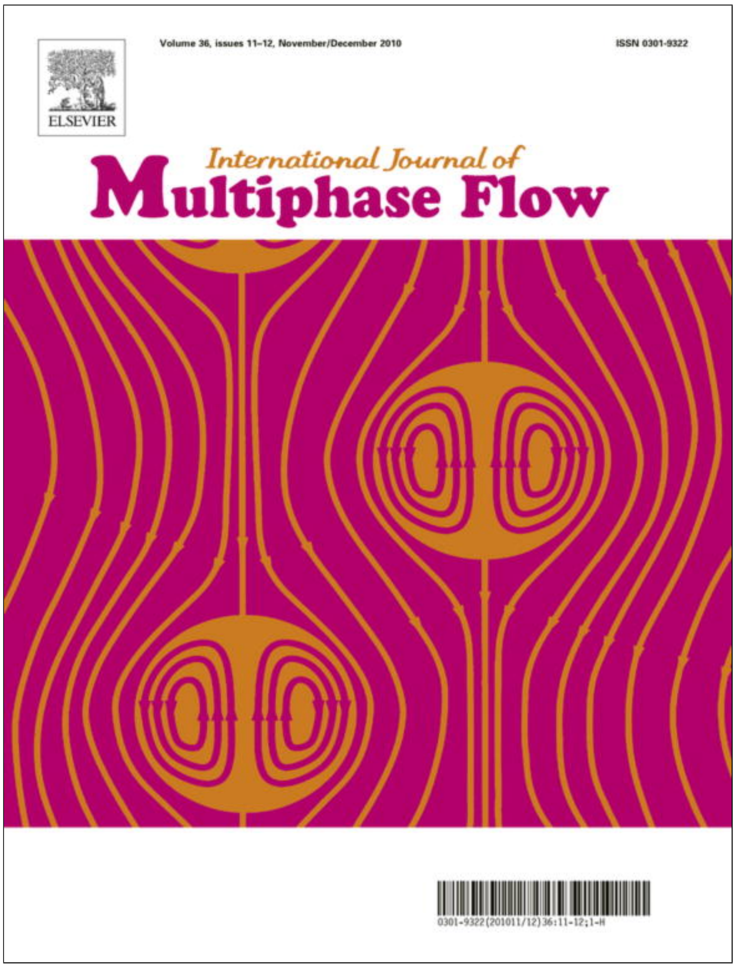
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Investigations of phase inversion and frictional pressure gradients in upward and downward oil–water flow in vertical pipes

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ABSTRACT

The present study has attempted to investigate phase inversion and frictional pressure gradients during simultaneous vertical flow of oil and water two-phase through upward and downward pipes. The liquids selected were white oil (44 mPa s viscosity and 860 kg/m^3 density) and water. The measurements were made for phase velocities varying from 0 to 1.24 m/s for water and from 0 to 1.87 m/s for oil, respectively. Experiments were carried either by keeping the mixture velocity constant and increasing the dispersed phase fraction or by keeping the continuous phase superficial velocity constant and increasing the dispersed phase superficial velocity. From the experimental results, it is shown that the frictional pressure gradient reaches to its lower value at the phase inversion point in this work. The points of phase inversion are always close to an input oil fraction of 0.8 for upward flow and of 0.75 for downward flow, respectively. A few models published in the literature are used to predict the phase inversion point and to compare the results with available experimental data. Suitable methods are suggested to predict the critical oil holdup at phase inversion based on the different viscosity ratio ranges. Furthermore, the frictional pressure gradient is analyzed with several suitable theoretical models according to the existing flow patterns. The analysis reveals that both the theoretical curves and the experimental data exhibit the same trend and the overall agreement of predicted values with experimental data is good, especially for a high oil fraction.

1. Introduction

The simultaneous flow of two immiscible liquids flow through vertical pipes is encountered in a diverse range of processes industries and particularly in the petroleum industry. In recent years, because of the presence of water in oil well or injection of water into the well for increasing oil production, oil extraction is often accompanied by a high water throughput. Therefore, oil production resulted in transportation of oil and water over long distances. The effect of the water phase with respect to the pressure gradient is of particular importance for oil field operating at high water cuts and low wellhead pressure. In recent years, considerable effort has been expended in studying the simultaneous oil and water two-phase flow in horizontal and vertical pipes. Compared to the investigations of the pressure gradient characteristics of mixture flow in horizontal pipes, only limited work has been reported in vertical pipes. Some significant literatures are listed in Table 1. By analyzing the data presented in the table, it can be found that there is very little experimental data available for the pressure gradient of oil and water flow in vertical pipes, especially for downward vertical flow.

Mukherjee et al. (1981) investigated the pressure gradient and water holdup for oil–water flow in 1.5-in-diameter pipe with inclination angle varying from ±30° to ±90° from the horizontal. Experimental data showed that the effective viscosity of an oil and water mixture was very sensitive to the input water fraction and had maximum value at the phase inversion water fraction. The maximum friction pressure gradient at the phase inversion point was a function of inclination angle. Luo et al. (1997) have studied an emulsion flow of oil and water in a vertical upward pipe. From the measured frictional pressure gradient, they obtained the effective or apparent viscosity of the oil and water emulsion. Their results showed that the effective viscosity of the emulsions was shear independent, exponential temperature dependent and was only weakly pressure dependent. Flores et al. (1998) have measured the holdup and pressure gradient of an oil and water flow in vertical and inclined pipes. The flow tests covered the mixture velocities ranging from 0.045 m/s to 2.542 m/s, and inclination angles of 45°, 60°, 75°, and 90° from the horizontal. They reported that the frictional pressure gradient showed a hump that could be associated with the phase inversion phenomenon. The hump effect was more evident in vertical flow and at higher mixture

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Table 1
Summary of the significant experimental investigations during the recent studies for an oil and water flowing in vertical pipes.

Author (year)	Diameter (m)	Length (m)	Oil physical properties (kg/m^3, mPa s)	Pipe material	Superficial velocity (or mixture velocity) (m/s)	Flow direction	Study aims	Pressure gradient data available
Mukherjee et al. (1981)	0.125	13.72	$\rho_o = 850$ $\mu_o = 3.5$	Metal	$U_{SO} = 0.1647–0.5185$ $U_{SW} = 0.1372–0.5185$	Upward downward	Pressure gradient and holdup	Yes
Flores et al. (1998)	0.0508	15.3	$\rho_o = 850$ $\mu_o = 20$	N/A	$U_{SO} = 0.0454–1.271$ $U_{SW} = 0.0454–1.271$	Upward	Pressure gradient and holdup	Yes
Farrar and Bruun (1996)	0.078	1.5	N/A	Acrylic resin	$U_M = 0.6455$	Upward	Flow rates measurement	No
Luo et al. (1997)	0.044	N/A	$\rho_o = 895$ $\mu_o = 452.6$	N/A	$U_M = 0–2.0$	Upward	Pressure loss and phase inversion	Yes
Nigmatulin et al. (2000)	0.0306	N/A	$\rho_o = 874$ $\mu_o = 250$	Acrylic resin	$U_W = 0.3$ $U_O = 0.0034$	Upward	Simulating the gravity bubbly flow phenomena	No
Oddie et al. (2003)	0.15	10.9	$\rho_o = 810$ $\mu_o = 1.5$	Plexiglass	$U_{SO} = 0.0315–0.6291$ $U_{SW} = 0.0315–2.0445$	Upward	Flow pattern and holdup	No
Abduvayt et al. (2006)	0.1064	11.95	$\rho_o = 800$ $\mu_o = 1.88 \pm 0.19$	Stainless steel	$U_{SO} = 0.025–1.502$ $U_{SW} = 0.025–1.502$	Upward	Flow pattern, pressure gradient and holdup	Yes
Descamps et al. (2006)	0.0828	15.5	$\rho_o = 830$ $\mu_o = 7.5$	Stainless steel	$U_M = 0.39–2.94$	Upward	Phase Inversion	Yes
Hu and Angeli (2006)	0.038	3.2, 2.3	$\rho_o = 828$ $\mu_o = 5.5$	Stainless steel	$U_M = 1.5, 2.0, 2.5$	Upward downward	Phase Inversion	Yes
Jana et al. (2006)	0.0254	1.4	$\rho_o = 792$ $\mu_o = 1.37$	Acrylic resin	$U_{SO} = 0.05–1.5$ $U_{SW} = 0.05–1.5$	Upward	Flow regime identification	No
Liu et al. (2006a,b)	0.018 ∗ 0.18 square	0.36	$\rho_o = 803$ $\mu_o = 1.62$	N/A	$U_M = 0–2.2$	Downward	Flow structures, flow pattern transition and phase inversion	No
Rodriguez and Bannwart (2006)	0.0284	2.5	$\rho_o = 930$ $\mu_o = 500$	Glass	$U_{SO} = 0.22–1.24$ $U_{SW} = 0.06–0.3$	Upward	Interfacial waves	No
Zhao et al. (2006)	0.040	3.8	$\rho_o = 824$ $\mu_o = 4.1$	Acrylic resin	$U_{SO} = 0.024–0.189$ $U_{SW} = 0.12–0.89$	Upward	Local characteristic and holdup	No
Hu et al. (2007)	0.038	3.2, 2.3	$\rho_o = 828$ $\mu_o = 5.5$	Stainless steel	$U_M = 1.5, 2.0, 2.5$	Upward downward	In situ holdup and velocity of dispersed phase	No
Jana et al. (2007)	0.0254	1.4	$\rho_o = 792$ $\mu_o = 1.37$	Acrylic resin	$U_{SO} = 0.05–1.5$ $U_{SW} = 0.05–1.5$	Upward	Pressure gradient and holdup	Yes
Lin and Tavlarides (2009)	0.0015	0.068, 0.5	Liquid CO_2 ($\rho = 818–967$, $\mu = 0.075–0.11$); *n*-HD ($\rho = 773$, $\mu = 2.5$)	Stainless steel	$U_M = 0.01887$	Upward	Flow pattern	No
Lucas and Panagiotopoulos (2009)	0.08	2.5	$\rho_o = 790$ $\mu_o = 1.58$	Perspex	$U_{SO} = 0.025–0.083$ $U_{SW} = 0.276–0.417$	Upward	Holdup and velocity profiles	No

velocities. When the water phase was continuous, the frictional pressure gradient neared the pure water line. However, when the oil phase was continuous, the test points aligned in a trend of higher readings than those corresponding to pure oil.

Recently, Descamps et al. (2006) studied experimentally the phase inversion for an oil and water flow through a vertical tube. The results showed that, for an oil and water vertical upward flow, the frictional pressure gradient led to a peak at the phase inversion point. The growth of the effective viscosity increased with increasing mixture velocity. The point of phase inversion was always close to an input water fraction of 30%, independent of the direction of change in water fraction during the experiments (from oil to water or from water to oil). During the same year, Hu and Angeli (2006) also reported their work for a co-current upward and downward oil–water flow in a vertical stainless steel test section with 38 mm diameter. It was found that phase inversion does not occur simultaneously at all locations in the pipe. In contrast to previous results in horizontal flows, the frictional pressure gradient was found to be minimum at the phase inversion point. This result is different from the work of Descamps et al. (2006). In a more recent study, Jana et al. (2007) carried out their experiments with a kerosene and water flow in a vertical pipe. The authors discussed the method for calculating the frictional pressure gradient. They suggested that the homogeneous model was suitable for predicting the pressure gradient of dispersed bubbly flow whereas bubbly and churn-turbulent flow pattern was better predicted by the drift flux model. However, the phase inversion phenomena have not been reported in their work.

In this work, efforts have been made to investigate the characteristics of the phase inversion and frictional pressure gradient for an oil and water flow through vertical upward and downward pipes in several different flow patterns. It is well-known that, from a practical viewpoint, one of the most important factors for predicting the frictional pressure gradient is to select accurately the model of the effective or apparent mixture viscosity. Therefore, to this aim, the phase inversion phenomenon is observed and the identity of the continuous phase is made firstly. The second decision concerned the appropriate model to represent the variation of the mixture viscosity. In the following study, we study firstly the flow pattern regimes in vertical pipes. Thereafter, we investigate experimentally the phase inversion point and discuss a number of literature correlations to predict the phase inversion point and to calculate both the mixture viscosity and the frictional pressure gradient.

2. Experimental set-up and procedure

An experimental facility was fixed to simulate flow conditions in vertical pipes and be able to identify and characterize the oil–water flow patterns and measured the pressure gradient and hold-up. A schematic diagram of the experimental system was shown in Fig. 1. All experiments were conducted using white oil and water at room-temperature and atmospheric outlet pressure. The system consisted of a steel frame supporting a transparent Perspex pipes. White oil and water were pumped from their respective storage tanks, metered, and introduced into pipes via a T-junction, which ensured minimum mixing. The mixture flowed along a 5 m long horizontal pipe from the entry point to the test section. The test section included two 3.5 m long pipe branches with 50 mm diameter connected by a U-bend. With this installation experiments on upward and downward flows could be carried out simultaneously. The two-phase mixture passed through the 50 mm diameter test section where the data was collected and then flowed down the return line into the liquid tank. Based on the experimental observation, the length of two horizontal pieces before the vertical test sections had few influences on the flow pattern. Using the same fluids, flow patterns observed in two horizontal pieces were similar to those obtained in a full development horizontal tube when having the same input conditions (Xu et al., 2008a). The length of the vertical development section had certain influences on the flow structure. In the present work, we set a vertical section of 40 internal diameters to stabilize the flow. Due to the fact that the mixture velocities were low (U_M < 3.11 m/s) and oil phase viscosity high (44 mPa s), this length provided sufficient length to stabilize the flow. It could be seen in the following Fig. 2 that, although Flores (1997) used the development length of about 200 diameters, their flow pattern map was similar to one observed in the test section in this work.

A total of 196 experimental tests have been conducted for the following conditions: superficial water velocity from 0 to 1.24 m/s and superficial oil velocity from 0 to 1.87 m/s. Different flow

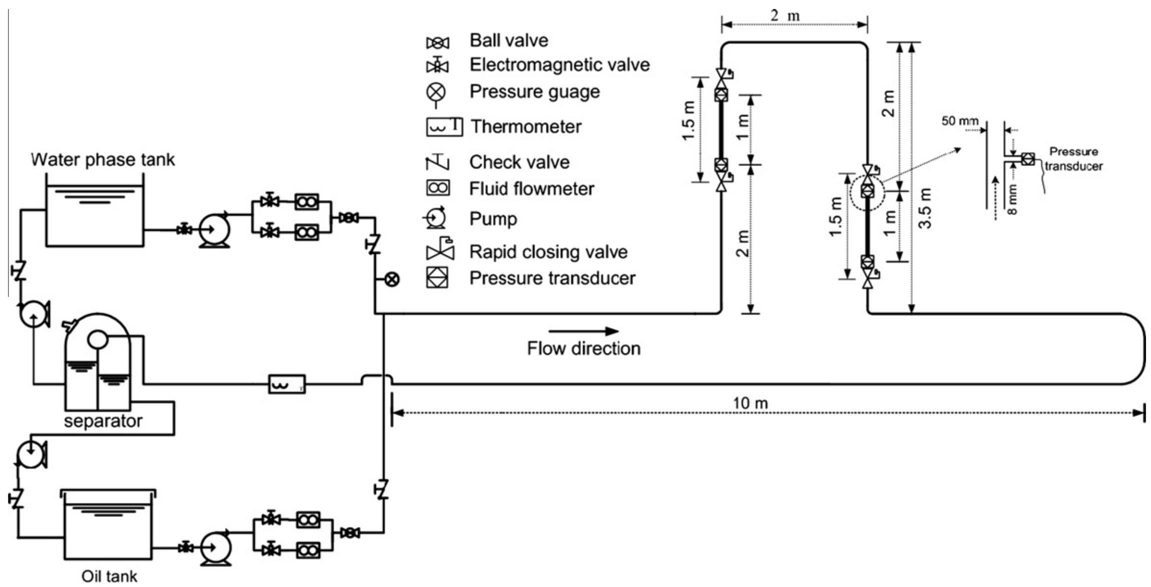

Fig. 1. Schematic view of the oil–water flow facility.

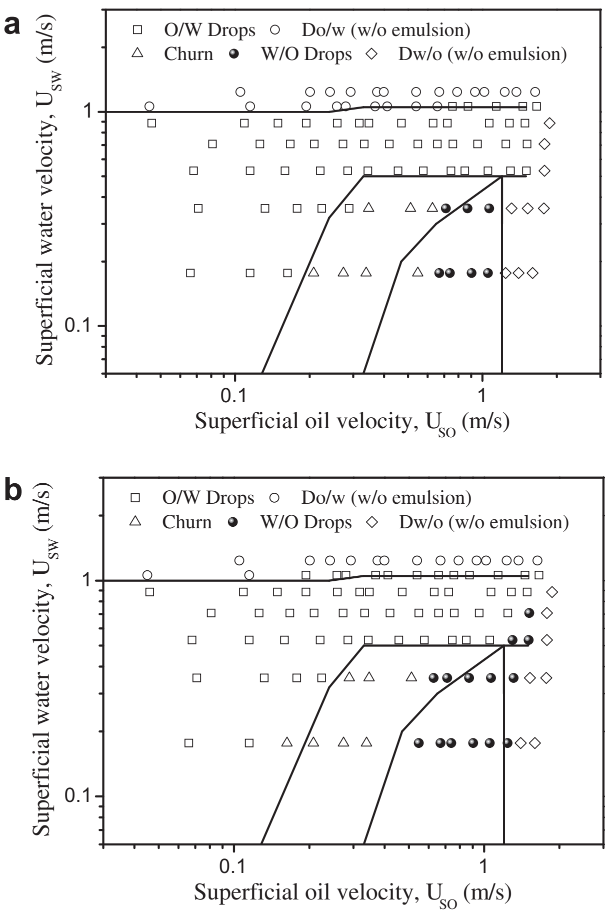

Fig. 2. Flow pattern map of Flores (1997) showing the superficial velocities for the experimental data reported in this work (a, upward vertical flow; b, downward vertical flow; the experimental conditions of Flores: upward vertical flow, $\rho_o/\rho_W = 0.85$, $\mu_o/\mu_W = 0.20$, $D = 50.8$ mm).

structures could be obtained through adjusting the input flow rates of water and oil by the pumps themselves. When the steady state was reached under a flow condition, the input flow fluids rates were measured. The high-speed camera recorded the continuous flow process synchronously when the camera frequency was set at 1 kHz, which was high enough to capture the details of the flow process. The physical properties of test liquids have been listed in Table 2. In this work the temperature of the oil and water mixture was kept at about 20 °C.

The holdups were obtained experimentally by the well-known rapid closing valve method. It included two rapid closing valves installed on run tube with 50 mm diameter, and two rapid closing valves on the bypass tube with 25 mm diameter. The rapid closing valves connected by mechanical linkages were installed in the test section at a distance of 1.5 m. The bypass was implemented to switch the flow between the run and the bypass when the two valves on run were closed to measure the average phase holdup. Similar equipment can be found in the works of Oddie et al. (2003). Furthermore, the operation time of two rapid closing valves was 0.5 s. This provided sufficient short time to measure accurately the volumes of each phase. During the holdup measurements runs, sufficient time was taken to allow fully developed flow to be established. The rapid closing valves were closed and the sample was then transferred to a graduated cylinder by carefully purging the liquid phases using pressurized gas. The samples of the liquid phases were left in graduated cylinders for a time period of about 6 h to assure virtually complete gravitational phase separation before measurements of the liquid phase volumes were made. By taking repeated samples it was found that the fluctuation of mean value of the measurements over the three times is around 7.3%. Pressure gradient in the test section was measured by two absolute pressure transducers, and accurate results can be obtained from the difference of the measurements between the two transducers which are located at both ends of the 1.0 m long test section. The sampling frequency of the pressure was 500 Hz and a total of 60,000 samples, which corresponds to 2 min sampling time, were collected.

Table 2
Physical properties of liquids measured at 20 °C and 0.101 MPa.

	Water	White oil
Density, ρ (kg/m^3)	998	860
Viscosity, μ (Pa s)	0.001	0.044
Interfacial tensions, σ (N/m)	Water/gas	0.071
	White oil/gas	0.044
	Water/white oil	0.031

3. Methods of data analysis

3.1. Phase inversion point

Phase inversion can be defined as the phenomenon by which the dispersed phase changes to become continuous and the continuous phase becomes dispersed. The phase inversion phenomenon has been investigated for many years (see a review by Yeo et al., 2000). Generally, the phase inversion is affected by phase viscosity ratio, velocity, flow orientation, pipe diameter and material and so on. In recent years, predicting the phase inversion point has become of importance in the long pipeline transportation of oils, due to the fact that there is an abrupt and significant change in the frictional pressure gradient associated in the region, where phase inversion from water to oil continuous occurs. Up to now, few methods have been developed to predict the phase inversion point based on the empirical relationship and the physical mechanism.

For the empirical correlation, Arirachakaran et al. (1989) suggested the following logarithmic relation by a large number of experimental data collected from the literature:

$$\varepsilon_o^I = 0.5 + 0.1108 \log\left(\frac{\mu_o}{\mu_w}\right) \tag{1}$$

where μ is the dynamic viscosity. The subscript o and w refer to the oil phase and water phase, respectively. ε_o^I is the critical oil holdup at phase inversion (i.e. the phase inversion point).

Predicting the phase inversion point by using the physical mechanism include mainly the instability of the dispersed phase drop size; zero interfacial shear stress; minimum system energy; minimal dissipation rate and so on. Assuming the flow of three thin layers and no shear at the interface, Yeh et al. (1964) obtained the following relation:

$$\varepsilon_o^I = \frac{\left(\frac{\mu_o}{\mu_w}\right)^{0.5}}{1 + \left(\frac{\mu_o}{\mu_w}\right)^{0.5}} \tag{2}$$

Another correlation based on the zero interfacial shear stress was proposed by Nädler and Mewes (1997):

$$\varepsilon_o^I = 1 - \frac{1}{1 + k_1\left[\frac{C_o \rho_o^{(1-n_o)} \mu_o^{n_o}}{C_w \rho_w^{(1-n_w)} \mu_w^{n_w}} (DU_M)^{(n_w - n_o)}\right]^{1/k_2}} \tag{3}$$

where $U_M = U_{SO} + U_{SW}$, U_{SW}, U_{SO}, ρ and D denote, respectively, the input mixture velocity, superficial water velocity, superficial oil velocity, density and pipe diameter. k_1 and k_2 are empirical parameters. C_o, C_w, n_o and n_W are parameters in the friction factor equation described in the following Eq. (12). This correlation indicates that, for a two-phase laminar–laminar flow, it can be simplified to Eq. (2) when $k_1 = 1$ and $k_2 = 2$ are given.

Based on the minimum system energy and ignoring the details of the pipe geometry, the mixture velocity and surface tension, Brauner and Ullman (2002) gave a simple model to predict the critical oil holdup:

$$\varepsilon_o^I = \frac{\left(\frac{\rho_o}{\rho_w}\right)\left(\frac{\mu_o}{\mu_w}\right)^{0.4}}{1+\left(\frac{\rho_o}{\rho_w}\right)\left(\frac{\mu_o}{\mu_w}\right)^{0.4}} \tag{4}$$

Recently, the method of minimal dissipation rate was proposed by Poesio and Beretta (2008) to correlate phase inversion data. The approach is based on estimating the relation between frictional pressure gradient and holdup by means of a homogeneous model. Based on the effective mixture viscosity of the Ball and Richmond (1980), the following expression was given by:

$$\varepsilon_o^I = \frac{1-\left(\frac{\mu_o}{\mu_w}\right)^{-2/5k}+k\left(\frac{\mu_o}{\mu_w}\right)^{-2/5k}}{1+\left(\frac{\mu_o}{\mu_w}\right)^{-2/5k}} \tag{5}$$

where $1/k$ is the maximum packing factor. For a mono-dispersed mixture flow, Yeh et al. (1964) suggested the maximum packing factor ($1/k$) is equal to 0.74. Thus, a corresponding crowding factor k of 1.35 is used as an approximation in the present study.

Ngan et al. (2009) presented a similar method to predict the phase inversion point based on the minimal dispersion viscosity. They suggested that phase inversion happened at the phase fraction where the difference in viscosities between the two possible dispersions, oil continuous and water continuous, was zero, which enabled the transition from one continuous phase to the other. A large number of the correlations of effective mixture viscosity in the literature were collected to predict the phase inversion point. The models of Brinkman (1952) and Roscoe (1952) and Pal (2001) were suggested to calculate the effective mixture viscosity, respectively, defined as:

Brinkman (1952) and Roscoe (1952) model:

$$\frac{\mu_e}{\mu_c} = (1-\varepsilon_d)^{-2.5} \tag{6}$$

Pal (2001) model:

$$\left(\frac{\mu_e}{\mu_c}\right)\left[\frac{2\left(\frac{\mu_e}{\mu_c}\right)+5\left(\frac{\mu_d}{\mu_c}\right)}{2+5\left(\frac{\mu_d}{\mu_c}\right)}\right]^{1.5} = \frac{9}{8}\left[\frac{(K\cdot\varepsilon_d)^{\frac{1}{3}}}{1-(K\cdot\varepsilon_d)^{\frac{1}{3}}}\right] \tag{7}$$

where ε_d is the dispersion phase fraction and the subscript e, d and c refer to the effective mixture viscosity, dispersion phase and continuous phase, respectively.

The methods described above are used to predict the phase inversion point and to compare the theoretical models with experimental data in the following study.

3.2. Frictional pressure gradient

For dispersed systems, the homogeneous model can be used to calculate the frictional pressure gradient when the apparent or effective viscosity correlation has been obtained (Vielma, 2006). For a fully developed dispersed flow in a vertical pipe and neglecting the acceleration gradient, the total pressure gradient comprising of gravity pressure gradient and frictional pressure gradient can be calculated as (Brauner, 1998):

$$\left(\frac{dp}{dz}\right)_{tp} = \left(\frac{dp}{dz}\right)_g \pm \left(\frac{dp}{dz}\right)_f \tag{8}$$

where, the '±' sign corresponds to vertical upward or downward flow, respectively. The gravity pressure gradient is given by

$$\left(\frac{dp}{dz}\right)_g = \rho_M g \tag{9}$$

and the frictional pressure gradient is defined by

$$\left(\frac{dp}{dz}\right)_f = 2f_{tp}\rho_M\frac{U_M^2}{D} \tag{10}$$

where ρ_M, f_{tp} and g denote, respectively, the mixture density, two-phase friction factor and gravitational acceleration. The mixture density is calculated from the individual phase density and the average oil holdups obtained by the rapid closing valve in the present study using the following equation:

$$\rho_M = \varepsilon_o\rho_o + \varepsilon_w\rho_w \tag{11}$$

where ε_o and ε_w are the oil holdup and the water holdup, respectively.

Once a solution has been obtained for the effective mixture viscosity by using the Eqs. (6), (7) for a homogeneous two-phase flow, the single-phase flow correlations for the friction factor can be calculated by:

$$f_{tp} = C\cdot \mathrm{Re}_m^{-n} \tag{12}$$

where $C = 0.079$, $n = 0.25$ for turbulent flow, and $C = 16$, $n = 1$ for laminar flow. The Reynolds number for two-phase flow is defined by

$$\mathrm{Re}_m = \frac{\rho_M D U_M}{\mu_e} \tag{13}$$

Furthermore, to improve prediction performance, another different method has been also used to process the experimental data. Flores et al. (1998) have proposed a method to calculate the two-phase friction factor by considering the difference of water-dominated flow and oil-dominated flow. The constants c and n in Eq. (12) will be determined from experimental data, and Re_m has been re-defined as follows:

$$\mathrm{Re}_m = \frac{\rho_M U_M D}{\mu_c} \tag{14}$$

The subscript c refers to the continuous phase.

4. Results and discussion

4.1. Flow patterns

In order to estimate accurately the frictional pressure gradient, it is necessary to know the actual flow pattern under the specific flow conditions. Several flow pattern maps for the vertical flow of an oil and water have been observed depending upon the physical properties and input fluxes of the two phases, and the size of pipe (Flores, 1997; Bai et al., 1992; Brauner, 1998). According to the classification by Flores (1997), the main flow regimes in a vertical pipe can generally be classified into six flow patterns in vertical flow with three being water-dominated, e.g., water is the continuous phase, and three being oil-dominated. Water-dominated flow patterns include dispersion of oil in water (*O/W gradients*), very fine dispersion of oil in water (*D_o/w, o/w emulsion*), and oil in water churn flow (*churn, transitional flow*). Oil-dominated flow patterns include water in oil churn flow (*churn, transitional flow*), dispersion of water in oil (*W/O gradients*), and very fine dispersion of water in oil (*D_w/o, w/o emulsion*). Here, the churn flow is characterized as intermittent flow of complex and irregular structures of continuous oil phase and continuous water phase (Brauner, 2002; Hu and Angeli, 2006). Due to the fact that the annular pattern in vertical flow can be observed only for highly viscous oils, the annular pattern has not been observed in this work and most of flow patterns are dispersed flow.

The flow pattern maps of Flores showing the superficial velocities for the experimental data reported in this work are demonstrated in Fig. 2. The solid line represents the boundary of the experimental data of Flores. As be shown in the figure, the region of the water-dominated flow is larger than that of the oil-dominated flow. In general, the map of Flores can satisfactorily describe our experimental data for an oil and water two-phase flow in vertical upward pipe with 0.05 m diameter. The basic flow construction for low superficial oil and water velocities is *o/w* drops flow, where the oil is dispersed in the water in the form of relatively large bubbles. With increasing the superficial water velocity, transition to D_o/w (*o/w* emulsion) takes place. In the same way, for sufficiently high superficial oil velocity, the transition to D_w/o (*w/o* emulsion) takes place. Interestingly, it can be seen in Fig. 3b that the transition boundaries also appear to very close for most of the cases for vertical downward flow, although this part work has been carried out in a different flow direction to the experimental data of Flores. A comparison between the Fig. 2a and b shows the influence of flow direction on flow structure when having the same superficial velocities. The main differences are that the transition from water-dominated flow to oil-dominated flow takes place under a much lower superficial oil velocity contribution in the vertical downward pipe than that in the upward pipe. Namely, it is easier to form the flow structure of oil phase continuous in downward vertical flow. The reasons for the discrepancies may be that the slip velocity in downward flow is larger than that in upward flow for the same input conditions.

4.2. Phase inversion phenomenon

One of the critical unknown parameters involved in calculating the pressure gradient of two-phase flow is the holdup. In this work, the holdup of the dispersion is obtained from the rapid closing valves with ±7.3% manual operating error. The results of the average oil holdup in upward and downward flows are shown in Fig. 3. Although all the test points have been measured by using the rapid closing valves to obtain the oil holdup, only selected one constant superficial water velocity is included in the Fig. 3. It can be seen that, at low input oil fraction corresponding to these data, the average oil holdup at the test section is slightly lower than that at the input oil fraction, i.e. oil travels faster in the pipe. But the reverse is true for high input oil fraction and such behavior can occur under the condition that water is the faster phase. Although the transition from ε_o greater than β_o to less than β_o should appear at intermediate input oil fractions, in fact this change appears at input oil fractions above 60% as shown in the figure. This result is also similar to that in horizontal flows (Xu et al., 2008b). However, all the experimental data points near the diagonal line for most of cases and the in situ fractions would be similar to the input ones. Thus, in the following study, the mixture effective viscosity are calculated instead of the oil holdup, ε_o with the input oil fraction, β_o.

The frictional pressure gradient can be determined from the measured total pressure gradient by using Eqs. (8) and (9). The frictional pressure gradient against different input oil fractions, using the experimental data studied in this work and for others systems reported in the literature, are shown in Fig. 4a for upward flow and Fig. 4b for downward flow, respectively. Experiments are carried either by keeping the mixture velocity constant and increasing the dispersed phase fraction or by keeping the continuous phase superficial velocity constant and increasing the dispersed phase superficial velocity. The inversion route from *o/w* to *w/o* is studied experimentally in this work. It can be found in the Fig. 4a that, for the experimental data obtained in this work, the frictional pressure gradient decreases slightly with increasing the input oil fraction. At higher input oil fraction, the frictional pressure gradient tends to slightly increase and then to sharply decrease. When the input oil fraction is increased further, the frictional pressure gradient passes through a minimum and finally increases again and eventually reaches the single phase oil value. Based on the experimental observation, the frictional pressure gradient reaches to its lower value at the phase inversion point in this work. This is in agreement with previous findings (Hu and Angeli, 2006). They investi-

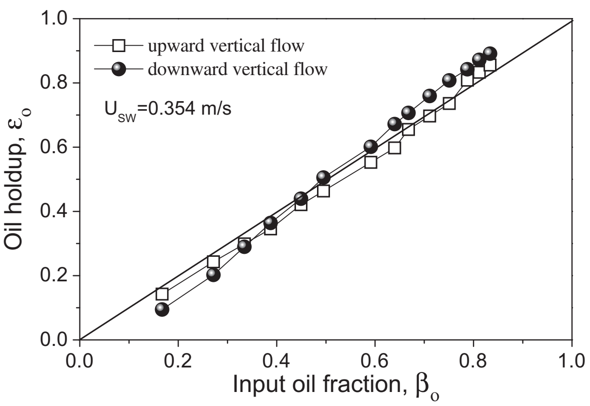

Fig. 3. Oil holdup at different input oil fractions for upward and downward vertical flow at a constant superficial water velocity.

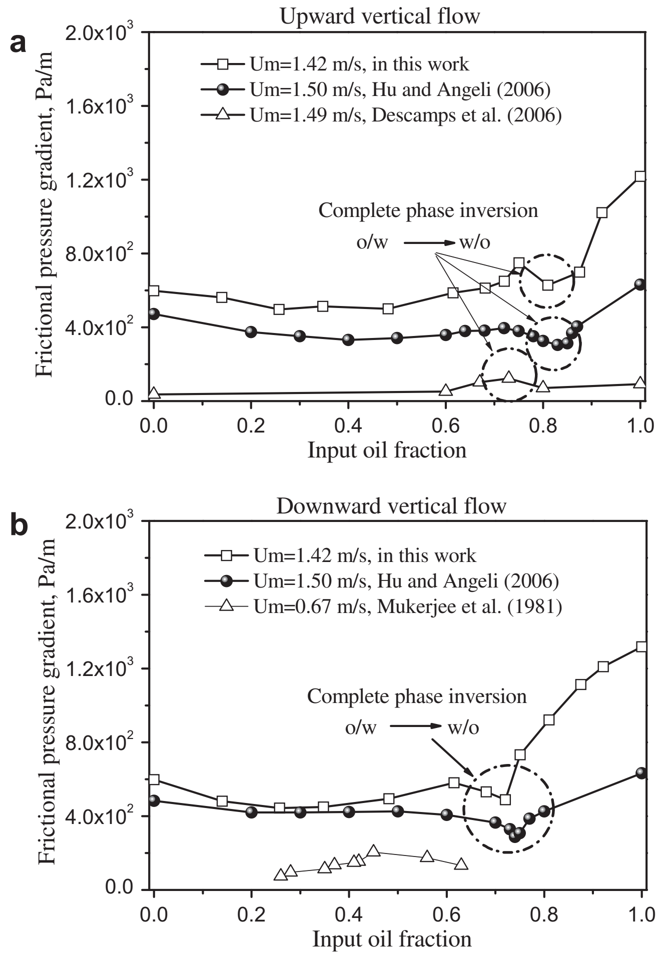

Fig. 4. Frictional pressure gradients against different input oil fractions for upward and downward vertical flows, respectively, by using the experimental data studied in this work and for others systems reported in the literature.

gated the phase inversion point by using the hot-film anemometer probe in a stainless steel pipe with 38 mm I.D. Tap water and oil (ρ_o = 828 kg/m^3, μ_o = 5.5 mPa s) were used as test fluids. They explained that a lack of pressure gradient maximum during phase inversion could be attributed to the large drop sizes encountered in the experiments. For a given volume fraction, the larger the drops are, the easier their deformation during flow and therefore the lower the viscosity of the mixture will be (Pal, 1993).

In contrast what has been observed from the above experiments, Descamps et al. considered that the phase inversion point occurred at the peak of frictional pressure gradient, as shown in Fig. 4a by using the triangular symbol. The fluids used were salted water and oil (ρ_o = 830 kg/m^3, μ_o = 7.5 mPa s). The results of Descamps et al. were similar to those of the oil–water flow in horizontal pipe. Namely, phase inversion was in all cases preceded by a large increase in the frictional pressure gradient, which was sharply reduced immediately after the new continuous phase was established. By analyzing the experimental data, they concluded that the phase inversion always takes place at an input oil fraction of about 70% regardless of the mixture velocity. Due to the considerable differences in liquid phase physical properties between their systems and ours, the frictional pressure gradient of the single oil flow in the works of Descamps et al. is lower than that of the phase inversion point. The frictional pressure gradient passes through the phase inversion point and then continues to decrease and eventually reaches the single phase oil value. Thus, during this process, there is no minimum occurred. In fact, the phase inversion point in the works of Descamps et al. is close to that in the current work (see Fig. 4a and b). Furthermore, it should be pointed out that it is difficult to define the complete phase inversion at a specific phase fraction point and the change in the continuous phases should happen over a range, during which the flow is transitional (Liu et al., 2006a; Piela et al., 2008).

This transitional range is a so-called ambivalent range of volume fractions over which both phases can either dispersed or continuous. Unlike a horizontal flow, few works has been reported on the ambivalent range for a vertical flow (Hu and Angeli, 2006; Liu et al., 2006a). On the basis of the visual observations, the ambivalent region in a vertical system is not the same clear as that observed in a horizontal system (Ioannou et al., 2005; Hu and Angeli, 2006). There is however, a narrow range of input phase fractions ($\Delta\beta$ = 3–5%) around the phase inversion point where complex structures may form. In the present study, we define this structure as the churn flow (Flores, 1997). It can be found in Fig. 2 that, when an experiment is carried out by keeping superficial water velocity constant and increasing the dispersed oil phase velocity, the flow structures can change from *o*/*w* drops flow to the complex structure flow (churn flow), and then to *w*/*o* drops flow. Here the complex multiphase dispersions and elongated drops are present during the churn structure. Similar structure was also obtained in the experimental works of Flores (1997) and Hu and Angeli (2006). It can be also found in the Fig. 4 that, for phase inversion point, several sets of data obtained by different authors are close to each other. In this study, the phase inversion

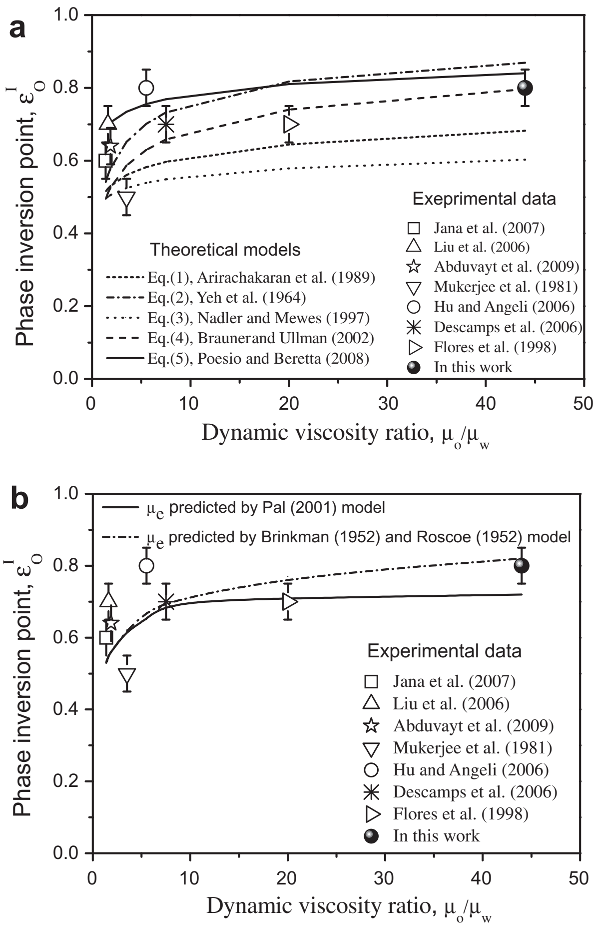

Fig. 5. Predicted inversion points by using different methods against the experimental data obtained with different test systems for an oil and water flowing in vertical upward pipes (a, five different models suggested in the literature; b, the minimal dissipation rate method using two correlations of effective mixture viscosity suggested by Ngan et al. (2009)).

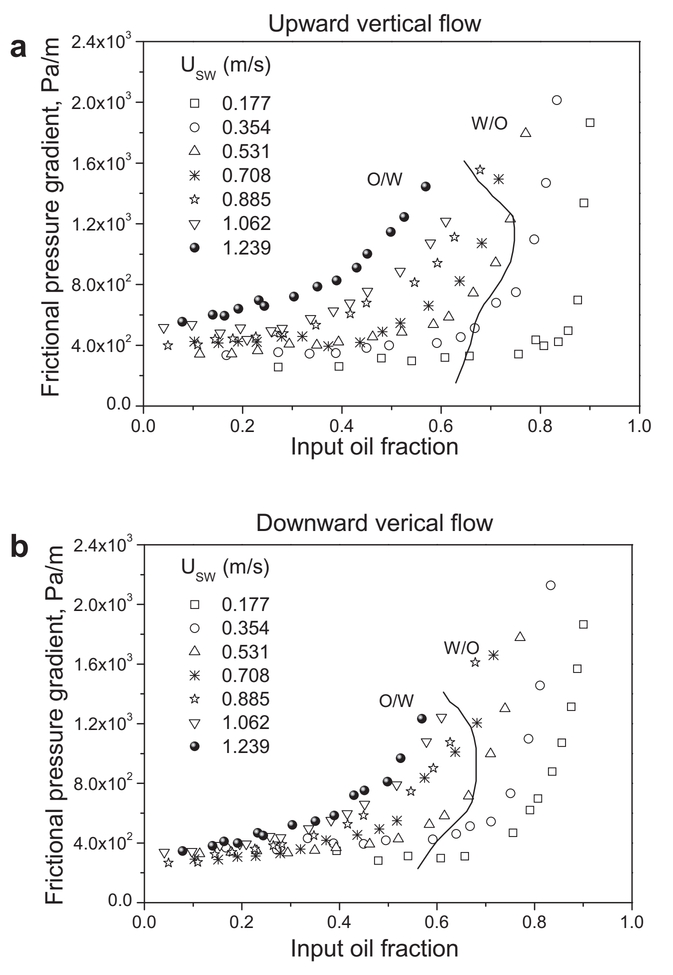

Fig. 6. Frictional pressure gradients against input oil fractions at different input superficial water velocities for upward and downward vertical flows, respectively.

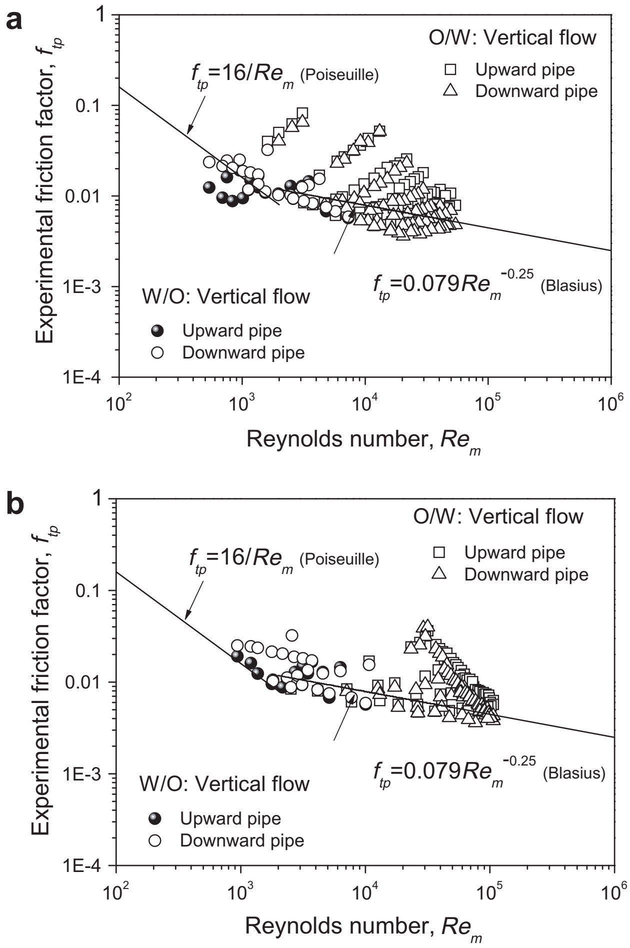

Fig. 7. Experimental friction factor vs. mixture Reynolds number by using the two methods of Brinkman (1952) and Roscoe (1952) and Pal (2001), respectively, tested against data in this work.

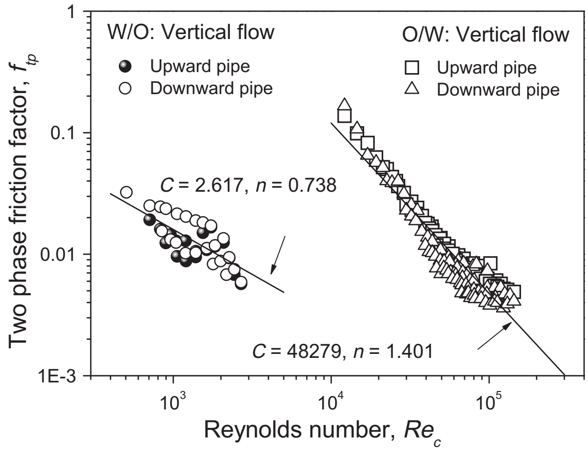

Fig. 8. Experimental friction factor vs. continuous phase Reynolds number by using the method of Flores et al. (1998) tested against data in this work.

takes place at an input oil fraction of about 80%. Interestingly, there is a similar tendency in the frictional pressure gradient data during phase inversion for downward vertical flow, as be seen in Fig. 4b. The difference is only the position of phase inversion point. The phase inversion takes place at an input oil fraction of about 75% in downward flow. Due to the lack of experimental data available in the literature for downward flow, further detailed experiments are needed to study this phenomenon.

Fig. 5 shows predicted inversion points by using different methods against the experimental data obtained with different test systems for an oil and water flowing in vertical upward pipes. Details of the properties of the oil phases and of the test systems used can be found in Table 1. Five models introduced in section 3 have been used to predict the critical oil holdup at phase inversion. It can be observed in Fig. 5a that Eq. (5) by Poesio and Beretta (2008) gives the highest critical oil holdup at a viscosity ratio range of 1–16. Eq. (3) by Nädler and Mewes (1997) predicts the lowest phase inversion point. Note that the curve proposed by Nädler and Mewes (1997) and plotted in Fig. 5a is a turbulent–turbulent flow and $k_1 = 1$ and $k_2 = 2$ are given. A comparison of the predicted curves with the experimental data shows that Eq. (2) by Yeh et al. (1964) and Eq. (5) by Poesio and Beretta (2008) are suitable to predict inversion at a low viscosity ratio range of 1–7.5.

In Fig. 5b, the phase inversion points, predicted by the minimal dissipation rate method using two effective mixture viscosity correlations suggested by Ngan et al. (2009), are compared against available experimental data for vertical flows. It can be observed that, at the dynamic viscosity ratio range of 1–7.5, both models give similar results. For a high viscosity ratio, the viscosity model of Brinkman and Roscoe predicts a slightly higher phase inversion point than that given by the viscosity model of Pal. Furthermore, a comparison between Fig. 5a and b shows that, for a high viscosity ratio ($\mu_o/\mu_W \gg 7.5$ mPa s in this work), the minimal dissipation rate method based on two correlations of effective mixture viscosity and Eq. (4) by Brauner and Ullman (2002) can better predict the phase inversion point.

Table 3
Statistical parameters, for experimental data in this work and those reported in the literatures, predicted by using the method of Flores et al. (1998).

Source	Abduvayt et al. (2006)	Descamps et al. (2006)	Flores et al. (1998)	Jana et al. (2007)	In this work
O/W					
C	9.078×10^7	1.786×10^1	6.677×10^1	1.287×10^3	4.828×10^4
n	1.822	0.658	0.834	1.177	1.401
Data points	29	26	26	29	155
R-square	0.962	0.612	0.573	0.884	0.949
W/O					
C	4.154×10^7	3.403×10^0	5.71×10^1	6.642×10^4	2.617
n	1.867	0.667	1.066	1.579	0.738
Data points	20	10	17	18	41
R-square	0.923	0.787	0.877	0.903	0.379

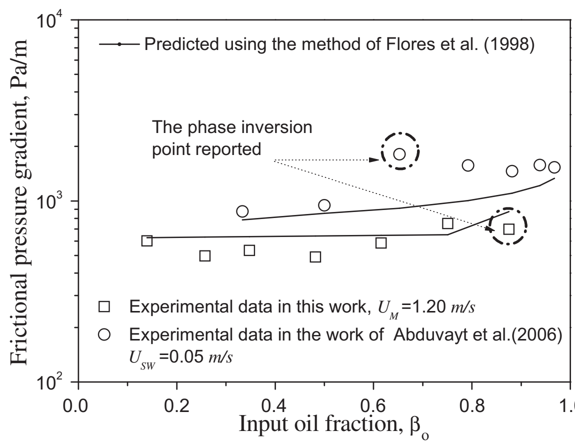

Fig. 9. Comparison of the predicted frictional pressure gradients with the data of Abduvayt et al. (2006) and those in this work by using the method of Flores et al. (1998) to calculate the effective mixture viscosity.

4.3. Frictional pressure gradient

The frictional pressure gradients measured in this work are graphed in Fig. 6a and b for upward and downward vertical flow, respectively. Here the measured frictional pressure gradient is reported as a function of the input oil fraction: different symbols represent different superficial water velocities. The solid lines represent the boundary of the flow pattern transition from *o/w* to *w/o*. As can be observed, in general, the frictional pressure gradient increases with an increasing superficial water velocity for a given superficial oil velocity. At constant superficial water velocity, the frictional pressure gradient increases with an increasing the input oil fraction. Comparing of the frictional pressure gradient figures and the flow pattern maps (see Fig. 2), it can be found that the changes of the frictional pressure gradient can be related to flow pattern transitions. The frictional pressure gradients in the flow pattern of *o/w* are lower than those in the flow pattern of *w/o*.

Fig. 7 presents that experimental friction factor vs. mixture Reynolds number using Eqs. (6) and (7) to calculate the effective mixture viscosity, respectively, tested against the data in this work. Here experimental friction factors, f_{tp} are back-calculated from experimental data by using the Eq. (10). It can be found that the experimental friction factors change rather unevenly and are scattered with comparison to both the Poiseuille and Blasius relations. The accuracy of the predictions is improved with increasing the mixture Reynolds number.

Experimental friction factor vs. continuous phase Reynolds number, calculated by using the method of Flores et al. (1998), is plotted in logarithmic coordinates shown in Fig. 8. A curve fit analysis of the data provides the *C* and *n* values of 48,279 and 1.401 for water continuous flow, and 2.617 and 0.738 for oil continuous flow, respectively. Furthermore, the available experimental data in the literatures (Flores et al., 1998; Descamps et al., 2006; Jana et al., 2007; Abduvayt et al., 2006) are also analyzed by this method. The results are presented in Table 3. As can be observed in the table, better fitting results are obtained for the experimental data of Abduvayt et al. (2006) and those in the present work with *R*-square of 0.962 and 0.949, respectively. For other experimental data the agreement is worse. Fig. 9 depicts a comparison of the predicted friction pressure gradients with the experimental data of the two fitting good results using the method of Flores et al. to calculate the effective mixture viscosity. A good agreement is obtained between theory and data for an average frictional pressure gradient. However, for the phase inversion procedure, the model fails to predict the change of frictional pressure gradient. The failure to predict the results may be due to the fact that this method is entirely empirical in nature, and therefore the method is a strongly dependent on a large number of experimental data.

Fig. 10 displays the comparison of the predicted frictional pressure gradients with experimental data of the present work and those reported in the literature by using Eq. (7) to calculate the effective mixture viscosity. Generally, a very good agreement is obtained between the theoretical and experimental frictional pressure gradients in the input oil fraction range of 0.2–1.0, especially for the high input oil fraction. However, the data in the low input oil frac-

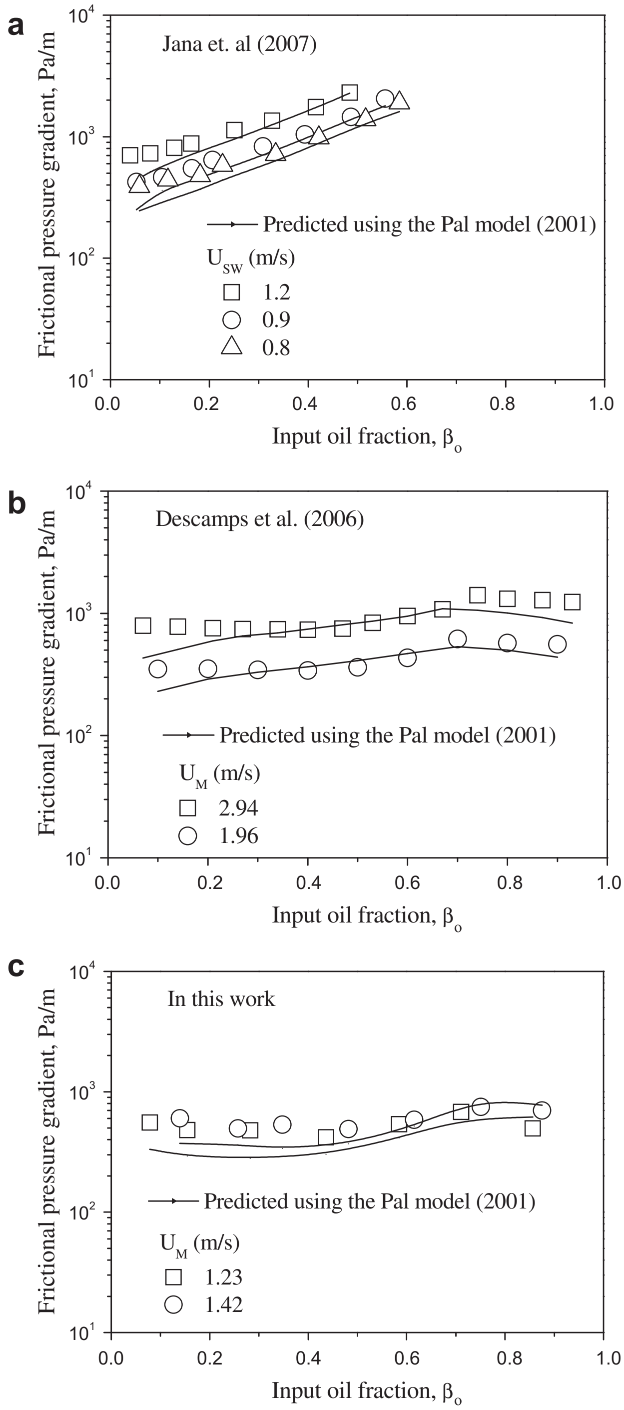

Fig. 10. Comparison of the predicted frictional pressure gradients with experimental data of the present work and those reported in the literature by using the model of Pal to calculate the effective mixture viscosity.

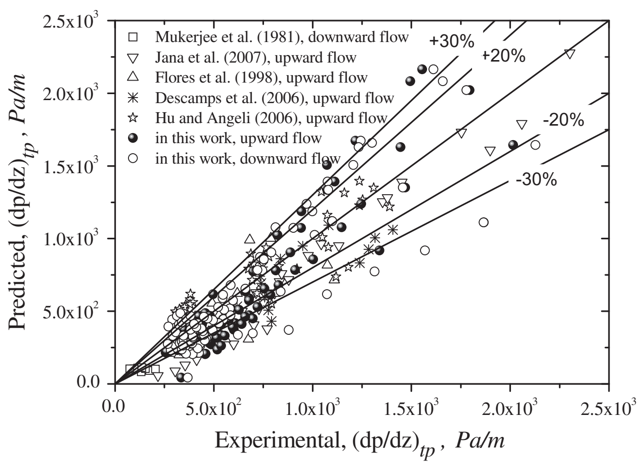

Fig. 11. Compared between experimental and theoretical values of the frictional pressure gradients, obtained by using the model of Pal to calculate the effective mixture viscosity, for vertical flow studied in this work and for others systems reported in the literature.

tion range of 0–0.2 are under-predicted by the model. In the whole range both the theoretical curves and the experimental data exhibit the same trend and the overall agreement of predicted values with experimental data is good. Finally, the model of Pal (2001) for calculating the effective mixture viscosity has been checked by plotting the experimental values of the friction pressure gradients vs. the predicted ones calculated. As Fig. 11 shows, most of the experimental values are well inside the 30% deviation region using 322 experimental data point collected from different references including the smooth and rough pipes.

5. Conclusions

An experimental study has been made of the simultaneous flow of two immiscible liquids flow through vertical pipes. Flow patterns, phase inversion and frictional pressure gradients for an oil and water vertical flow through upward and downward pipes were studied experimentally. The inversion route from o/w to w/o was carried out to investigate the behavior of phase inversion. Experiments were carried out either by keeping the mixture velocity constant and increasing the dispersed phase fraction or by keeping the continuous phase superficial velocity constant and increasing the dispersed phase superficial velocity.

From the experimental results, it is concluded that the frictional pressure gradient reaches to its lower value at the phase inversion point in this work. The points of phase inversion are always close to an input oil fraction of 0.8 for upward flow and of 0.75 for downward flow, respectively. Several theoretical models published in the literature have been presented to predict the phase inversion point. In general, the models of Poesio and Beretta (2008) and Yeh et al. (1964) are suitable to predict the phase inversion point at a low viscosity ratio range of 1–7.5. The minimal dissipation rate method, based on two correlations of effective mixture viscosity (Brinkman, 1952 and Roscoe, 1952 model; Pal, 2001), and the model of Brauner and Ullman (2002) can better predict the phase inversion point at a high viscosity ratio range of 7.5–44.

For the prediction of frictional pressure gradients, in the whole range both the theoretical curves, predicted by the effective mixture viscosity of Pal (2001), and the experimental data exhibit the same trend and the overall agreement of predicted values with experimental data is good, especially for a high oil fraction. The method, proposed by Flores et al. (1998) to calculate the two-phase friction factor, is suitable to the program with a large number of experimental data. Such studies will help to better describe the phase inversion phenomenon and to select a suitable model for predicting accurately the frictional pressure gradients for an oil and water two-phase vertical flow.

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