International Journal of Multiphase Flow 000 (2018) 1–15

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Experimental and numerical evaluation of slugs in a vertical air–water flow

J. Jaeger[a], C.M. Santos[a], L.M. Rosa[a], H.F. Meier[a], D. Noriler[b,*]

[a] University of Blumenau (FURB), 3250 Rua São Paulo, Blumenau, SC 89030-000, Brazil
[b] University of Campinas (UNICAMP), School of Chemical Engineering, P.O. Box 6066, 500 Rua Albert Einstein, Campinas, SP 13083-852, Brazil

A R T I C L E I N F O

Article history:
Received 2 February 2017
Revised 11 October 2017
Accepted 6 January 2018
Available online xxx

Keywords:
Slug flow regime
Air–water flow
Computational fluid dynamics
Volume of Fluid
Discretization schemes

A B S T R A C T

Multiphase flows are often present in chemical processes and they include gas-liquid transport, which may become intermittent depending on the operating conditions. One type of flow structure is the presence of large gas bubbles that can occupy the entire duct diameter, separated by liquid portions. This can result in large pressure fluctuations, which are normally associated with damage to equipment over time. The intermittent nature and the chaotic distribution of the phases in a turbulent flow complicate the design and optimization of the equipment. In this context, computational fluid dynamics is a useful technique since it can provide important information on several flow conditions, but the use of suitable models and boundary conditions is required. In this study, an air and water flow with the presence of slugs is evaluated in a system consisting of horizontal and vertical ducts, with an inner diameter of 94 mm. Experimental data on the pressure and void fraction were analyzed and compared to the predictions obtained from numerical simulations, obtained considering the VOF approach. It was observed that the use of the geometrical reconstruction scheme to simulate a compressible flow resulted in a better agreement with the experimental results. Using this setup, the average volume fraction and pressure values showed the expected behavior. The frequency of slugs, established using three different methods, was around 1.5 Hz for the evaluated conditions evaluated. The pressure probability density function (PDF) indicated good agreement between numerical simulations and experimental data, while the volume fraction PDF indicated that the flows evaluated have the characteristics of a churn flow regime. Moreover, it was found that an increase in the water flow rate can lead an increase or a decrease in the average velocity.

1. Introduction

Gas-liquid flow in ducts can occur in different regimes, such as bubbly, slug, churn and annular flows, and the development of these regimes depends on the flow rates, fluids properties and geometry (Shao et al., 2009). Details regarding the characteristics of each flow regime can be found in the literature (Abdulmouti, 2014). These flow regimes occur within a wide range of flow rates and can often be found in industrial application, for instance, exploitation of oil and natural gas, airlifts, nuclear reactors and membrane separation processes (Ahmad et al., 1998; Gao et al., 2016).

The occurrence of slugs in flows is an issue that must be taken into account in the design and operation of a unit, because it leads to an unstable flow, with long periods without gas or liquid feed. Furthermore, the liquid portions move at high speed relative to the average flow, which can cause vibration, erosion, and even ruptures (Thaker and Banerjee, 2015).

Equipment design requires a knowledge of the flow characteristics, such as the length and frequency of slugs and the pressure drop, which in turn are a function of the volume fraction of the phases (Abdulkadir et al., 2014). The volume fraction is an important variable in flows with slugs and it is used in the estimation of the pressure drop and heat transfer (Zheng and Che, 2006). The volume fraction is affected by the gas and liquid flow rates, fluid properties and flow gradient (Andreussi and Bendiksen, 1989; Tony et al., 1995). For its prediction, several empirical models have been developed. Vertical flows with slugs are affected by several variables. The Taylor bubble length, the volume fraction, the pressure drop and the mass transfer coefficient near the wall increase with the air flow rate and decrease with the liquid flow rate (Zheng and Che, 2006). Conversely, the frequency of slugs increases with the liquid flow rate.

* Corresponding author.
E-mail address: dnoriler@feq.unicamp.br (D. Noriler).

https://doi.org/10.1016/j.ijmultiphaseflow.2018.01.009

Nowadays, fluid dynamics simulations are used in order to obtain these data. However, experimental data obtained from controlled experiments in laboratories are still needed to validate the mathematical models used in simulations. In a study described in the literature (Taha and Cui, 2006) the VOF approach was used in conjunction with the Geometric Reconstruction scheme to predict the flow behavior of a Taylor bubble in a vertical pipe. Simulations were performed with the Fluent software to estimate features such as bubble size, liquid film thickness and wake patterns created by the passage of the bubble, and the influence of changes in the flow and the fluid properties on these characteristics was investigated. It was concluded that the bubble shape was dependent on the liquid viscosity and surface tension but not on the bubble size. Predicted results for a horizontal duct with the generation and development of slugs showed, qualitatively, similarities with experimental data (Razavi and Namin, 2011). These simulations also considered the VOF model with the Geometric Reconstruction scheme in a quasi-3D geometry.

The shape of Taylor bubbles becomes more complex as the pipe diameter increases. As a consequence, the slug flow regime does not appear to occur for diameters greater than 100 mm (Sharaf et al., 2016). In larger diameters, as commonly found in industry, there is a gradual transition from the slug flow to the churn flow regime. Thus, smaller diameters are considered in most studies available in the literature (Abdulkadir et al., 2014; Araújo et al., 2013; Costigan and Whalley, 1997; Rosa and Souza, 2015; Waltrich et al., 2013).

This study was aimed at finding a numerical model to represent the presence of slugs in a concurrent flow of air and water in a system with horizontal and vertical ducts with relatively large diameters. Experimental pressure and volume fraction data were obtained for four different flow rates and compared to the corresponding results obtained from the CFD simulations using the VOF model. The frequency of slugs was analyzed, and the flow characteristics were evaluated in detail, providing information regarding the flow regime. This study provides fluid dynamics data on air–water flows in the presence of slugs, measured in a duct with an uncommon diameter. In addition, a methodology for the treatment of these data and a comparison with experimental results are described.

2. Materials and methods

2.1. Experimental unit

An experimental unit was designed to assess the two-phase flow and acquire experimental data (Fig. 1). This unit was composed of vertical and horizontal sections (8), pressure and flow meters (2 and 4), a feed mixer (3), a reservoir (6), a pump (5) and a compressor (1).

Water from a municipal water treatment system and atmospheric air were used as process fluids. The unit operation was initiated when water was fed by a centrifugal pump (BTM-30, Bombetec) coupled to a 2 CV engine (WEG), while the air was supplied by a radial compressor (model CJ4, Ibram) coupled to a 4 CV engine (WEG). Both phases were directed to the horizontal and vertical pipes, composed of ducts with an internal diameter of 94 mm. The data acquisition section was composed of a vertical plexiglass duct with 3.3 m of height, in which the analyzes were carried out, followed by a horizontal and then another vertical section, with lengths of 1 m and 2.5 m, respectively. With the height of 3.3 m, the flow does not reach the developed region. A higher height is needed for this aim, which we could not properly evaluate in our facility. However, the phenomenological approach considered in this study is able to predict even the complex behavior of developing regions.

The pressure data were acquired using the following pressure transmitters, distributed in the vertical duct of the experimental unit:

- a differential transmitter (TPS-1BP, Samrello), with a measuring range of 0–2 kPa and maximum static pressure of 30 kPa;
- a differential transmitter (RTP-420-DIF, Rücken), with a measuring range of 0–20 kPa and maximum static pressure of 200 kPa;
- a manometric transmitter (GTP-1000, Samrello), with a measuring range of 0–2500 kPa;
- a manometric transmitter (RTP-420, Rücken), with a measuring range of 0–20 kPa.

These sensors generate a linear signal output from 4 to 20 mA, which is sent to the acquisition card (USB-6000, National Instruments). This card performs the electrical signal conversion into values for the pressure, acquired at a frequency of 1 kHz.

2.2. Experimental methods

Two average flow rates were defined for each phase, in order to evaluate the influence of the air and water flow rates on the slug behavior. The flow rates required in order to develop the slug flow regime were established and were limited according to the capacity of the experimental unit. Thus, four cases were defined and their operating conditions are detailed in Fig. 2.

Each experiment was performed in two stages. Firstly, the gauge pressure was collected at all measurement points of the ascending duct. The differential pressures were then measured. These values were needed to determine the volume fraction, using an inexpensive and non-intrusive method for flows with bubbles and slugs in vertical ducts (Jia et al., 2015; Lin and Hanratty, 1987). In this method, the mean volume fraction α is obtained from the energy balance, using the differential pressure measurements in the Bernoulli expression (Eq. (1)).

$$\alpha = \frac{\Delta P - (\rho_{water}\ \mathbf{g}\ \Delta h)}{(\rho_{air} - \rho_{water})\ \mathbf{g}\ \Delta h} \tag{1}$$

where ΔP is the pressure difference, ρ is the density, $\mathbf{g}$ is the gravitational acceleration, and Δh is the distance between the differential pressure sensors.

After the activation of the pump and the compressor, the flow was established after one minute, reaching a quasi steady-state. Data acquisition from the pressure sensors was carried out for 2 min. The unit was then turned off to install the manometer at a different height. The temperature was maintained at 20 °C during the experiments, which were performed in quadruplicate in order to ensure the meaningfulness of the acquired data. Also, the pressure measurements were taken in a random heights sequence to minimize the occurrence of systematic errors.

The frequency of slug occurrence was assessed by three different methods in all cases. The first method consisted of visually counting the number of slugs that passed through a region of the equipment during certain time interval. Three counts were carried out for each case and each count lasted 2 min. This ensured that a representative number of slugs were counted. However, this method has inaccuracies associated with the difficulty involved in identifying slugs at certain times, when there are a large number of bubbles, which influenced the results.

In the second method, a code was developed to analyze the pressure data collected at different times during the experiment and a list containing the local maxima of the pressure values acquired was compiled. Since the pressure signals of the flow undergo large oscillations during the passage of a slug, the number of pressure oscillations represents the number of slugs flowing through the sensors. It was assumed that the amount of slugs remains the same at different heights. Thus, the average frequency