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Experimental study of vertical and horizontal two-phase pipe flow through double 90 degree elbows

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ABSTRACT

This paper presents an experimental study of the characteristics of the two-phase flow through vertical and horizontal pipes connected using 90-degree elbows with an inner diameter of 101.6 mm. 66 flow conditions are performed in this experiment, covering bubbly, plug, slug, pseudo slug, and stratified flow for horizontal pipe, and bubbly, cap bubbly, churn turbulent, and falling film/annular flow for vertical pipe. A detailed flow regime analysis for both horizontal and vertical pipe flow are discussed. Flow regime maps for both horizontal flow and vertical downward flow agree with the existing maps (Mandhane et al., 1974; Qiao et al., 2017). The effect of the elbow on the flow regime transition is primarily discussed based on the experimental results and observations. The effect of elbow observed in this experiment mainly contributes to the large bubble breakup and the change of void distribution. Area averaged void fraction development is presented and the sharp drop of void fraction in vertical downward test section is observed which results from kinematic shock phenomenon. A frictional pressure drop analysis is also studied using Lockhart-Martinelli correlation and it is found that $C = 40$, 100, and 125 are correlated with the frictional pressure drop data for horizontal, vertical, and whole test sections with minimum differences. With the database, the drift flux model for vertical downward flow (Goda et al., 2003) is validated and the relative difference between model and data is 15.95%.

1. Introduction

Two-phase flows traveling through elbows to change flow direction is commonly seen in industrial applications. The change of the two-phase flow characteristics when flow passes through elbows is crucial to safety analysis, especially for flow with a vertical direction angle change. Many studies have been done on the two-phase flow characteristics for either vertical or horizontal flow channel. The flow patterns for horizontal and vertical flow have been well studied in both experimental and theoretical approaches. The most commonly referred flow regime map for horizontal flow channel is developed by Mandhane et al. [1] using a large experimental database. Taitel and Dukler [2] developed their flow regime map through theoretical modeling. For vertically downward flow, Goda et al. [3] investigated the air-water flow characteristics in 25.4 mm and 50.8 mm round pipes and developed a flow regime map for these flow geometries. Usui [4] also developed a vertical downward flow regime map using theories and the experimental data taken from 16-mm and a 24-mm inverted U-bend test sections. However, some of these criteria of flow regime transition can be inappropriate when being applied to large diameter vertically downward flow. With the development of high speed video camera and advanced instrumentations, two-phase flows can be clearly visualized and accurately measured. Experimental flow regime analysis based on the method of visualization or continuous signals is gradually dominant [5–8]. However, the mentioned flow regime analysis work was studied with either horizontal or vertical flow. Many differences exist between single vertical or horizontal pipe flow and industrial piping systems, such as the two-phase injecting methods and the effect of elbows. Additional study is needed for the characteristics of flow regime change and transition when flow direction changes in piping systems.

Several valued studies have been performed on characteristics of the two-phase flow through elbow in the past years. Kim studied and performed a series of experiments on two-phase flow pressure drops and interfacial structures through different types of elbows [9–11], yet his experiment only focused on bubbly flow with high liquid flow rates. Spedding et al. [12] experimentally investigated the pressure drop through a vertical to horizontal 90-degree elbow in a 26 mm ID pipe. Liu et al. [13] conducted an experimental study

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Nomenclature

C	constant of Lockhart-Martinelli correlation [–]
C_0	distribution parameter [–]
D	diameter [m]
f	frictional factor [–]
j	mixture volumetric flux [m/s]
L	length [m]
N	non-dimensional number [–]
p	pressure [Pa]
t	time [s]
v	velocity [m/s]
V_{gj}	drift velocity [m/s]
X	martinelli parameter [–]
z	axial location [m]

Greek characters

α	void fraction [–]
Φ^2	two-phase frictional multiplier [–]
ρ	density [kg/m^3]
μ	dynamic viscosity [Pa·s]

Sub/superscripts

f	quantity for liquid phase
g	quantity for gas phase

Mathematical symbols

$\langle\ \rangle$	area-averaged quantity
$\langle\langle\ \rangle\rangle$	void fraction weighted-mean quantity

on the two-phase flow induced fluctuating force on a 90-degree elbow. However, almost all the experiments performed are either horizontal to upward vertical flow or vertical upward to horizontal flow.

In order to analyze and model the characteristics of vertical and horizontal two-phase flows traveling through elbow, an experiment is performed to investigate the characteristics of two phase flow with the change of flow direction and the effect of elbow. Flow regime maps are developed based on an unsupervised artificial neural network and flow visualization. The evolution of the two-phase flow parameters including the void fraction and the pressure drop are presented and discussed. The experimental data is also used for the drift flux model validation. This experiment aims to establish a reliable two-phase flow database with both horizontal and vertical flow exist in the experiment.

2. Experimental setup

The experiment is performed adiabatically using the air-water in a 101.6 mm ID stainless steel pipe test facility. The schematics is shown in Fig. 1. The whole test facility is made of stainless steel except for the view ports, which are made of transparent plastics and glass, providing clear views of the flow along the flow channel. The total length for the test section is $z/D = 136.32$, consisting of top horizontal part (z/D from 0 to 63.78), vertical downward part (z/D from 63.78 to 105.02), and bottom horizontal part (z/D from 105.02 to 136.32). Two 90-degree standard elbows with $r/D = 1.5$ are used to connect the 3 parts. The liquid flow rate is measured using magnetic flow meter and the gas flow rate is measured either by rotameters in a low gas flow rate or Venturi meters in a high gas flow rate. 7 ring-typed impedance void meters are used for the area averaged void fraction measurement with an uncertainty less than 10%. The design of the impedance meter is shown in Fig. 2. They are installed as denoted in Fig. 1 from RIMP1 to RIMP7. With 2 impedance meters ($z/D = 44.50$ and 55.25) located at the top horizontal section, 3 measurements ($z/D = 72.88$, 85.63, and 102.63) located at the vertical section, and 2 measurements ($z/D = 114.75$ and 121.25) located at the bottom horizontal section, all the void fractions along the test facility are measured. In addition, 6 view ports are located along the test sections for flow visualization, marked in Fig. 1. The locations of the 7 pressure taps for local pressure measurement using the pressure transducer (uncertainty is 0.0375% of the range, 40 kPa in the vertical section and 10 kPa in the horizontal section) are also shown in the figure.

The structure of the gas inlet injector is given in Fig. 3. A 25.4 mm standard pipe instead of a sparger is utilized as a gas inlet connecting the compressed air through a blind flange. The gas injector is installed on a standard tee fitting. The pipeline is 25 mm offset from the centerline of the top horizontal test section. This design originally aims to produce separated flow at the top horizontal part to investigate the gas transport through the elbow for separated flow and sweeping phenomena. By injecting the air into the upper side of the pipe, the developing distance that two phases separated due to gravitational force is reduced.

66 flow conditions are taken in this experiment and refer to the flow regime map in the following section. In this paper, both flow regime analysis and the measurement results including void fraction and pressure will be presented.

3. Results and discussions

The discussions of the experiment results consist of three parts: flow regime identification, void fraction, and pressure drop.

3.1. Flow regime identification

The flow regime identification methods in this study including visualization and unsupervised artificial neural network [15,16]. In the current approach, the probability density function of the impedance probe signal is supplied as input to a Kohonen self-organizing neural network, also called the self-organizing map (SOM), for identifying the patterns. Fig. 4 shows a schematic of the Kohonen neural network. The basic concept behind the SOM is the preservation of topology (i.e., the relation among data). The SOM is a two-layer network that can cluster input data into several categories that include similar objects detected in the input data. The input data is fed to the network as a collection of vectors. The weighting factors on the branches of the neural network form vectors which have the same dimensionality as that of the input vectors. The number of weight vectors is the same as the number of output neurons. The Kohonen network algorithm adaptively minimizes the distance between these vectors and the input data vectors, thereby aligning the weight vectors with the intrinsic clusters in the data, if such clusters exist. Thus, the weight vectors corresponding to each cluster characterize each cluster and hence classify the input data. The classified results of the network show inherent relations among the patterns that are the features of the input data. Any number of inputs may be used if that number is greater than the number of the dimensionality of the vector space. The SOM is trained through unsupervised competitive learning using a “winner takes all” policy. The number of the categories or outputs is subjectively specified primarily by visualization.

Local flow regimes are identified and compared with former experimental study. Flow regimes at the measurement location