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Detailed analysis of phase distributions in a vertical riser using wire mesh sensor (WMS)

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ABSTRACT

This paper looks into the results of an experimental study concerned with the phase distributions of gas–liquid multiphase flows experienced in a vertical riser. Scale experiments were carried out using a mixture of air and silicone oil in a 6 m long riser pipe with an internal diameter pipe of 67 mm. A series of pipe flow experiments were performed for a range of injected air superficial velocities over the range 0.05–4.73 m/s, whilst the liquid superficial velocities ranged from 0.05 to 0.38 m/s. Measurements of cross-sectional void fraction and radial time averaged void fraction across a pipe section located 4.92 m from the pipe flow injection were obtained using a capacitance wire mesh sensor (WMS). The data were recorded at a frequency of 1000 Hz over an interval of 60 s. For the range of flow conditions studied, the average void fraction was observed to vary between 0.1 and 0.83. An analysis of the data collected concluded that the observed void fraction was strongly affected by the gas superficial velocity, whereby the higher the gas superficial velocity, the higher was the observed average void fraction. The average void fraction distributions observed were in good agreement with the results obtained by other researchers. The accuracy and performance of void fraction correlations were carried out in terms of percentage error and Root Mean Square (RMS) error. Reasonably symmetric radial void fraction profiles were obtained when the air–silicone oil was fully developed, and the shape of the symmetry profile was strongly dependent on the gas superficial velocity. The data for air/water and air/silicone oil systems showed reasonably good agreement except at gas superficial velocity of 0.05 m/s. A comparison of the experimental data was performed against a published model to investigate the flow structure of air–water mixtures in a bubble column. A satisfactory report was observed for radial void fraction profile (mean relative error is within 5.7%) at the higher gas superficial velocities.

1. Introduction

Gas–liquid flow is ubiquitous and an extremely complicated physical phenomenon occurring particularly in the petroleum industry during the production and transportation of oil and gas due to its unsteady nature and high attendant pressure drop. The most common and safest means of transporting oil and gas from the sand face of wells to consumers is through pipelines. Pipelines used to transport fluids from the wellhead through different production facilities takes into consideration the pressure gradient along the pipelines. The spatial distribution of the phases inside the pipe and the pipe geometry plays an extremely important role in the accurate determination of pressure gradient and flow hydrodynamic characteristics.

A vital characteristic of two-phase flow is the presence of moving interfaces and the turbulent nature of the flow that make theoretical predictions of flow parameters greatly more difficult than in single-phase flow. Thus, experimental measurements play an important role in providing information for design, and supporting analysis of system behavior. Because of this, there is a real need to make certain measurements of void fraction distribution for model development and testing. As it happens, theses quantities must also be measured for control and monitoring of industrial two-phase systems. Void fraction is an important variable in any two-phase flow system for determining pressure loss, liquid holdup, and prediction of heat transfer. However, several studies concerning void fraction distribution have been carried out in vertical pipes (Abdulkadir et al. [1], Azzopardi et al. [2], [3–7],

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and Szalinski et al. [8]). In addition, several empirical and mechanistic correlations have been proposed in the literature using air/water as the operating fluid. Hence, engineers are often confronted with plethora of correlations to choose from for predicting void fraction. In addition, most of the reported works were confined to pipes with small internal diameters. But, only few studies have been published for void fraction distribution analysis in vertical pipes using more viscous fluid other than water [1,8].

Investigations by Harms and Forrest [9] and Jones [10] revealed that there are problems associated with inaccuracies in obtaining void fraction measurements owing to fluctuations.

1.1. Background to the study

1.1.1. Cross-sectional void fraction distribution

A critical literature review on cross-sectional void fraction distribution was included in Abdulkadir et al. [1]. In this section the summary is included. Gardner and Neller [11] conducted an experimental study to investigate the distribution and redistribution of the multiphase flow phenomena observed in air–water flow systems. They used a traversing probe to measure the time averaged void fraction at any point over a range of chosen cross-sections. They concluded that reasonably symmetric air concentration profiles were obtained at a distance of 3.3 m from the mixing section. However, they did not investigate the influence of gas superficial velocity on flow development and symmetry.

Morooka et al. [3] carried out a detailed measurement of void fraction of a vertical (4×4) rod bundle in a steam–water two-phase flow using an X-ray computing tomography (CT) scanner. They found that the cross-sectional averaged void fraction data for a bundle can be correlated by the Drift-Flux model and that the Zuber–Findlay correlation underestimated the data in a void fraction area of 80% or more. Based on this finding, they developed a modified correlation based on their data.

Ohnuki and Akimoto [12] studied the effect of air injection methods on the development of air–water two-phase flow along a 0.48 m internal diameter and 2.016 m height vertical pipe. The two injection methods, porous sinter and nozzle injection, were used to obtain different flow structures in the developing region. From an analysis of their experimental data they found that no air slugs occupying the flow path were recognized regardless of the air injection methods even under the condition where slug flow is realized in the small-scale pipe. They concluded that the lower half of the test section was affected by the air injection method, whilst for the upper half of the test section, the effects of the air injection methods observed were small.

Later, Ohnuki and Akimoto [4] extended their earlier work to studying the transition of flow pattern and phase distributions in the upward air–water flow observed along a 0.2 m internal diameter and 12.3 m height vertical pipe. They observed flow patterns and recorded measurements of axial differential pressure, phase distribution, bubble size and bubble and water velocities. They compared the data of other workers with their experimental data. They concluded that further detailed measurements were needed to investigate the flow structure under the agitated bubbly flow.

Prasser et al. [5] carried out detailed study of the evolution of flow structure with growing distance from the gas injection using a WMS. They carried out measurements in a vertical 51.2 mm internal diameter pipe using air–water as the working fluid at atmospheric pressure and a temperature of 30 °C. They found that the bubble size distributions clearly showed the effect of coalescence and fragmentation.

Shen et al. [7] studied two-phase distribution in a vertical 0.2 m internal diameter and a 24 m high pipe. They used optical probes and pressure transducers to record local measurements including; void fraction, Sauter mean diameter and pressure loss. From an analysis of their experimental data they concluded that the phase distribution patterns could be subdivided into basic patterns, namely, wall peak and core peak using the concept of Fisher skewness. However, the weakness of Fisher skewness is its sensitivity to irregular observations at the extremes where the difference between the mean and the value is cubed.

Prasser et al. [6] carried out a detailed comparison of data obtained from an ultra-fast X-ray CT and a WMS. The work was carried out in a vertical 42 mm internal diameter pipe using air–water as the operating fluid. They found that the WMS has a significant higher resolution than the X-ray CT and that unlike the CT images; the WMS was capable of capturing small bubbles. They claimed that the WMS underestimated the gas fraction inside large bubbles. They concluded that the WMS caused a significant distortion to large Taylor bubbles for small liquid velocities up to 0.24 m/s and that this effect vanished with an increase in superficial water velocity.

Azzopardi et al. [2] carried out wire mesh sensor studies in a vertical 67 mm internal diameter pipe using air–water as the operating fluids. Measurements of radial time averaged void fraction and cross-sectional average time series of void fraction were carried out. They determined that the wire mesh sensor was capable of providing insight into the details of phase distributions in a pipe. The cross-sectional time averaged air void fraction was expressed in terms of the gas mass fraction. Also, these studies were restricted to the use of air–water flow mixtures.

Manera et al. [13] compared wire mesh sensor and conductive needle-probe measurements of vertical two-phase flow parameters using an air–water system. They determined that the WMS is capable of delivering a full mapping of the interfacial area density and a full three-dimensional reconstruction of gas bubbles. However, the needle probe was found to be less intrusive and produced fewer disturbances to the downstream flow.

Szalinski et al. [8] used a conductivity measuring WMS for air/water flow and a permittivity measuring one for air–silicone oil flows. The experiment was conducted in a 67 mm internal diameter and 6 m long vertical pipe. They made a direct comparison between both types of two-phase flow for the given pipe geometry and volumetric flow rates. Time series of cross-sectionally averaged void fraction was used to determine characteristics in amplitude and frequency space. They also used radial gas volume fraction profiles and bubble size distributions to compare air–water and air–silicone oil flows. The information from the time series and bubble size distribution was used to identify flow patterns for each of the flow rates studied.

Abdulkadir et al. [1] carried out an experimental investigation to characterize the phase distributions of two-phase air–silicone oil flow in a vertical pipe using WMS. This study concluded that reasonably symmetric profiles were obtained when the air–silicone oil was fully developed and that the shape of the profile was strongly dependent on the gas superficial velocity. They also determined that symmetric parabolic profiles can be represented as spherical cap bubble and slug flows and that flattened symmetric profile can be represented as churn flow. This paper is a follow-up of the work of [1]. Here, we present a detailed evaluation of the void fraction profile equations and comparison of air–silicone oil with other fluid systems.

1.1.2. Radial void fraction distribution

In two-phase gas–liquid flow, the local void fraction and local velocity vary across the pipe cross section. A modelling approach that takes into account this behavior is that called Drift Flux model. Here, the main assumption is that the velocity difference is due to the drift velocity between the phases. This approach, however, relies on several empirical parameters, such as the distribution parameter C_o. Analysis presented in Wallis [14] shows that C_o