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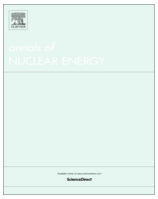

Effect of diameter and axial location on upward gas–liquid two-phase flow patterns in intermediate-scale vertical tubes

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ABSTRACT

In the present research, a two-phase flow system is designed, manufactured, assembled and adjusted to study two-phase flow behavior isothermally. Test sections are tubes standing in vertical position and are made of transparent acrylic with inner diameters of 40 mm and 70 mm. Two axial locations of 1.73 m and 3.22 m are chosen for data acquisition. Flow pattern maps are presented for both tubes. Effects of tube diameter and axial location on pattern transition boundaries are investigated. Air and water are chosen as working fluids. The range of air and water superficial velocities are 0.054–9.654 m/s and 0.015–0.877 m/s for the 40 mm diameter tube, but these values are 0.038–20.44 m/s and 0.036–1.530 m/s for 70 mm diameter tube. The results show that for both tubes, increasing axial location does not affect flow transition boundaries significantly. However, slug pattern region shrinks considerably by changing tube diameter from 40 mm to 70 mm. Using image processing techniques, recorded high speed movies were investigated accurately. As a result, bubbly flow in the 40 mm tube can be divided into three sub-patterns as dispersed, agitated and agglomerated bubbly. Also, two types of slug pattern are also recognized in the same tube diameter which are called small and large slugs. Semi-annular flow is observed as an independent pattern in the 70 mm tube that does not behave as known churn or annular patterns.

1. Introduction

Systems including two-phase gas-liquid flows are widely used in various industries such as petrochemistry and power plants. These flows can also exist in pipelines or risers and may cause damage or improve working conditions. For instance in slug or churn flow pattern, great pressure fluctuations can damage equipment or halt fluid flow in pipelines. On the other hand, a two-phase airlift pump can transfer oil up to desired height without any electrical motors as Samaras and Margaris (2005) described. So, one needs to predict and control flow of fluids to prepare safe working conditions for systems. In a common view, two-phase flows can flow in several topological structures that are so called flow patterns or flow regimes (Brennen, 2003).

Transition from one pattern to another is a gradual process that depends strongly on geometrical and physical parameters of flow. In other words, there is a mutual coupling between phases and flow geometry that add a lot of complexity to two-phase flow equations (Prosperetti and Tryggvason, 2007). So identification of flow patterns and distinguishing the transition conditions between them are the issues that many two-phase flow researchers are enthusiastic to study (Ansari et al., 2013; Azadi et al., 2014).

Totally, flow pattern recognition studies of two-phase flows, can be grouped as theoretical, visual and non-visual methods. In theoretical methods, researchers try to present relations based on physical characteristics of flow such as density and void fraction. Taitel et al. (1980) and Kaichiro and Ishii (1984) presented such relations for pattern transitions in vertical upward tubes, which are comparison basis for many newly published studies.

Visual observation is another way of flow pattern recognition which is totally based on utilization of high speed cameras and image processing techniques. The effect of geometrical or physical properties of two-phase flows on flow pattern structures, can be investigated visually. Cheng et al. (1998) studied the effect of diameter size on two-phase gas–liquid flow in vertical tubes with inner diameters of 28.9 mm and 150 mm. They reported that slug flow is observed in the small tube, but such a pattern does not appear in the 150 mm tube. Chen et al. (2006) studied upward two-phase flow of R134 in four mini pipes and found that the transition regions of slug-churn and churn-annular, strongly depend on tube diameter. But transition boundaries for bubbly to churn and bubbly to slug are slightly affected by change in diameter size. Furukawa and Fukano (2001) studied the effect of viscosity on transition regions between flow patterns in vertical tubes with

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inner diameters of 19.2 mm and height of 5.4 m. Water and aqueous glycerol solutions with viscosities of 1×10^{-6} up to $14.7 \times 10^{-6}\ \mathrm{m^2/s}$ were used as working fluids. They found that increasing liquid viscosity shifts the bubbly-slug transition boundary to lower air superficial velocities and the froth-annular transition boundary to regions of higher air superficial velocities. Mydlarz-Gabryk et al. (2014) studied air–petroleum two-phase flow in a vertical tube with inner diameter of 30 mm. They investigated recorded movies by high speed camera and identified three different flow patterns as petroleum dominant, transition and water dominant regions and finally presented flow pattern maps for their experimental results. Liu et al. (2014) investigated the effect of surfactants on variables such as void fraction, pressure drop and drag force in a tube with inner diameter of 40 mm and height of 5.6 m. They observed bubbly, slug, churn and misty annular flow patterns. Maximum drop in void fraction due to surfactants is reported 88.6% in slug flow. Hanafizadeh et al. (2011) studied flow characteristics on the upriser part of an airlift pump with inner diameter of 50 mm and height of 6 m. These researchers introduced six different flow patterns that they called bubbly, bubbly-slug, small slug, large slug, churn and annular. Based on obtained results, they found the slug pattern as the most appropriate regime for their designed two-phase air-lift pump. Liu (2014) introduced negative pressure drop as a new phenomenon in two-phase flows in vertical tubes. By uncertainty analysis, he showed that negative pressure drop cannot be due to measurement error. He showed that there exists a term like the buoyancy force term that by considering it, resultant energy loss for his experiments becomes positive while frictional losses are negative, so energy conservation is conserved. Venkatesan et al. (2011) investigated the effect of tube diameter on pressure drop in vertical tubes with inner diameter less than 3.4 mm. They proposed several correlations to estimate frictional pressure drop which work well for their experimental results.

Statistical parameters of pressure (Matsui, 1986), chord length (Juliá et al., 2008) or void fraction (Azzopardi et al., 2015) distributions can be used to identify flow patterns by non-visual techniques. To identify the flow patterns, Ghanbarzadeh et al. (2012) utilized a fuzzy interface method which uses the extracted information from images captured from the flow patterns such as number or area of bubbles. They fed the ANFIS (Adaptive Neuro Fuzzy) input using the extracted textural features of the images to identify the flow patterns based on these features. Shaban and Tavoularis (2014) presented a new flow classification method based on elastic maps. They claimed that differential pressure probability density function is a strong and reliable indicator of flow regime, and it is also insensitive to pipe size and absolute pressure, within common ranges of interest.

As mentioned above, distributions of physical properties of two-phase flows can be used to identify flow patterns; to achieve this, different measuring instruments are used. Lucas et al. (2005) studied development of flow patterns in a vertical tube of inner diameter 51.2 mm. They used a wire-mesh sensor to acquire a rich time-dependent database of void fractions in several cross sections. These researchers found that direction of lift force changes according to bubble size in dispersed bubbly flow. Abdulkadir et al. (2014) performed an accurate study on phase distributions in vertical tubes using a wire mesh sensor. They presented an acceptable pattern classification by using statistical characteristics of distributions. Tian et al. (2014) studied upward and downward vertical flow in a tube with inner diameter of 50.8 mm using a four-sensor optical probe. According to their results, void fraction in low flow rates for downward flow, shows core peak distribution, but for these flow rates, distributions are wall peak in upward flow. Zhao et al. (2013) presented an optimized method to extract flow parameters by using and analyzing gamma ray intensity. They used a transparent acrylic tube with inner diameter of 20 mm and height of 2.8 m. These researchers focused on three main flow patterns in vertical tubes: bubbly, slug and annular and distinguished these patterns by analyzing wave amplitudes of gamma densitometer.

Definition of scale for tubes, mainly depends on physical properties of flow. According to Taitel et al. (1980), tubes satisfying the following equation are called *small scale* tubes.

$$D \leqslant \frac{19}{\rho_L}\sqrt{\frac{\sigma(\rho_L - \rho_G)}{g}} \tag{1}$$

In Eq. (1), D is tube inner diameter, σ is surface tension coefficient between phases, g is gravitational acceleration, ρ_L and ρ_G are densities of liquid and gas phases, respectively. For water as liquid phase and air as gas phase at ambient conditions, the criteria becomes $D \leqslant 5.15$ cm. In other words, tubes with inner diameters less than 50 mm are grouped as small tubes, and tubes with diameters equal or more than 50 mm are categorized as large tubes.

Isao and Mamoru (1987) state that Taylor bubbles do not exist for tubes with diameters more than specified values, which are observed in small tubes. They believe this is due to Taylor bubble instability. When Taylor bubbles reach the critical diameter, no liquid slug can be created between consecutive Taylor bubbles. Thus, cap-bubbles with different diameters will be observed. Taylor instability causes large Taylor bubbles to collapse, so this critical diameter is defined based on Taylor wave length as below:

$$D_H^* \equiv \frac{D_H}{\sqrt{\frac{\sigma}{g\Delta\rho}}} \geqslant 40 \tag{2}$$

where D_H is hydraulic diameter, D_H^* is dimensionless diameter and $\Delta\rho$ is density difference between phases. For air and water at ambient conditions, the criteria becomes $D_H \leqslant 10.86$ cm. In other words, according to Eq. (2), for tubes with diameters larger than 108 mm, no Taylor bubbles will be observed. So, tubes can be categorized based on their diameter size as: 1 – small tubes ($D \leqslant 50$ mm), 2 – intermediate tubes (50 mm $\leqslant D \leqslant$ 108 mm) and 3 – large tubes ($D > 108$ mm).

Reviewing previous research articles in different vertical systems, shows that a slight change in effective parameters such as diameter, axial location, cross section or inlet type has a significant effect on flow patterns and transition regions between them. Most previous studies have focused on small scale tubes, and the effect of diameter on intermediate tubes is rarely studied. Thus, in the present research, air–water two-phase flow is studied on two tubes with different intermediate diameters.

The main purpose of this study is to investigate the effect of tube diameter and axial location on distribution of flow patterns for two tubes of intermediate diameters. Flow pattern maps are presented and transition boundaries are compared. Also, image processing techniques are used to group flow patterns into more detailed sub-patterns. These classifications are rarely mentioned in the literature.

2. Experimental set-up

The piping and instrumental diagram of the experimental set-up is shown in Fig. 1. This test rig is designed to operate as a multi-functional system in a way that one can change air and water path lines easily to have co-current, counter-current, upward or downward flows in pipes of different diameters.

Air is supplied to the system by a 45 kW compressor with maximum flow rate of 1400 $\mathrm{m^3/h}$. The outlet of the air tank is adjusted by a pressure regulator to supply the required air pressure. To satisfy the isothermal condition for the air–water interface, air