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Kerosene-Water Multiphase Flow in Vertical and Inclined Pipes

Faik Hamad, Nadeem Ahmed Sheikh and Muzaffar Ali

Abstract

This chapter presents the volume fraction distribution of kerosene-water two-phase flow in vertical and inclined pipes. The study of liquid-liquid two-phase flow is very significant to oil industry and many other processes in industry where two liquids are mixed and flow together. Pitot tube and optical probes are used for the measurement of velocity of water and volume fraction. The experimental measurements of the local parameters demonstrate that the single-phase and two-phase flows reached the fully developed axisymmetric conditions at $L/D \geq 48$ (L , pipe length; D , pipe diameter). The results also showed the severe asymmetry distributions of the volume fraction at the entrance region ($L/D = 1$) downstream the bend and in the inclined pipe. The comparison of volume fraction profiles with void fraction profiles indicated a significant difference in their shapes. The results also showed that the kerosene accumulated at the upper wall of the inclined pipe and the distribution improved by increasing the volumetric quality.

Keywords: volume fraction, kerosene-water two-phase flow, vertical and inclined pipes, optical probe, pitot tube

1. Introduction

Multiphase flows are important for the design of steam/water flow in steam generators, jet engines, condensers, extraction and distillation processes, gas and oil mixture in pipelines, and refrigeration systems. The mixture of two immiscible liquids is characterized by the existence of interfaces between the two fluids, associated with a discontinuity of properties across the interface. The single-phase flow is traditionally classified into laminar, transitional, and turbulent flows according to the flow Reynolds number. The two-phase flow in vertical pipe can be classified, according to the geometry of the interfaces.

The primary condition for all two-phase flows is specified by the volumetric quality β , which is defined as:

$$\beta = \frac{Q_d}{Q_c + Q_d} \quad (1)$$

where Q_d is the flow rate of the dispersed phase and Q_c is the flow rate of the continuous phase.

For a pipe of radius R , the corresponding (area averaged) superficial velocities are defined as:

Continuous phase superficial velocity:

$$\bar{U}_{cs} = \frac{Q_c}{\pi R^2} \quad (2)$$

Dispersed phase superficial velocity:

$$\bar{U}_{ds} = \frac{Q_d}{\pi R^2} \quad (3)$$

For both gas-liquid and liquid-liquid flow systems, the continuous phase is usually water.

In spite of the large number of published work in multiphase flow area, the publication on using local probe measurements for liquid-liquid flow is very limited compared to the gas-liquid two-phase flow. The purpose of this chapter is to publish some data on volume fraction profiles for liquid-liquid flow in vertical and inclined pipes. The following data are presented in this chapter: (i) the void fraction distribution for gas-liquid two-phase flow in vertical pipe, (ii) the volume fraction distribution for flow development of kerosene-water flow in vertical pipe, and (iii) the volume fraction distribution for the fully developed kerosene-water flow in vertical and inclined pipes.

2. Void fraction/volume fraction definition

Most experimental results for the void fraction α (volume fraction for liquid-liquid flow) have been obtained by a point sensor, which was used to discriminate in time between the two phases. Experimentally the void fraction α has been evaluated from the time record from such a probe as:

$$\alpha = \frac{\sum \Delta t_d}{T} \quad (4)$$

where $\sum \Delta t_d$ is the time the probe is located in the dispersed phase and T is the total sampling time used for record. It should be noticed that in many investigations, reference is made to the (average) void fraction $\bar{\alpha}$. The proper reference would have been the volumetric quality (β) obtained for gas-liquid systems by the quick closing valve method, X-ray or neutron techniques. For liquid-liquid systems, β can be obtained by measuring the two flow rates Q_d and Q_c .

Experimental studies of the phase distributions in concurrent two-phase upflow in vertical pipes present a complex picture that has not yet been systematically evaluated. The common flow patterns for vertical upward flow, in which both phases flow upwards in a circular tube, are shown in **Figure 1**. As the volume flow rate of gas increased for constant water flow rate, the flow patterns would vary. The following types of flow patterns can be found in vertical pipes:

- i. Bubbly flow: bubbles of gas or liquid in a continuous liquid phase appear, and the size of the bubbles can be very small or large.
- ii. Slug flow: in this type a bullet-shaped plug of gas is formed from many bubbles concentrated in one part to make larger bubbles, which approach the diameter of the pipe. The liquid phase is in continuous flow.
- iii. Churn flow: braking down of large vapor bubbles in plug flows form the churn flow. This is a highly oscillatory flow, and there is tendency for each phase to be continuous with irregular interfaces.

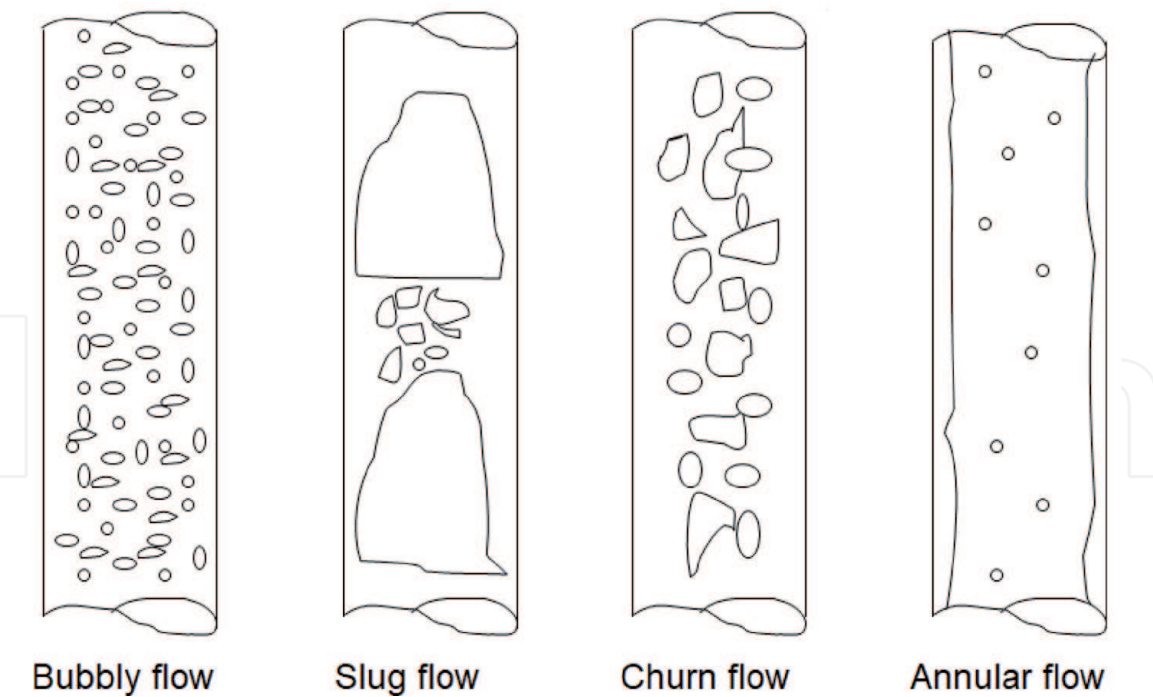


Figure 1.
Flow patterns in vertical upward flow in a pipe [1].

- iv. Annular flow: the liquid forms a film around the wall of the tube. The gas phase flows in the centre.

3. Gas: liquid void fraction distribution in vertical pipes

A significant number of measurements have been made for upflow in vertical pipes. Several investigators, e.g. Malnes [2], Serizawa et al. [3], Michiyoshi and Serizawa [4], Wang et al. [5] and Liu and Bankoff [6], have observed the peaking phenomenon of the local void fraction near the wall as shown in **Figure 2**. Some investigators, such as Van der Welle [7], Moujaes and Dougall [8] and Johnson and White [9], have observed a maximum void fraction at the centreline as shown in **Figure 3**. Other researchers, such as Nakoryakov et al. [10], Spindler et al. [11] and

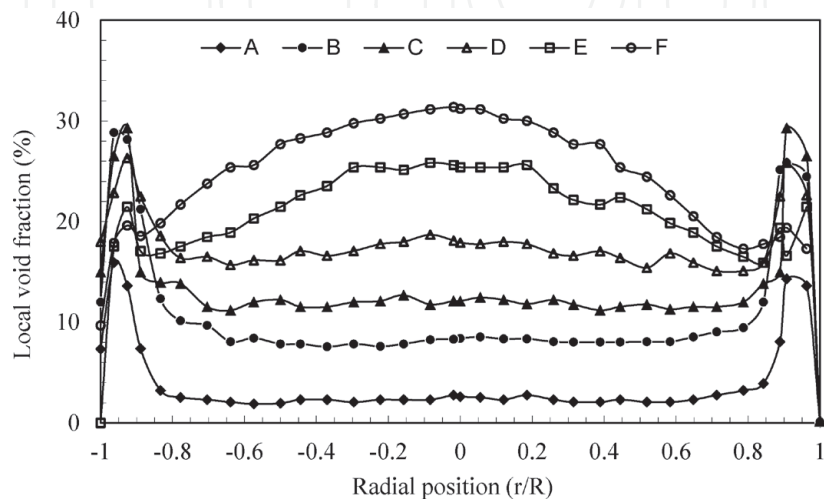


Figure 2.
Void fraction distributions for air-water upflow in a pipe with a continuous phase mean velocity = 1.03 m/s, Z/D = 30. A–D are bubbly flow, and E and F are slug flow [3].

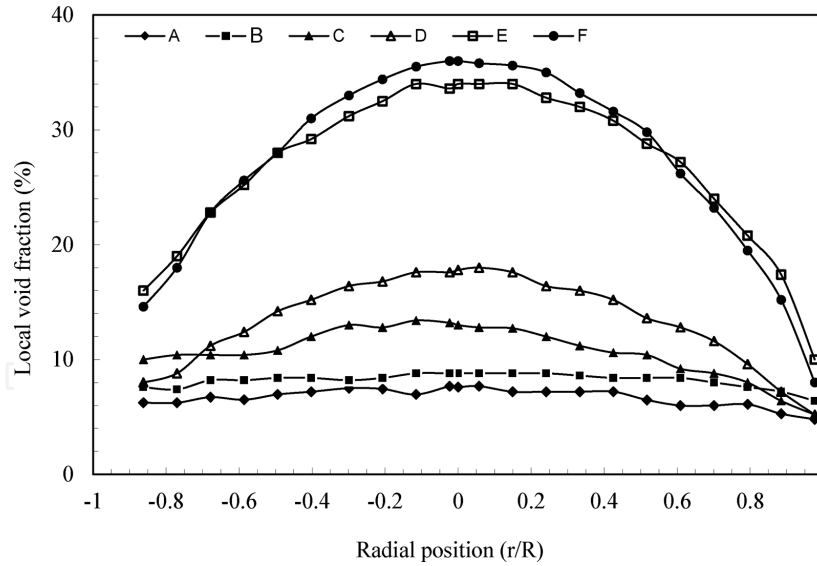


Figure 3. Void fraction distributions for air-water upflow in a pipe with different flow rates, $Z/D = 42.5$. A–D are bubbly flow, and E and F are transitional flow [9].

Liu [12], observed both wall and centreline peaking void fraction distributions for two-phase flow. The actual void fraction distribution configurations have been found to depend on the initial conditions: bubble size and flow rates, physical properties of the fluids, and the test section condition geometry.

4. Liquid: liquid volume fraction

Compared to the large number of publications on gas-liquid flows, less work have been published on liquid-liquid flows.

Most of the papers on liquid-liquid mixture flow were published by research group at the University of Bradford ([13, 14]; Hamad et al. [15]; Hamad and Bruun [16]). Most of these papers focused on the development of optical techniques for kerosene-water upward flow in vertical pipes. However, Farrar and Bruun [13] highlighted the problem of the severe asymmetry, and the swirl generated upstream the inlet due the existence of 90° bend as part of the experimental facility.

Zhao et al. [17] used a double-sensor conductivity probe to measure the local oil phase fraction distribution for flow in a vertical pipe at $L/D = 72$. They found that the volume fraction profiles were uniform for $\beta < 9.2\%$ and changed into wall peak for $\beta > 9.2\%$. The local oil phase fraction profiles at (a) constant water flow rate ($J_w = 0.33$ m/s) and (b) constant oil flow rate ($J_o = 0.066$ m/s) are given in **Figure 4**.

A comprehensive experimental data on kerosene-water two-phase flow were published by Hamad et al. [18, 19] and Hamad et al. [20] in vertical and inclined pipes. A summary of the results from each paper is given in the following sections.

4.1 Development of kerosene-water flow in vertical pipe

Hamad et al. [18] studied the flow development in a vertical pipe of 77.8 mm inner diameter and 4500 mm length downstream of a 90° bend experimentally at $L/D = 1, 16, 38$ and 54 using the experimental facility in **Figure 5**. Single-phase (water) flow measurements were made to check the establishment of fully developed symmetrical flow conditions. **Figure 6** shows the radial distribution of axial velocity in the plane parallel to the bend at different L/D ratios. Two values of \bar{u}_{ws}

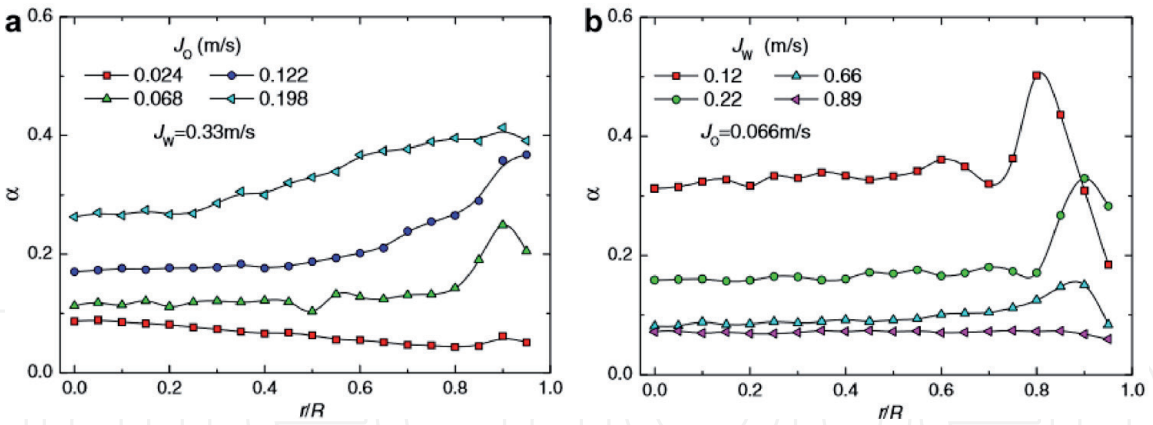


Figure 4. Oil volume fraction profiles at (a) constant water flow rate ($J_w = 0.33\text{ m/s}$) and (b) constant oil flow rate ($J_o = 0.066\text{ m/s}$) [17].

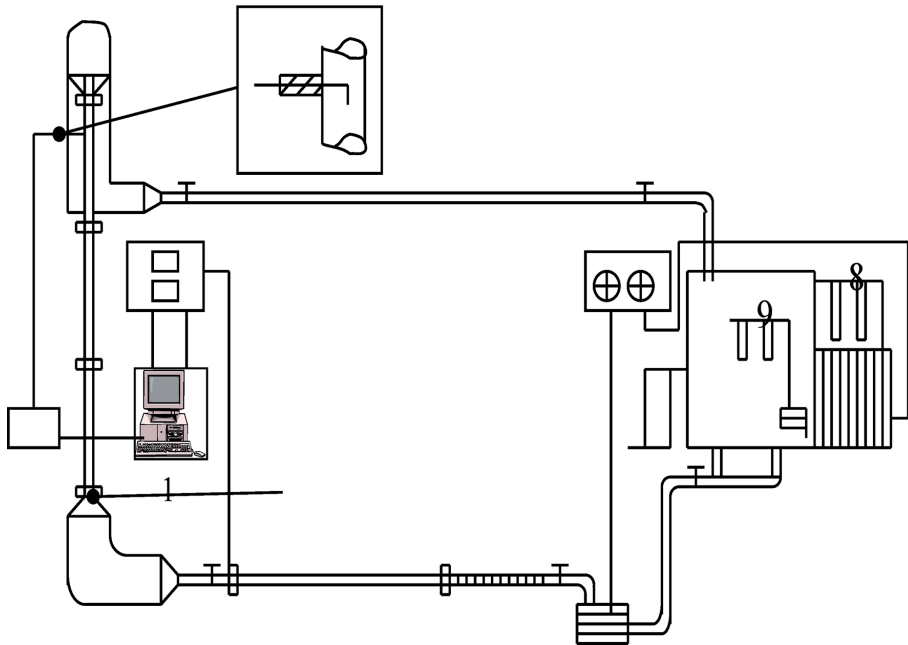


Figure 5. Schematic diagram of two-phase flow experimental facility [18].

are used (0.44 m/s ($Re = 33,800$) and 0.77 m/s ($Re = 60,000$)). The results show that water velocity distributions become fully developed at $L/D > 48$. The empirical power law velocity distribution given in Eq. (5) for single-phase turbulent flow [21, 22] was also included in **Figure 6** to confirm the accuracy of the measurements:

$$\overline{U} = \overline{U}_{cl} (1 - r/R)^{1/n} \tag{5}$$

Then, the kerosene was introduced to perform volume fraction measurements using optical probe [14] at four different axial positions at $L/D = 1, 16, 38$ and 54 downstream of the pipe bend. Three different flow conditions are considered: Case 1: water superficial velocity, $\overline{u}_{ws} = 0.44\text{ m/s}$, and volumetric quality, $\beta = 9.2\%$; Case 2: $\overline{u}_{ws} = 0.44\text{ m/s}$ and $\beta = 18.6\%$ and one high \overline{u}_{ws} condition; and Case 3: $\overline{u}_{ws} = 0.77\text{ m/s}$ and $\beta = 18.6\%$. For Case 1, the axisymmetric distribution is very poor at $L/D = 1$ (**Figure 7(a)**) with high volume fraction values of 20% near the inner side of the bend to the lower value near the outer wall of the bend of 4%. For Case 2, increasing β to 18.6% for the same \overline{u}_{ws} (**Figure 7(a)**) improves the axisymmetric distribution across the pipe. For Case 3, the axisymmetric distribution improved

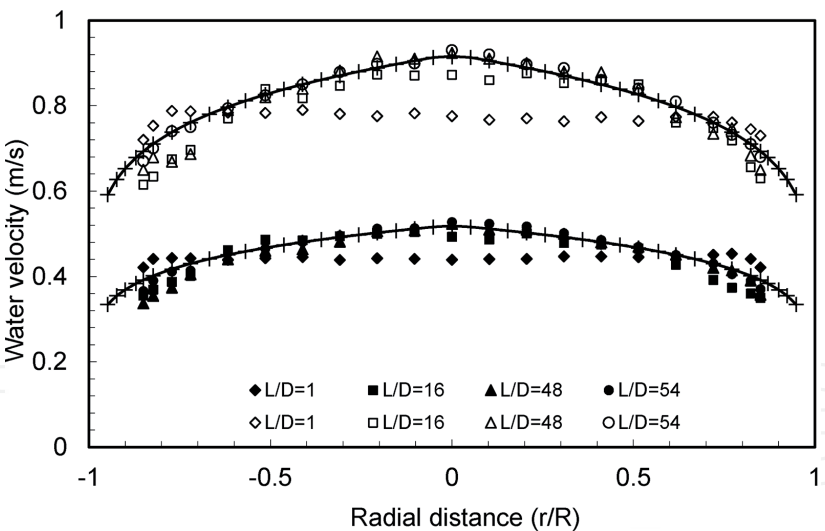


Figure 6. Local single-phase velocity distribution at different L/D ratios for average water velocity = 0.44 m/s (solid symbols) and 0.77 m/s (open symbols). The power law velocity distribution (solid line) is also included [18].

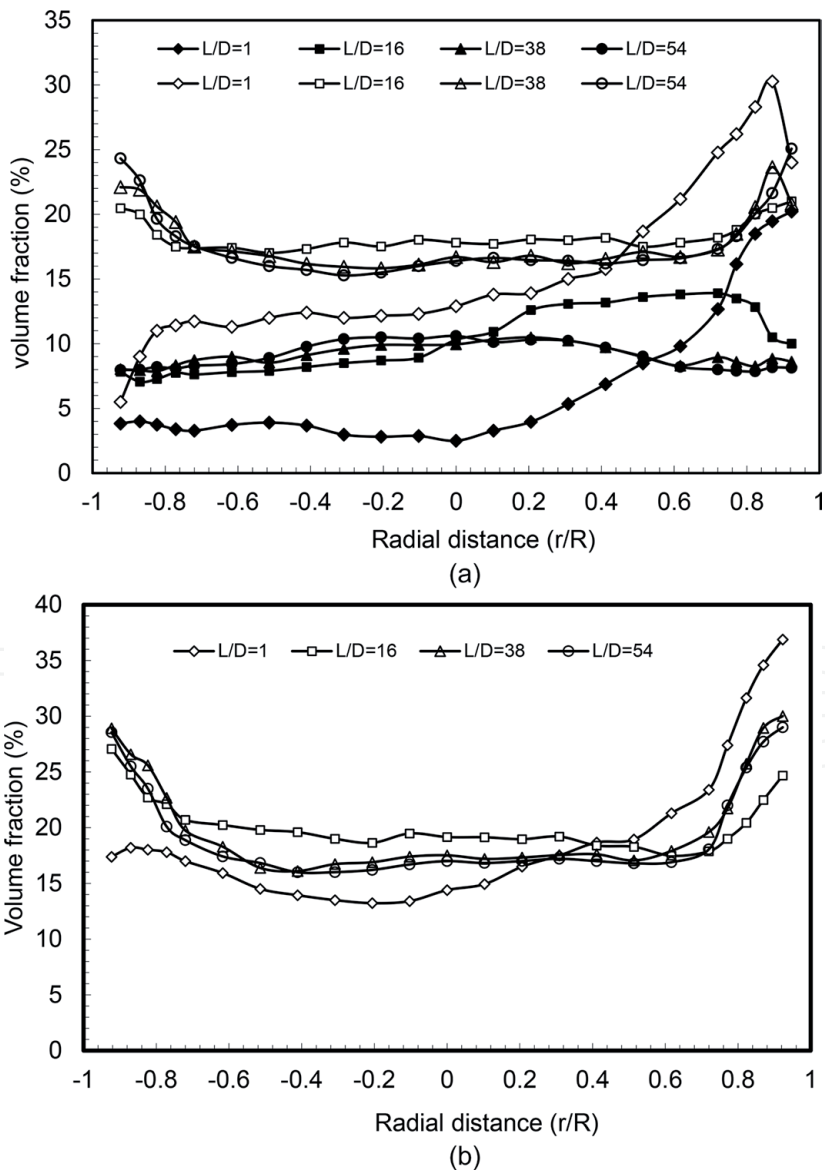


Figure 7. Volume fraction distributions at different (a) L/D for $U_{ws} = 0.44$ m/s and $\beta = 9.2\%$ (solid symbols) and 18.6% (open symbols) [18], (b) L/D for $U_{ws} = 0.77$ m/s and $\beta = 18.6\%$ [18].

further by increasing \bar{U}_{ws} for the same β (**Figure 7(b)**). The main conclusion is that the axisymmetric becomes better for higher β and \bar{U}_{ws} . The change in volume fraction distribution may be attributed to the improvement of the mixing process of the kerosene with water which acts against the effect of the buoyancy force and the centrifugal force at the outlet of the bend. However, the distribution becomes nearly symmetrical at $L/D = 16$. There appear to be no significant differences between the distributions at $L/D = 38$ and 54 , which suggests that fully developed, symmetrical condition was achieved.

4.2 Fully developed flow of kerosene-water flow in vertical pipe

Hamad et al. [19] studied the flow of kerosene-water upward flow in a vertical pipe at ($L/D = 54$) using optical probes. The effects of \bar{U}_{ws} and β on radial volume fraction distribution [$\alpha(r)$] of two-phase flow parameters were investigated.

The local volume fraction is calculated from the output of the leading sensor of the dual optical probe by determining the average drop residence time using the procedure described in Hamad et al. [14]. Comprehensive measurements

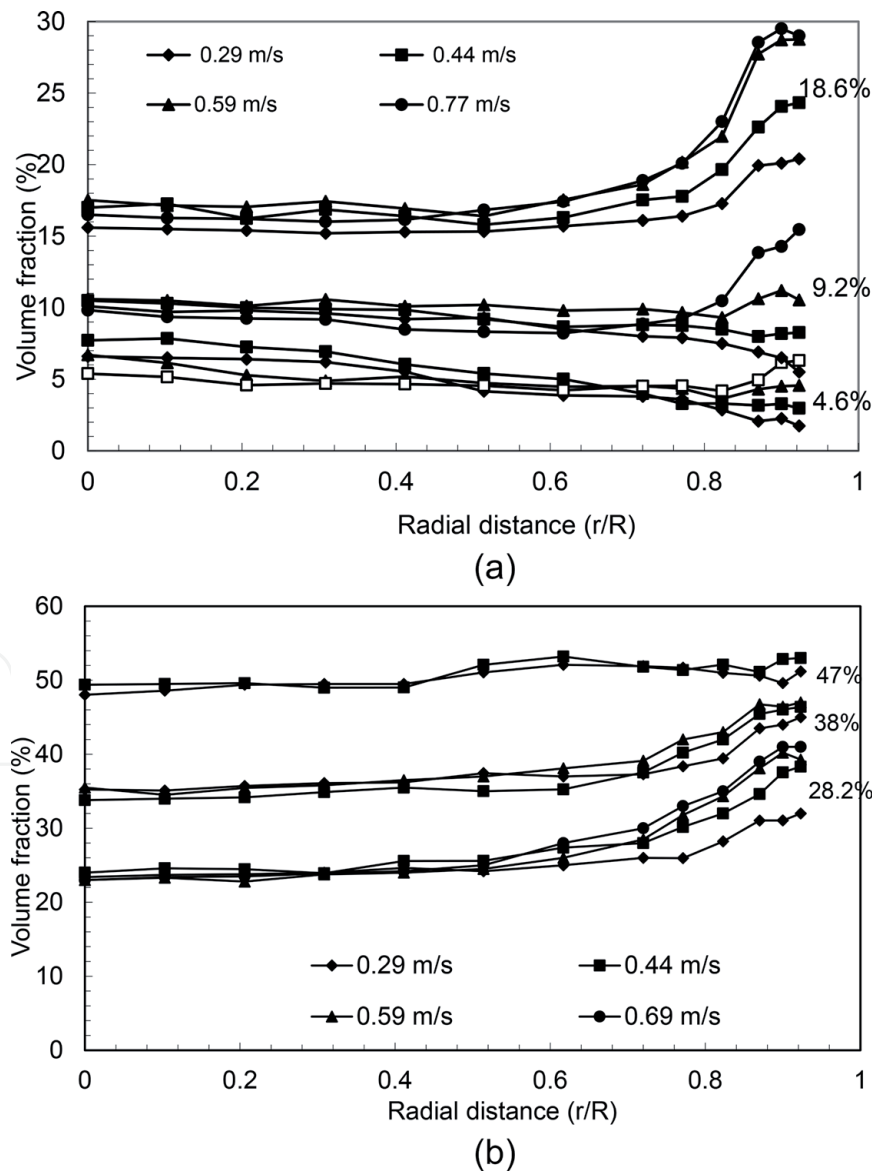


Figure 8. Volume fraction profiles for different (a) \bar{U}_{ws} and $\beta = 4.6, 9.2$ and 18.6% [19], (b) \bar{U}_{ws} and $\beta = 28.2, 38$ and 47% [19].

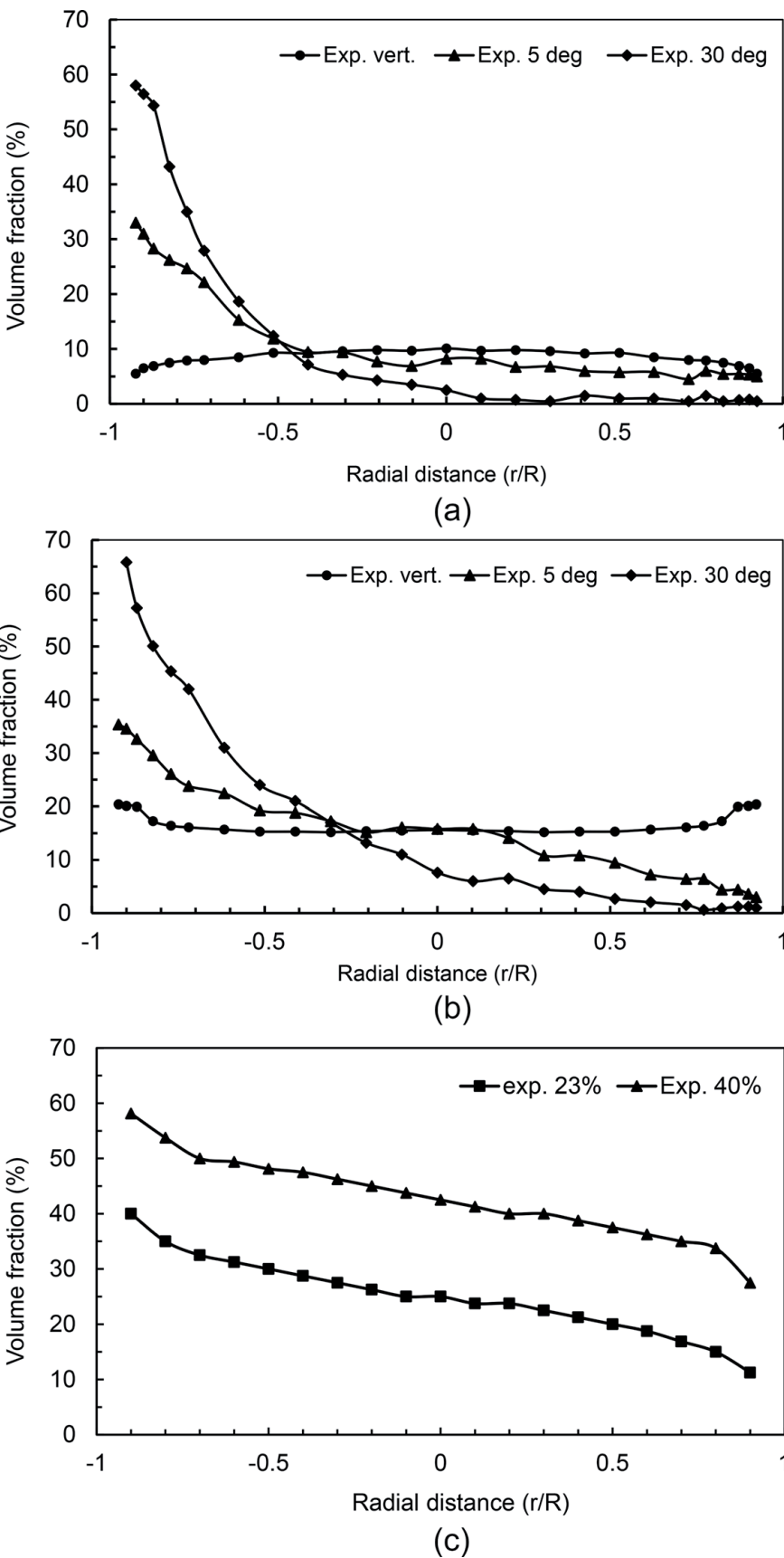


Figure 9. The effect of pipe inclination on volume fraction distribution (a) ($U_{sw} = 0.29$ m/s, $\beta = 9.2\%$) [20], (b) ($U_{sw} = 0.29$ m/s, $\beta = 18.6\%$) [20]. (c) the $\alpha(r)$ distribution from Vigneaux et al. [24].

of $\alpha(r)$ were performed for a number of β values in the range of 4.6–47% and constant \bar{U}_{ws} of 0.29, 0.44, 0.59, 0.69 and 0.77 m/s. The $\alpha(r)$ profiles have been plotted together for various values of \bar{U}_{ws} for each value of β as shown in **Figure 8(a)** and **(b)**.

As the $\alpha(r)$ profile primarily reflects the kerosene content in the mixture flow, it follows that the related $\alpha(r)$ profile sets for $\beta = 4.6\%$, 9.2% , 18.6% , 28.2% , 38% and 47% are centred around these values. The graphs also show distinct variations, both within each β group and between groups with different β values.

The results from **Figure 8(a)** and **(b)** show that increasing \bar{U}_{ws} with low β ($<20\%$) will change the $\alpha(r)$ profiles from convex shape with peak at the pipe centreline to flat shape and then to concave shape with peak near the wall. For moderate β ($20\text{--}40\%$), the $\alpha(r)$ profiles have a concave shape for different \bar{U}_{ws} with peak near the wall which has high values for higher \bar{U}_{ws} . In the case of $\beta \approx 50\%$, the $\alpha(r)$ profile shapes are flat for the two cases in **Figure 8(b)**.

The $\alpha(r)$ profiles from centreline which peaked to uniform to wall peaked and then to uniform can be attributed to the change in lift force due to the change in drop diameter, slip velocity and radial velocity distribution of both phases. The present finding is supported by the results for liquid-liquid flows from Zhao et al. [17] and Hua et al. [23] for the same range of \bar{U}_{ws} and β .

4.3 Kerosene-water flow in inclined pipe

Hamad et al. [20] used an optical probe to study the kerosene-water flow inclined at 5° and 30° from vertical at $L/D = 54$. The volume fraction was measured for $\bar{U}_{ws} = 0.29$ m/s and $\beta = 9.2\%$ and 18.6% .

Figure 9(a) shows the radial $\alpha(r)$ distributions of the volume fraction, $\alpha(r)$ for 0° , 5° and 30° inclination angles at \bar{U}_{ws} of 0.29 m/s and two values of $\beta = 9.2$ and 18.6% .

The results in **Figure 9(a)** and **(b)** show that the inclination has a significant influence on the distribution of $\alpha(r)$. The kerosene drops were separated from the water accumulated at the upper zone of the pipe due to the gravity effect. The effect of increasing β in an inclined pipe leads to dispersion of the drops to the lower zone of the pipe due to the recirculation cells of the moving droplet swarms.

The present results are supported by the findings reported by Vigneaux et al. [24] and Flores et al. [25]. **Figure 9(c)** presents the two sets of experimental data reported by Vigneaux et al. [24] in a pipe inclined at 15° from vertical. In the first case, $\beta = 23\%$, and $U_{sw} = 0.27$ m/s, and in the second case, $\beta = 40\%$, and $U_{sw} = 0.21$ m/s.

5. Conclusion

The results on void fraction profiles from literature show the complexity of the flow behaviour. It is reflected in different types of profiles due to the local interaction between the bubbles and the continuous phase. This may be attributed to the various forces at interface between the phases including drag, lift and virtual force as well as the size of bubbles and compressibility effect. In contrast, the volume fraction profiles for liquid-liquid two-phase flow have similar shapes. This behaviour may be attributed to smaller drops, smaller density ratio, smaller slip velocity and the incompressible nature of the liquids.

The results show that fully developed condition for liquid-liquid flow can be achieved at lower L/D compared to gas-liquid flow. This is due to incompressible nature of liquid drops which have the same volume compared to the gas bubbles which expand continuously due to the pressure drop in flow direction.

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