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Characterization of flow homogeneity downstream of a slotted orifice plate in a two-phase flow using electrical resistance tomography

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ABSTRACT

Two-phase flows are complex and unpredictable in nature, commonly encountered in a majority of fluid transport systems. The accurate measurement of two-phase flow is critical for a wide range of applications from wet stream to multiphase flows. There are different methods to meter two-phase flow in various industries. One approach is to produce a flow meter that does not require the individual flow components to be separated and measured separately. This goal can be met if a homogenized mixture is produced which can be measured by a standard single phase flow meter. The slotted orifice plate was invented as a flow meter for single phase flows, it is independent upon upstream flow conditions. Slotted orifice plate flow meter's utilization in two-phase flow revealed that it is highly capable of working as a flow conditioner transforming most of the multiphase flow regimes into a fairly uniform mixture. This study measures how the relative homogeneity of an air/water mixture varies downstream of the slotted plate in a horizontal pipe for various upstream conditions including elongated bubble and slug flow regimes using electrical resistance tomography (ERT). According to this study, the optimal location with a maximum homogeneity was determined to be between 1.5 and 2.5 pipe diameters downstream of the slotted orifice plate. This indicates that placing a slotted orifice plate at the obtained distance upstream of another flow meter such as a venturi coupled with a density measuring device like a radiation based densitometer or an electrical impedance device will help in obtaining accurate multiphase flow rate measurement.

1. Introduction

Today, oil and gas, chemical, and aerospace industries are interested in accurate flow metering as well as characterizing the two-phase flows as they have a significant bearing on the cost. Characterizing how different components are distributed in a two-phase flow helps in identifying the flow regime, which is very important as most of the existing flow meters are flow regime dependent. Commercially available flow meters such as orifice plate, venturi meter, turbine meter, coriolis flow meter, etc. are capable of measuring multi-phase flows. These flow meters need the flow to be conditioned and homogenized at the inlet of the flow meter. In order to obtain a homogeneous two-phase flow mixture, a slotted orifice plate as shown in Fig. 1 was developed by Morrison et al. [1]. Slotted orifice plate is similar to a standard orifice plate in its working principle but differs in its design. The slotted orifice plate has rectangular slots arranged in a radial pattern whereas the standard orifice plate has a hole in the center. Hall et al. [2] and Morrison et al. [3] determined the required geometry details of slotted orifice plates to obtain the optimized performance. A slotted orifice plate is specified using beta ratio which is defined as,

$$\beta = \sqrt{\frac{A_{slots}}{A_{pipe}}} \tag{1}$$

where A_{slots} is the area of the slotted region and A_{pipe} is the cross-sectional area of the pipe.

Sparks [4] studied the response characteristics of slotted orifice plate to the standard orifice plate and a V-cone for different liquid-gas flow conditions. From the results, the slotted orifice plate homogenizes the flow better than a standard orifice plate and a V-cone. The slotted orifice plate was independent of the upstream flow condition and created a uniform, turbulent mixing downstream.

Muralidharan [5] compared the performance of slotted orifice plate to standard orifice plate and venturi meter with varying two-phase flow conditions in a horizontal pipe. According to the author, the slotted orifice plate showed better repeatability in

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Nomenclature

A_{slots}	Cross sectional area occupied by slotted region, m^2
A_{pipe}	Cross sectional area of the pipe, m^2
β	Beta ratio of slotted orifice plate
GVF	Gas volume fraction

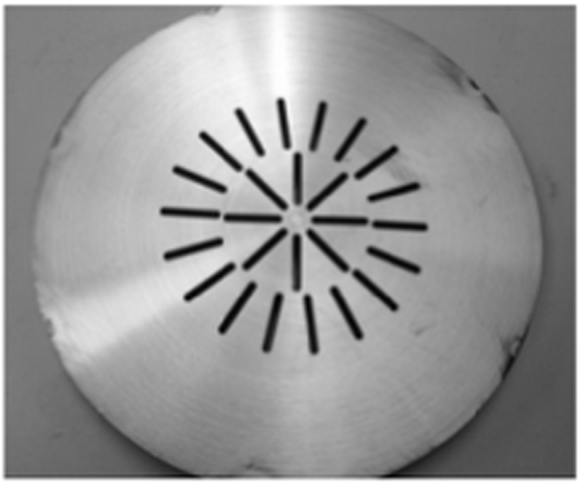

Fig. 1. Slotted Orifice Plat, Morrison et al. [1].

comparison to a standard orifice plate and the performance of the slotted orifice plate was unaffected by the location of the plates. The response of the venturi was unpredictable even though it showed good repeatability. Also the slotted orifice plate had lower differential pressures, lower sensitivity to upstream flow conditions, higher coefficient of discharge values, better consistency, higher accuracy, and better repeatability than the standard orifice plate.

In two phase flow measurements, Hua et al. [6] utilized slotted orifice plate along with swirl flow meter in wet gas measurements for GVF values larger than 99%. The measured gas mass flow rate was reported to have $\pm$6% error among 89.2% of all tested samples. A large distance to diameter ratio (L/D) of 20 between the slotted orifice plate and swirl flow meter was chosen.

In another study, Pirouzpanah et al. [7] implemented a closed couple slotted orifice plate and swirl flow meter for a wider range of GVF from 60% to 95% with $\pm$0.63% uncertainty in GVF measurements. In this work, the authors chose to install the swirl flow meter in distance to diameter ratio of 1 downstream of the plate. The same research group utilized an electrical impedance sensor [8–10] closely coupled to slotted plate to obtain independent measurements for GVF and total mass flow rate in the GVF range from 0% to 100%.

According to these studies, determining the homogenous location downstream of the slotted orifice plate is of great importance in order to increase the accuracy in two phase flow measurements.

The ERT system is useful in determining local void fraction of the dispersed phase which can be used in obtaining the relative flow heterogeneity in a two component flow in different applications by using the conductivity distribution of the flow field [11]. It works for fluids having different conductivities. In this technique, multiple electrodes are flush mounted circumferentially around the boundary of the flow. An electrical contact is established between the electrodes and the flow which measures instantaneous conductivity distribution across the circumferential plane. Maxwell's equation is used to convert conductivity distribution into concentration or void fraction.

Razak et al. [12] used ERT system to study phase hold up and individual phase velocities in a liquid-solid flow. An optical fiber was also used to compare the results from an ERT system.

Bolton et al. [13] used an ERT system in a radial flow fixed bed reactor to visualize flow component distribution. The images from the experiments were used for validation of the CFD simulations.

Deng et al. [14] employed an ERT system coupled with an electromagnetic flow meter to measure two phase flow conditions. An ERT system was used to identify the flow regime and void fraction whereas the electromagnetic flow meter was used to measure the average flow velocity.

Jin et al. [15] performed experiments to determine gas hold up in gas-liquid flows using an ERT system and a differential pressure method. The results from both the measurements are similar.

In another work, Jia et al. [16] used ERT and Wire-mesh sensor measurements as the benchmark to obtain void fraction in order to correlate the differential pressure measurement values to void fraction and derive a model.

Triplett et al. [17] performed two phase flow measurements in micro channels using an ERT system. According to the author for bubble and slug flow regimes the homogenous mixture model predicts void fraction distribution comparable to ERT measurements. For annual flow, the model over predicts the void fraction.

Olerni et al. [18] used an ERT system to determine the volumetric void fraction of the dispersed phase (air) on each pixel in a two-phase flow using the Maxwell's equation. The Maxwell's equation took into account the non-miscible phases and thus the overall air void fraction was deduced from the average of the pixel void fraction. The experiment was conducted in bubble flow and slug flow regime in the GVF range of 10%–60%.

Jia et al. [19] investigated the capability of Maxwell's relationship to convey full void fraction using the Electrical Impedance Tomography (EIT) system. It was determined that the EIT system was in good agreement with the reference void fractions over the range from 0 to 1.

Jin et al. [15] presented ERT experiments on an air-water bubble column. From the ERT data, the local conductivity can be reconstructed and once these values are known, the local void fraction follows from Maxwell's equation for the conductivity of the mixture. The reconstructed void fraction from the tomography method was more accurate than the values obtained from the pressure drop measurements.

In the current study, an ERT system is used to determine the relative homogenous location downstream of a slotted orifice plate in a horizontal pipe for different two phase flow conditions. Electrodes were placed circumferentially around the pipe at 8 different planes along the pipe to measure the instantaneous localized concentration distribution across each plane. The effect of upstream flow conditions on the slotted orifice plate is also discussed. The possibility of metering errors because of non-homogenous flow condition is also analyzed. The horizontal pipe was selected since the homogeneity of the flow varies rapidly in the downstream direction due to the effects of gravity. For a vertical pipe, the rate of change is much slower.

2. Experimental setup

The flow loop for this experiment is shown in Fig. 2. Air is supplied by a compressor having an outlet pressure of 760 kPa. Water is supplied by a centrifugal pump from a 19 m^3 tank. Turbine flow meters are used to measure the liquid and gas flow rates

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