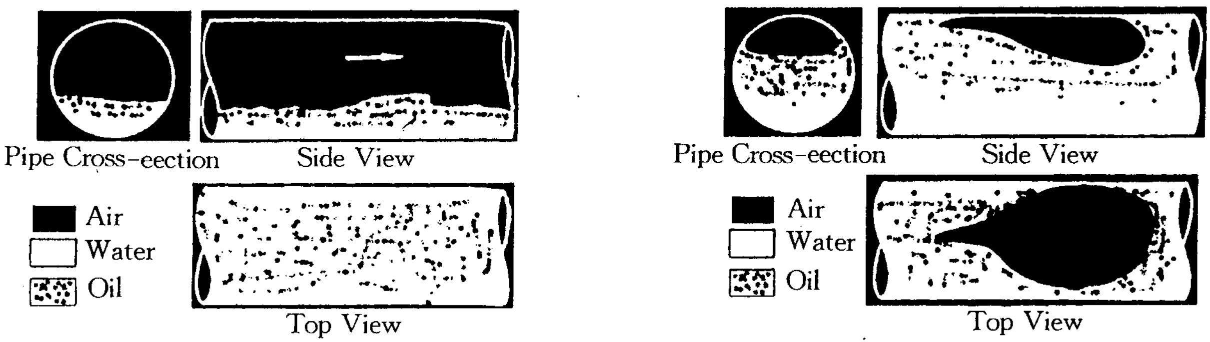
When the oil flow rate is high enough, the oil will behave as a continuous phase, flowing along the tube wall as an oil annulus, while water flows in the core of the tube as a dispersed phase; this regime is defined as Annular Oil Flow (AO). With increasing water flow rate, the dispersed water coalesces into a continuous phase, but the oil is dispersed. This is the so-called phase inversion. The prediction of phase inversion in liquid–liquid systems is of great importance for the design of such systems because near the phase inversion point the viscosity of the mixture generally changes sharply, and this leads to a great change in the system pressure drop. Although lots of work has been done so far on this issue, there still exist some uncertainties. It is generally accepted that parameters such as the water fraction (water-cut), oil viscosity, mixture velocity, oil droplet size and distribution, flow pattern and flow channel geometry affect the phase inversion characteristics. Since it is a crucial parameter for the design of liquid–liquid flow systems and there are only limited results, further investigation of this phenomenon is highly necessary to assure the safe operation of the liquid–liquid flow systems.

3.1.2. Oil–water–air three-phase flow

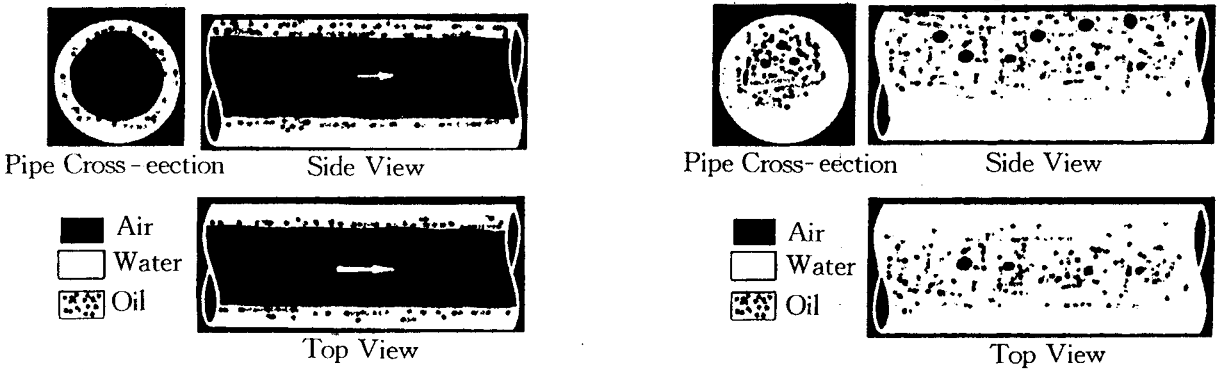
The most important difference between two-phase flow patterns and those in three-phase flows is that due to the behavior of the liquid phase. Basically, the liquid phase appears in a separated or dispersed form. In the case of separated flow, distinct layers of oil and water can be discerned, though there may be some inter-entrainment of one liquid phase into the other. In dispersed flow, on the other hand, one liquid phase is completely dispersed as droplets in the other. One recognizes two cases, namely that where the oil phase (O) is the continuous and that where the water (W) is the continuous one. The flow patterns of three-phase flow were designated by analogy with two-phase gas–liquid flow using a three-letter system, for example, DOS being a dispersed oil phase continuous stratified flow.

Because the input water fraction in our experiments is greater than 50%, the water always appears as a continuous phase and oil always dispersed in the continuous water phase; the flow patterns observed in these experiments are all water-based ones. Four main flow patterns have been observed and illustrated by the sketches in Fig. 6(a–d), respectively.The flow patterns are:

1. Water based dispersed stratified/wavy flow. As shown in Fig. 6(a), this flow pattern looks similar to a two-phase stratified flow, in which the air and liquid are separated completely, the air flowing at the upper side of the test section, or it is an intermediate stratified flow in which the top of the tube wall is wetted sometimes by the liquid in curved tubes, but the liquid that hits the top wall of the test section has no actual movement in this case.
2. Water-based dispersed slug flow. For relatively low air and high water flow rates, air bubbles having very distinct tails were observed. For this flow regime, the air phase was the driving phase. As can be seen in Fig. 6(b), a relatively high concentration of oil droplets in the regions following air-bubbles was observed. With increasing air flow rate, the distinct



6(a) *Water-based dispersed stratified/wavy flow* 6(b) *Water-based dispersed slug flow*



6(c) *Water-based dispersed stratifying-annular flow* 6(d) *Water-based dispersed bubbly flow*

Fig. 6. Classification of oil–water–air three-phase flow patterns in coiled tubes.

boundaries between the air plus tails and the water phase were replaced by a froth appearance at the back of the air plug.

3. Water-based dispersed stratified annular flow. In this flow pattern in Fig. 6(c), the pipe perimeter is wetted continuously by a water-based film containing small dispersed oil droplets. The difference in water film thickness between the top and bottom of the pipe was most noticeable at lower superficial air velocities, and became smaller with increasing air flow rate. Except for the dispersed oil droplets this pattern looks very much like two-phase stratified-annual flow.
4. Water-based dispersed bubbly flow. As can be seen in Fig. 6(d), this flow regime looked similar to a two-phase bubbly flow the except for the dispersed oil droplets.

It is of importance for sand separation from the mixture, that the air–oil–water–sand four-phase flow patterns looked similar to the air–oil–water three-phase flow pattern except for the sand entrainment. We found that maintaining the separators operating in the region of stable-stratified/wavy flow pattern leads to sand high separation efficiency.

Fig. 7(a) and (b) shows the air–oil–water flow pattern map in the horizontal exit of the helically coiled tubes. These maps are similar to those in horizontal straight tubes except for the transition boundaries from one flow pattern to another and the development tendencies of stratified flow.

In coiled tubes, the stratified flow evolves from slug flow with increasing gas flow rate, but in the straight tube the slug flow evolves from stratified flow. The range of stratified flow in horizontal coiled tubes is significantly enlarged. When the ratio of oil to water is less than 30%, the effect of this ratio on the transition of flow patterns is minor. According to non-dimensional analysis, the following criteria for the flow pattern transition were deduced from the experimental data.

For the transition from stratified to annual flow

$$Fr_{\mathrm{g}} = 1.05 We_{\mathrm{g}}^{0.398} De_{\mathrm{l}}^{0.055} R_v^{0.160} \beta^{0.012} \tag{2}$$

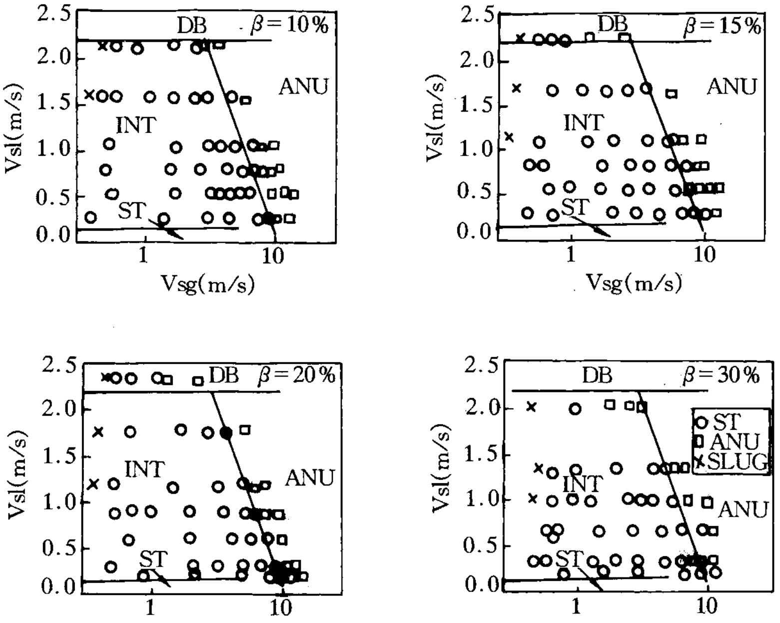
where $Fr_{\mathrm{g}} = J_{\mathrm{sg}}/(gd)^{0.5}$, Froude number of the gas; $De_{\mathrm{l}} = Re_{\mathrm{l}}(d/D)^{0.5}$, Dean number of the liquid flow; $We_{\mathrm{g}} J_{sg}^2 \rho_g d/\sigma$, Weber number; $R_v = J_{\mathrm{sg}}/J_{\mathrm{sl}}$, the ratio of superficial velocity of gas to total liquid; β, the volumetric ratio of oil to total liquid

For the transition from slug to annular flow:

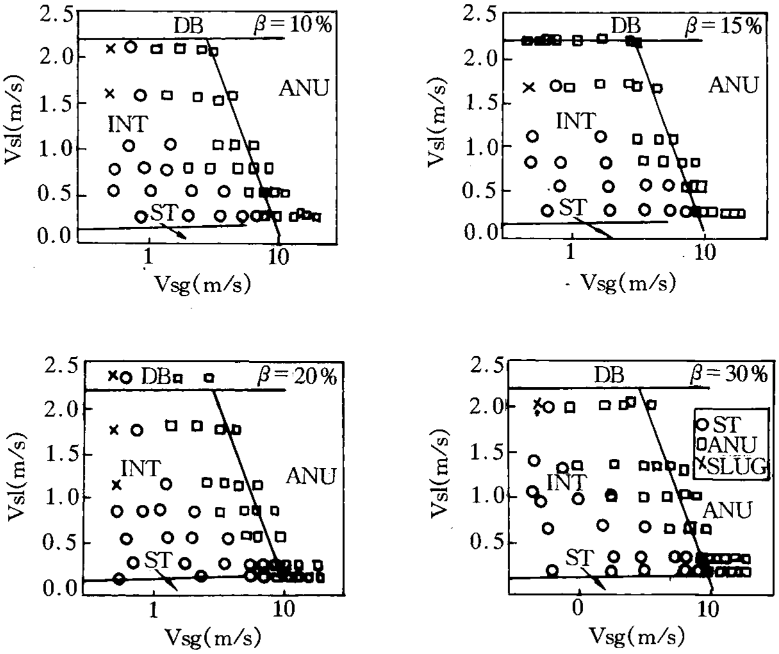
$$Fr_{\mathrm{g}} = 1.12 We_{\mathrm{g}}^{0.423} De_{\mathrm{l}}^{0.012} R_v^{0.134} \beta^{0.006} \tag{3}$$

Generally good agreement is obtained between the experimental data and the above equations for both straight tubes and helically coiled tubes.

As with gas–liquid two-phase flow, the transition boundaries in three-phase flows are also very important regions in the pattern maps. However, new transition boundaries exist in three-phase flow at which there is a transition of the base fluid between the oil-based and water-based bases. Due to the many possible transport properties of three-phase flow mixtures, the quantification of three-phase flow pattern boundaries will be a difficult and challenging task. Nevertheless, the work presented here hopefully makes a good starting point to our understanding of three-phase flow regimes.



(a) D=265mm



(b) D=522.5mm

Fig. 7. The flow pattern maps for oil–water–air three-phase flow in horizontal hellically coiled tubes.

Separation of the sand particles from air–oil–water–sand four phase flow is widely demanded in petroleum production. All oil/gas/water separation is based on differences in density and most separators are gravity separators, i.e, they utilize the common acceleration of gravity. Later developments have brought compact, reliable high-*g* equipment to the market, particularly hydro-cyclones and centrifuges for oil and water polishing. Many cyclone separators are used for sand separation from oil–gas–water–sand multiphase mixtures. But the cyclone separator has some limitations operation. The separation performance of a cyclone is influenced by the centrifugal force acting on the solid particle, in the cylindrical chamber. High velocity of rotation is needed to obtain large centrifugal forces, but the increase of the velocity of rotation to obtain high separation performance is limited by many factors. The rotating flows in the cyclone separator are unstable for large rotation velocity. The frictional losses of the cyclone separator are too high to be suitable for the practical requirements of petroleum production.

In this work, a new type of centrifugal separator avoiding these limitations, constructed of a helically coiled tube, was designed and examined. In the stratified flow regime, the new separator can attain high efficiency for sand separation and low frictional losses, possesses good hydrodynamics and is suitable for practical utilization in petroleum production, not only on-shore but also off-shore.

3.2. Frictional pressure drop in horizontal helically coiled tubes

So far there are no specific models or correlation for the prediction of pressure drop in air–water–oil three-phase flow. After summing up the previous studies, Pan et al. (1995) pointed out that the pressure drop correlation developed for gas-liquid two-phase flow can be used for air–water–oil three-phase flow, provided a correct effective liquid viscosity can be provided. And they also compared the differences in existing oil–water mixture prediction methods. They state that both the linear and non-linear visocity equations are useful and valuable for multiphase calculations, depending on the flow situation. Using the concept of the mixing degree coefficient, they proposed a new model for calculating the viscosity of the liquid–liquid mixture.

In the present study, the input oil fractions are less than 30% (the input water fraction is greater than 70%). In this case, the water phase is always the continuous phase, and phase inversion does not occur, as elsewhere stated above. Therefore, it is suitable for us to use the linear viscosity to predict the viscosity of oil–water mixtures (Pan et al., 1995).

3.2.1. Lockhart–Martinelli method

The Lockhart–Martinelli method was used to predict the pressure drop of oil–air–water three-phase flow, The oil and water mixture was regarded as one phase whose physical properties such as density and viscosity were obtained by the linear method mentioned above (Pan et al., 1995). The results obtained are shown in Fig. 8, where the abscissa is the reciprocal of the Martinelli parameter X and the ordinate is the two-phase frictional multiplier based on the pressure gradient for liquid flowing alone. It is found that the relationship between two-phase multiplier and the reciprocal of the Martinelli parameter X is not monotonous. Generally, at a certain combination of oil and water flow rates, the multiplier increases with

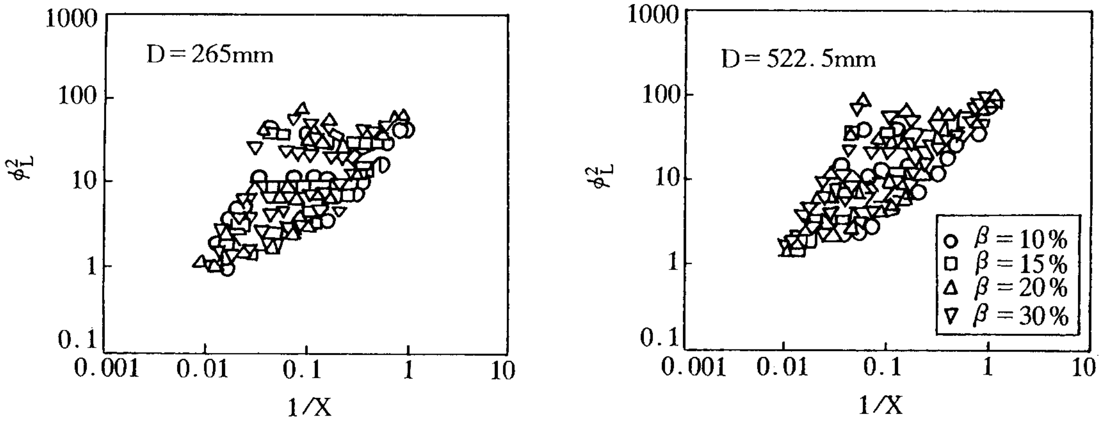


Fig. 8. Frictional pressure drop for oil–water–air three phase flow in horizontal helically coiled tubes.

increasing $1/X$, that is the multiplier increases with an increase in gas superficial velocity. From these two figures, it is also found that the input oil fraction has an influence on the pressure gradient. The greater the oil fraction in the liquid, the larger the pressure drop. The coil diameter has no the distinct effect in these two figures.

3.2.2. Modified Chisholm method

A modified Chisholm method is also presented. The formula for predicting the pressure drop is as follows:

$$\phi_{L1}^2 = f(\theta)\left(1 + \frac{C}{X} + \frac{1}{X^2}\right) \tag{4}$$

where $\phi_{L1}^2 = (\mathrm{d}P)_{TP}/(\mathrm{d}P)_{L1}$, three-phase flow frictional multiplier, is the ratio of three-phase flow frictional pressure drop $(\mathrm{d}P)_{TP}$ to that of liquid-alone flow $(\mathrm{d}P)_{L1}$; C is a parameter; $X^2 = (\mathrm{d}P)_{L1}/(\mathrm{d}P)_{Lg}$, is the ratio of frictional pressure drop of liquid-alone flow $(\mathrm{d}P)_{L1}$ to that of gas-alone flow $(\mathrm{d}P)_{Lg}$; $f(\theta)$ is a modifying coefficient, which is a function of physical properties, flowing parameters and geometrical parameters. The experimental data were fitted by the above equation; the result is given by:

$$f(\theta) = R^{0.0172}\left(\frac{1526}{\rho u}\right)^{1.596}\left(\frac{d}{D}\right)^{0.175}\left(\frac{\eta_g\rho_o}{\eta_o\rho_{g_o}}\right)^{-1.238}\left(\frac{\eta_w\rho_o}{\eta_o\rho_w}\right) \tag{5}$$

$$\phi_{L1}^2 = f(\theta)\left(1 - \frac{0.603}{X} + \frac{1}{X^2}\right) \tag{6}$$

where ρu is the mass flask of the oil–water–gas flow (kg/m^{2}s).

The predictions oil–gas–water three phase flow in horizontal coiled tubes were compared with the experimental data in Fig. 9. The plural relative coefficient is 0.969, the standard

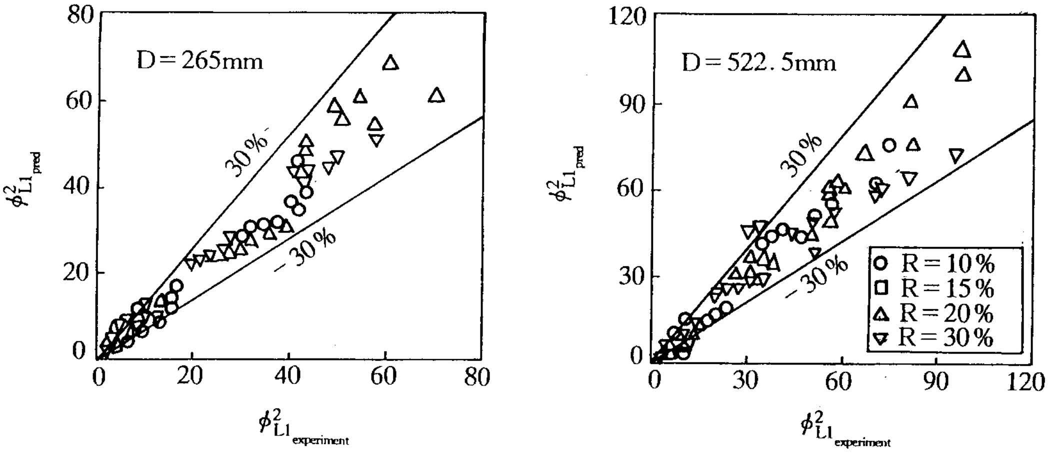


Fig. 9. Comparison of the experimental results to the present correlation.

square deviation is 3.510, and the maximum deviation between experimental data and predicted values is within 30%.

4. Conclusions

An experiment investigation on oil–water liquid–liquid two-phase flow pattern characteristics in helically coiled tubes positioned both horizontally and vertically was conducted. Four different flow patterns, namely Stratified, Oil-Droplet Stratified, Oil-Droplet and Annular Oil flow, were observed and defined. The flow pattern maps were delineated and compared with the results in horizontal straight pipe. Great differences in the transition conditions were found. The transition mechanism between two different flow patterns was discussed and analyzed. The phase inversion characteristics in coiled tubes were analyzed and compared with those in horizontal straight tubes. The reduction of water cut for phase inversion in coiled tubes was discussed and investigated qualitatively.

Three-phase flow of air–oil–water mixtures present a rich variety of flow patterns and posses their own unique characteristics. The mixing behavior of the two liquids is an important and challenging problem. In the range of low ratio of oil to water, the flow patterns of air–oil–water in horizontal straight tubes can be regarded as an extension of gas–liquid two-phase flow, but they are very different in helically coiled tubes. Particular flow regimes may or may not be desirable in different three-phase flow applications. In order to obtain optimal design parameters and operating condition, it is important to clearly understand three-phase flow regimes and the boundaries between them. The present paper has contributed to the knowledge of three-phase flow regimes and makes a starting point to motivate further investigation in this field.

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