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Study on oil–water two-phase upflow in vertical pipes

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ABSTRACT

This paper attempts at identifying flow patterns and measuring hold-up during liquid–liquid two-phase flow through a vertical pipe. The test fluids used in the research were L-AN 15 machine oil and water. The measurements were conducted for superficial velocities of the phases ranging from 0.024 to 0.578 m s^{-1} for oil and 0.010 to 1.045 m s^{-1} for water. The internal diameter of the tested pipe was 30 mm. In the study of flow patterns, the paper reports performed experimental work, which was based on systematic observations and measurements using a high speed video camera. The HOmatic membrane valves were used for the measurement of hold-up of oil. The values of hold-up and the type of flow patterns were as predicted. The results of void fraction measurements were compared with the predictions from various hold-up models and correlations.

1. Introduction

A system consisting of two immiscible liquids flowing through a vertical pipe forms a non-stationary system as it exists only under certain flow conditions. Such a system is characterized by instability both in terms of the shape and quantities of the specific flow patterns. The knowledge of characteristics of two-phase liquid flow is useful in the design of processes and selection of equipment that is most suitable for a particular metering application.

Nowadays this kind of flow is a focus in a greater number of research institutes as a consequence of the greater interest in the phenomena occurring in it, such as the possibility of undesirable emulsification of a system or a sudden effect of phase dissipation. This type of flow is encountered in the chemical, food and energy industries. Examples of such applications include extraction columns, continuous reactors, cooling devices and pipelines used in the transport of crude oil and coal tar.

Two-phase gas–liquid flow is one of the most familiar and widely reported type of flow of multiphase flow. In contrast, little research focused on the flow of two immiscible liquids, though in the recent years the interest in the subject has increased.

Govier et al. (1961) described oil–water flow in a vertical pipe with the internal diameter of 26.4 mm and a length of 11,278 mm. The research was realized by application of oils with various physical properties but in each case lighter than water ρ_o=880–780 kg m^{-3}, η_o=0.936 m Pa s. The authors in the paper identified four basic flow patterns, i.e., drops of oil in water, oil slugs, froth and drops of water in oil. They concluded that the considered oil–water mixtures revealed a similar behavior to the air–water mixtures tested previously. The authors of this paper also undertook to attempt an assessment of the slip coefficient *S* of the liquid oil–water mixture. The measurements of the actual water and oil volume fractions were carried out by use of concurrent closure of two valves which were situated at the ends of a measurement section.

Zavareh et al. (1988) tested upflow of water–oil mixture through a vertical pipe and identified four basic flow patterns. The patterns listed in their paper indicated similarity to the ones established research by Govier et al. (1961). The authors did not identify a pattern with water drops in oil nor oil drops in water. They concluded that the forming pattern included water dispersion in oil as well as annular flow.

Vigneaux et al. (1988) conducted experiments involving upstream two-phase oil–water flow in a vertical pipe with the internal diameter of 200 mm and identified an area of transitory flow. This structure was identified during the flow with the measured specific volume fraction of water in the range α_w=0.2–0.3. However, neither the plug nor the slug pattern was identified, in contrast to what had been observed by Zavareh et al. (1988).

The identification of two-phase patterns during upstream flow of liquid–liquid system in a vertical pipe was also the subject of experiments conducted by Farrar and Bruun (1996). The experiments conducted with regard to a two-phase paraffin–water system were realized on a vertical pipe with the internal diameter of 78 mm and a length of 1500 mm. The pipe was acrylic to enable flow patterns to be observed. In addition, computer aided thermo-anemometry method was applied in order to study the forming

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Nomenclature

d	internal diameter of pipe, mm
$\breve{g}$	gravitational acceleration, m s^{-2}
g	mass flux density, kg m^{-2} s^{-1}
t	temperature, °C
u	superficial velocity, m s^{-1}
Re	Reynolds number, dimensionless
S	slip coefficient, dimensionless
Q	volumetric flow rate, m^3 s^{-1}
We	Weber number, dimensionless
α	hold-up, dimensionless
β	input volume fraction, dimensionless
η	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}
x	mass flow rate ratio, dimensionless

Subscripts

2P	two-phase mixture
o	oil
w	water
cal	calculated value
exp	measured value
W/O	dominant oil phase (water in oil)
O/W	dominant water phase (oil in water)

patterns. Digital technique was used to distinguish between the continuous phase and dispersed one. The result of this work involved identification of three flow patterns: bubble flow, bubble flow with a spherical dome and slug flow.

In a study of two-phase oil–water flow, Flores (1997) identified four basic flow patterns: three with a dominant water phase (slightly dispersed oil in water flow, dispersed flow of oil in water and oil slugs in water) and one with a dominant oil phase (slightly dispersed flow of water in oil).

Asheim and Grødal (1998) described the results of experimental testing of upward flow of water and oil mixture (ρ_o=783 kg m^{-3}, η_o=1.4 m Pa s) in a vertical pipe with the internal diameter of 42.6 mm and a length of 7800 mm. The focus in the research was only on the type of flow in which the continuous phase was formed by water with various ratios of oil phase in it, i.e., bubble flow. On the basis of experiments the authors determined the measured superficial values of the volume fraction of water. The measurement of the volume fraction of water hold was performed on the basis of values of conductivity and electrical capacitance of the water–oil mixture.

Jin et al. (2003a, 2003b) conducted measurements of upward oil–water mixture flow (ρ_o=820 kg m^{-3}, η_o=3.26 m Pa s) through vertical pipes with internal diameters of 18 and 25.4 mm with a length of 1400 mm using electrical conductivity method.

Zhao et al. (2006) in their study tested upward flow of dispersed oil in water in a vertical pipe, which applied oil with the following physical properties ρ_o=824 kg m^{-3}, η_o=4.1 m Pa s. The pipe had an internal diameter of 40 mm and a length of 3800 mm. The authors developed a map of such flow in a co-ordinate system which corresponds to the superficial velocities of the phases.

Jana et al. (2006) conducted a study of liquid–liquid two-phase upflow through a vertical pipe with an internal diameter of 25.4 mm and a length 1400 mm. They applied dyed kerosene oil (ρ_o=720 kg m^{-3}, η_o=1.37 m Pa s) and water and observed type of flow patterns. The information obtained in this way was represented in the form of a flow pattern map.

The literature in this field, most of which are experimental, offers only limited insight into the phenomena specific for this type of flow. The existing papers mainly indicate stochastic characteristics of the flow and complexity of the hydrodynamic phenomena which accompany it. This statement has encouraged the authors to undertake research into the flow patterns during liquid–liquid flow and means to be used to identify the values of liquid hold-up.

2. Experimental apparatus

The principal elements of the installation were a vertical pipe (1) made of plexiglas, water (15) and oil (16) feeding system, a system used for regulation and measurement of the flow rates of the media – water and oil (7 and 10), a mixing chamber (2) and a system for water–oil mixture separation (14). The diagram of the experimental facility is presented in Fig. 1. The testing was performed in a vertical pipe with an internal diameter of 30 mm and a length of 7120 mm. The circulating media used in the testing were water and machine oil L-AN 15, whose density and viscosity at the temperature of 20 °C were equal to 856 kg m^{-3} and 29.20 m Pa s, respectively. The flow parameters of the tests are summarized in Table 1.

Water was pumped by a multi-stage rotodynamic pump while oil by a toothed pump (9) from the respective tanks (5 and 8) into float flowmeters and electronic ones by Rotameter and Kobold (7 and 10) and into the mixing chamber (2). The diagram of the mixing chamber is presented in Fig. 2. Two-phase mixture was formed in chamber (2) and pumped into a measurement channel (1), which consisted of two sections: one for measurement (section A) with a length of 6786 mm and including an initial section and another one used for reducing the discharge effect (section B) with a length of 334 mm. Flow pattern identification (section A1) as well the measurement of hold-up (section A2) was performed in the measurement section. After the mixture passes the section of the channel used for reduction of the discharge effect (section B), the mixture was directed in a separator (14) where gravitational separation of oil and water occurred.

The flow rates of the phases were regulated by means of throttle valves while the surplus of any of the phases was reversed through extraction and into a storage tank. The measurement of the oil density was performed by a float metering technique by use of an aerometer. The dynamic viscosity was determined by a digital Brookfield DV-II+ cone./plate type viscometer and the value of the surface tension of the oil was established by a bubble method. The registration of the particular components of the mixture, as they were measured by electronic measuring equipment, involved a central system for the acquisition of experimental data (11). In turn, temperature measurements, involving both circulating media prior to their entry into the system and in the particular section of the measurement channel applied a multiplexer (13).

The identification of the flow patterns was undertaken in a light passing through a water–oil mixture by illuminating the channel (1) with a 2000 W halogen lamp. This observation was performed in the measurement section (A1 section) whose design ensured that the flow patterns could develop sufficiently. The registration of the patterns was performed by means of a Canon 300 D digital camera and a VDS Vosskühler HCC-1000 video camera.

The measurement of the hold-up was undertaken by a classical volume method, by using fast-closing HOmatic pinch valves (4) coupled together by means of direct acting solenoid valves.