Flow Measurement and Instrumentation 41 (2015) 75–80

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Void fraction measurement of gas–liquid two-phase flow from differential pressure

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ARTICLE INFO

Available online 4 November 2014

Keywords:
Differential pressure
Void fraction
Frictional pressure loss

ABSTRACT

Void fraction is an important process variable for the volume and mass computation required for transportation of gas–liquid mixture in pipelines, storage in tanks, metering and custody transfer. Inaccurate measurement would introduce errors in product measurement with potentials for loss of revenue. Accurate measurement is often constrained by invasive and expensive online measurement techniques. This work focuses on the use of cost effective and non-invasive pressure sensors to calculate the gas void fraction of gas–liquid flow. The differential pressure readings from the vertical upward bubbly and slug air–water flow are substituted into classical mathematical models based on energy conservation to derive the void fraction. Electrical Resistance Tomography (ERT) and Wire-mesh Sensor (WMS) are used as benchmark to validate the void fraction obtained from the differential pressure. Consequently the model is able to produce reasonable agreement with ERT and WMS on the void fraction measurement. The effect of the friction loss on the mathematical models is also investigated and discussed. It is concluded the friction loss cannot be neglected, particularly when gas void fraction is less than 0.2.

1. Introduction

Two-phase flow is any type of flow containing more than one phase of liquid, gas or solid. These processes are frequently encountered in the process industries. Mean volumetric void fraction is a key parameter to characterise two-phase flows. Many researches were carried out to correlate differential pressure and void fraction in two-phase flow, but hindered by inability to generate one model that was valid for all flow regimes. This is due to the complex nature of the different flow patterns and energy interactions in flow [1]. Lockhart and Martinelli [2] gave the general correlation of pressure drop for two-phase flow. Wallis [3] fitted an equation to the plot of liquid hold up "1-α_g" against Lockhart and Martinelli "X" parameter which was a function of the two-phase pressure drop. This postulate implies that the pressure drop in the two-phase flow is higher than that of gas phase or liquid phase alone, because the gas phase is involved in irreversible work on the liquid phase and the presence of more than one phase in the flow conduit reduces available cross sectional area of flow for either fluids present in the two-phase flow. In support of the Lockhart and Martinelli correlation, Merchuk and Stein [4] came up with another correlation by including the impact of all the energies acting on the multiphase flow mechanism quantified as pressure drop due to frictional force. Tang and Heindel [5] further stated that pressure drop of two-phase flow was partially because of mechanisms within the system which caused energy losses, namely; the frictional force existing between flowing fluid and conduit internal surface. It also came from turbulence between the liquid and the gas phases, due to the slip ratio, which was the difference in velocities of two phases. On the contrary the frictional pressure drop was neglected by Hasan [6] and Shafquet et al. [7] on ground that it was negligible because the mass flow rate of the liquid phase was far higher than that of the gas phase. A comparison of results from different authors on multiphase pressure drop was done by Müller–Steinhagen and Heck [8] to match many correlations for two-phase pressure drop. This analysis showed a large variation over the different correlations given by different authors applying to the same experiment. Gharat and Joshi [9] also made a similar analysis by comparing results from another 15 authors some already in by Müller–Steinhagen and Heck's analysis [8] and attributed the discrepancies to inability of the models to be valid across various flow regimes. According to Gharat and Joshi [9], the two-phase

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http://dx.doi.org/10.1016/j.flowmeasinst.2014.10.010
0955-5986/

Nomenclature

ρ	density
v	velocity
g	acceleration due to gravity
h	static head above pressure tapping point
P	pressure
F_p	frictional pressure loss
α	the gas void fraction
ΔP	differential pressure
C_f	fanning friction factor
D	internal diameter of pipe
Re	Reynolds number
μ	viscosity

Subscripts

m	mixture
g	gas
l	liquid
p	pipe
1 and 2	are sensor positions

frictional pressure loss was dependent on two mechanisms, first was shear stress due to turbulence on the conduit wall and secondly due to presence of bubbles in the mixture, with some additional parameters like eddy diffusivity of bubble and mixing length.

Electrical Resistance Tomography (ERT) and Wire-mesh Sensor (WMS) are tomographic modalities and they have more complicated measurement mechanism than pressure sensors. Both ERT and WMS can measure gas void fraction without the consideration of friction loss in the two-phase flow, which provides an alternative approach to validate the gas void fraction model based on differential pressure. The void fraction measurement accuracy of ERT and WMS were discussed by Faraj [10] and Sharaf [11]. The principle behind ERT is to determine the electrical conductivity by measuring the voltage between the ERT electrodes mounted on the internal circumference of the conveying conduit. The measured conductivity is subjected to the Maxwell's equation [12] to calculate the local cross-sectional void fraction of the dispersed phase. This is an invasive but non-intrusive local void fraction measurement technique in two-phase mixtures, which is also capable of providing tomographic cross-sectional images. WMS consists of two planes of wire electrodes arranged perpendicularly to each other at an angle of 90° covering the flowing cross-sectional area. One plane of the wires is the current transmitter while the other plane is the current receiver. The conductivity is measured by injecting a voltage pulse into one of the transmitting wires, while the other transmitting wires are kept at ground voltage [13], the current flowing to all receiving wires are measured simultaneously and conductivity estimate made from that. The void fraction of gas is derived from the normalised conductivity. Both ERT and WMS can present local cross-sectional void fraction. All local void fractions are averaged to obtain the mean void fraction.

2. Experiment setup and procedures

The experiment was carried out on the flow loop facility at the University of Leeds. The sketch of the flow loop is shown in Fig. 1. In the experiment, air and tap water are gas and liquid phase respectively. The channel in blue represents the water flow and the red channel represents the air supply. The cyan section represents the mixed air–water flow. The stabilised air flow rate is regulated by the air mass flow controller. After the loop bend, the upwards air–water mixture goes through the flow instrumentations, 5.80 m horizontal section and then back to the water tank, where air is released and water is recycled. The detailed information on flow meters was described in literature [12].

This flow loop only can create bubble and slug two flow regimes. As indicated in Table 1, bubble flow regime was created from the cross combination between three inlet water flow rates and five inlet air flow rates. Slug flow regime was created from the cross combination between three inlet water flow rates and eight inlet air flow rates.

A wet/wet differential pressure sensor with two tubes was adopted first. It was not suitable for the air–water flow measurement, because the small air bubbles entering the tube affected the accuracy of readings. The diaphragm gauge pressure sensor was tested later. It worked well when the pressure inside the loop was larger than that of atmosphere, however, because of the working principle of the gauge pressure sensor, it failed to provide the correct readings if the pressure inside the loop was less than atmospheric pressure. Eventually two absolute pressure sensors (Omega PXM209) with 0～2.50 bar measurement range and 0.25% full scale accuracy were selected. The differential pressure is obtained from the subtraction of two individual absolute pressure sensors. The front-end interface of the pressure sensor is intrusive but non-invasive with fluids. The schematic of the experimental sensors is shown in Fig. 2 below. Wire-mesh sensor, ERT sensor and electromagnetic flowmeter (EMF) are installed along the vertical Perspex pipe with 500 mm inner diameter. Two absolute pressure sensors are 600 mm apart.

Before dynamic experiment, the pressure sensors were calibrated against atmospheric pressure and static water head to eliminate the systemic error. After each water flow had been established steadily in the flow loop, reference measurement concurrently was taken for ERT and WMS. The pressure readings were sampled via a data acquisition system with 16 bits resolution of analogue to digital conversion. Upon completion of measurement taken for reference, the flow rate of water was kept constant while air was introduced at different flow rates controlled via the gas mass flow rate controller. Once the air flow rate was stable, ERT, WMS and pressure readings were taken concurrently for 10 s to get the mean value. The experiment procedures were repeated for different flow conditions.

While the above process was running, readings were also taken for water flow rate via the turbine flow meter, air flow rate via the mass flow meter and water velocity via the electromagnetic flow meter (EMF). The fluid temperature was monitored throughout the whole process. Once all the data had been downloaded, numerical correlations shown in the next section were conducted on the data to estimate the air volumetric void fraction.

3. Differential pressure correlation for void fraction

The correlation of differential pressure and void fraction is based on the classical Bernoulli's principle of energy conservation