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Flow regime identification of two-phase liquid–liquid upflow through vertical pipe

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Abstract

The present work has attempted to identify the flow patterns during liquid–liquid two phase flow through a vertical pipe. Dyed kerosene and water have been selected as the test fluids. The measurements have been made for phase velocities varying from 0.05 to 1.5 m/s for both the liquids. The conductivity probe technique has been adopted and three different probe designs have been used to identify the patterns under different flow conditions. A parallel wire type probe traversing the entire cross-section along a diametral plane has indicated the existence of bubbly flow at low phase flow rates and dispersed bubbly flow at high velocities of water. Apart from the visual appearance of the signals, different statistical analysis namely the probability density function and wavelet analysis have been performed for a better appraisal of the flow situation. The information in the PDFs have been quantified by means of the statistical moments. The existence of the core-annular flow at high kerosene and low water velocities has been confirmed from measurements using a different probe design. The intermediate region between the bubbly and annular flow patterns is characterized by a random distribution of the two liquids with continually changing interface between them. This has been named as the churn turbulent flow pattern. The information thus obtained has been represented in the form of a flow pattern map.

Keywords: Multiphase flow; Hydrodynamics; Vertical pipe; Dispersion; Annular flow; Instrumentation

1. Introduction

Flow of a mixture of two immiscible liquids occurs in many industrial processes and in the petroleum industry in particular, where oil and water are often produced and transported together. During their cocurrent flow in a pipe, the deformable interfaces of the two fluids can assume a variety of characteristic configurations, which can be classified into different flow patterns or flow regimes. The flow patterns cannot be predicted from the independent variables of the system such as the phase flow rates and their physical properties in a straightforward manner. An identical observation has also been reported for gas–liquid flows by the past researchers. They have mostly presented observations of flow patterns in the form of a plot termed as the flow pattern map where the most commonly used axes represent the superficial velocities of the two phases.

The interest on flow patterns arises due to the fact that the hydrodynamics of flow depends on the interfacial configurations. When these distributions are taken into account, more accurate models can be developed for two-phase flows. Clearly the flow patterns would be expected to vary with (for a given pipe diameter and orientation) the velocities, the volume fractions and physical properties (density and viscosity) of the respective phases. A further parameter which is likely to be important for liquid–liquid cases is the wetting characteristics of the tube wall. Wetting effects can be important in gas–liquid flows for hydrophobic channel walls but are not usually taken into account. It has been reported that the manner in which the phases are introduced into the conduit also influences the prevailing pattern.

Experimental studies on flow pattern maps during horizontal oil–water flows were successfully done by Russell et al. (1959), Charles et al. (1961), Hasson et al. (1970), Guzhov et al. (1973), Arirachakaran et al. (1989), Trallero (1995), Valle and Kvandal (1995) and Nadler and Mewes (1995). In addition

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to the experimental studies on flow regimes, criteria of flow pattern transition have been given by Brauner and Maron (1992) (for stratified, stratified-dispersed, annular, slug and dispersed flow regimes), Brauner (2001) (for dispersed flow boundary) and Brauner and Ullmann (2002) (for oil-in-water dispersion and water-in-oil dispersion).

Experimental studies of oil–water flow in inclined pipes were reported by Mukherjee et al. (1981), Vigneaux et al. (1988), Flores et al. (1998). Mukherjee et al. (1981) measured pressure loss and water holdup for oil–water flow in 1.5 in diameter pipe with inclination angle varying from ±30° to ±90° from the horizontal. Vigneaux et al. (1988) measured the distribution of the water volume fraction across a pipe section during oil–water flow. They used local high frequency impedance probes in a 20 cm ID pipe at mean velocities between 2.7 and 35 cm/s, at deviation angle between 0° and 65° from vertical, and at water volume fraction between 30% and 100%. Flores et al. (1998) carried out theoretical as well as experimental investigations of oil water flow in vertical and inclined pipes. The tests covered inclination angles of 90°, 75°, 60° and 45° from the horizontal. They reported the holdup and pressure drop behaviors to be strongly affected by oil–water flow patterns and inclination angle.

One of the earliest experimental studies on liquid–liquid two-phase flow through vertical pipes dates back to Govier et al. (1961). The authors studied pressure drop and holdup using three different oils. Brown and Govier (1961) studied pressure drop, bubble velocity and bubble size distribution in oil–water vertical flow using high-speed photography. Hasson et al. (1974) have presented analytical as well as experimental studies on liquid–liquid annular flow through vertical conduits. The analysis has considered laminar flow in both the liquids and described the flow field as a superposition of an undisturbed field and a disturbance field. Their experimental results have validated the analysis and defined its range of applicability. The authors have further shown the Lockhart–Martinelli model to be inadequate for liquid–liquid annular flows. Farrar and Bruun (1996) applied a hot film anemometer based technique in the study of kerosene–water two-phase flow in the bubbly, spherical cap bubble and churn flow regimes. The authors presented radial bubble volume fraction profile, bubble cut chord length profile, bubble mean velocity profile and turbulent intensity profile. Hamad et al. (1997, 2000) developed optical probe systems and studied kerosene–water two-phase flow through vertical pipe.

Some studies have also been performed to study the effect of pipe material on the hydrodynamics of liquid–liquid flow. Angeli and Hewitt (1998) performed experiments in stainless steel and acrylic tube and proposed that the material of the tube wall can strongly influence the pressure gradient during two-phase liquid–liquid horizontal flow. Pressure gradients under all conditions were higher in the steel than in the acrylic tube for the same mixture velocities and flow volume fractions, the difference being greater than what would be expected from the difference in the wall roughness. Angeli and Hewitt (2000) carried out experiments in horizontal stainless steel and acrylic tube and concluded that in the stainless steel tube the propensity for dispersion was greatly increased; in the acrylic tube oil tended to be the continuous phase for a wider range of flow conditions than in the steel tube. Ioannou et al. (2005) studied phase inversion in steel and acrylic pipes and concluded that the pressure gradient peak around phase inversion is sharper and larger in the acrylic pipe as compared to the steel one with the same diameter.

The above survey shows that unlike gas–liquid flows, the flow patterns in liquid–liquid systems and consequently the flow pattern map has not yet been standardized. Moreover, the majority of the studies in liquid–liquid flows are confined to horizontal pipes. This has motivated the present study to perform an indepth investigation of the flow patterns during liquid–liquid up flow through vertical conduits and to develop an objective method for identifying the transition between subsequent patterns.

2. Experimental setup and procedure

The schematic diagram of the experimental set up designed and fabricated to investigate vertical up flow of kerosene–water mixture is shown in Fig. 1. It consists of a test rig and accessories namely water tank, kerosene tank, kerosene–water separator, two centrifugal pumps and measuring equipment. The test section comprises of a vertical transparent acrylic resin (perspex) tube of 0.0254 m diameter and 1.4 m length. Acrylic resin was selected as the material of construction to facilitate visual observation of the flow phenomena. An entry length of 2.0 m is provided to ensure fully developed flow. After the test section, there is an exit length of 0.60 m to avoid any flow disturbance in the test rig. In the test section, a glass view box (VB) of 0.30 m length is attached for photography. The test fluids are water and dyed kerosene. Blue dyed kerosene has been used in the experiments for better visualization of the flow phenomena. They are pumped through pumps (P1 and P2) from their respective storage tanks. The flow rates are metered by previously calibrated rotameters. The two liquids are then introduced by a T arrangement at the entry where water and oil enter from the vertical and horizontal directions, respectively. After the test section, the kerosene–water mixture enters a separator. Both liquids are then directed into their respective storage tanks after getting separated by gravity.

The superficial velocities of both water and kerosene have been varied from 0.05 to 1.5 m/s. The experiments are carried out by increasing kerosene velocity at a constant water velocity. The water velocity is then changed and the readings are repeated. Next, all the measurements are carried out in the reversed way i.e., keeping kerosene superficial velocity constant, the water superficial velocity has been increased continuously within the range to study the existence of hysteresis. The physical properties of water and kerosene are given in Table 1.

2.1. Measurement technique

Numerous techniques exist for estimation of flow patterns in gas–liquid flow. The most common way to identify the different flow patterns is to observe the flow in a transparent