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Experimental study of the characteristics of an upward two-phase slug flow in a vertical pipe

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ABSTRACT

Characteristics of the slug flow, mean void fraction, liquid slug and Taylor bubble lengths; and structure frequency were all extracted from the void fraction time series. Average void fractions at nine axial positions have been measured on a 6 m long (and 34 mm diameter) pipe test section by using conductance probes.

For the flow conditions used, bubbly (with spherical cap bubble), slug/plug and churn/semi-annular flow patterns were observed. These observations were also confirmed by using statistical numbers.

Time series analysis of the mean void fraction and its corresponding PDFs show that the effect of the mixer on the flow becomes, practically, negligible from a distance of 95 pipe diameter.

It was found that, generally, the structure velocity can be well predicted from other available correlations in the literature.

The theoretical model of Brauner and Ullmann was used to estimate the liquid in slug void fraction. It was inferred that this model is able to predict well the liquid slug void fraction; thus, it can be considered as one of the useful methods for predicting such parameter and to ascertain slug flow regime.

The total pressure gradient was found to decrease with increasing gas superficial velocity.

1. Introduction

Flows of gas-liquid mixtures are frequently encountered such as in chemical, petroleum and energy production industries.

In vertical flow, several flow patterns are observed and can be classified according to the increase in the gas superficial velocity into; bubbly, slug, churn and annular flow. Depending on the flowrates, properties of each phase, as well as pipe's size (diameter and length), one of these flow patterns, may take place. Among these flow patterns, slug flow is widely encountered. In the nuclear industry, for example, an understanding of slug flow structure, as well as its dynamic behavior, is very important for an optimal and safe design of the process equipment such as reactor vessel. Such vessels can be exposed to periodical impacts caused by intermittent slugs which might lead to unsafe operational conditions. In addition, water used as cooling fluid in nuclear reaction applications can exceed the boiling point when the temperature of the core of a Boiling Water Reactor (BWR) reaches high values; this leads to the coexistence of a steam/water mixture.

In heat exchanging power/processing systems, operating temperature during transient scenario can be much lower than the steady operating condition. As a result, void fraction tends to be lower than designed value which may result in the occurrence of slug or churn flow regime (Miwa et al., 2015).

Mi et al. (2001), also studies the transient situations in the nuclear reactor and mentioned that this can cause the appearance of the slug flow during which the velocity of the slug units varies considerably.

In nuclear reactors, the pressure drop is also one of the phenomena which can, significantly, affect the safety of nuclear reactors. Huang et al. (2005) reported that the Loss of Coolant Accidents (LOCA) are mainly due to small crevasses created in the reactor's wall.

In addition, the degradation and the diminution of the pipe wall thickness caused by the corrosion/erosion are due to the existence of the intermittent flow-regimes, namely slug and plug flows (Thaker and Banerjee, 2016). The authors insisted on the necessity to tackle deeply all aspects related to intermittent regimes in order to increase the safety of the nuclear reactor.

The existence of the slug flow in nuclear reactors was also studied by Wang et al. (2015). The authors investigated the slug flow regime in narrow rectangular channels as an application for nuclear reactors with plate type fuels. They determined velocities, lengths, and frequencies of the Taylors bubbles and slug units.

Miwa et al. (2015) focused on the induced vibration by phase

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changing (boiling or condensation in boiling water reactors or pressurized water reactors), to insure a safe conception and avoid structural damage due to the interaction of fluids and solids. The authors also noted that the forces acting on the structure, when the two slug unites (liquid slugs and Taylor bubbles) passes through U-tube regions, fluctuate considerably causing the vibration of the structure, and major failure.

Slug flow clearly exhibits periodic structure which composed of a gas bubble (surrounded by a thin liquid film) often called Taylor bubble, that occupies almost the entire cross-sectional pipe area.

Since the early studies of Dumitrescu (1943) and Davies and Taylor (1950) a great work theoretically, experimentally and numerically has been performed to analyze and characterize such complex flow. In general, the dynamic behavior of the slug flow can be characterized by five main parameters such as (i) gas volume fraction, (ii) Taylor bubble's velocity, (iii) Taylor-bubble's and liquid-slug's lengths, (iv) frequency of the Taylor bubble and (v) the thin oscillating liquid film which can be deduced from the void fraction data.

In fully developed slug flow, the velocity, u_g, of the Taylor bubble can be expressed as;

$$u_g = C_0\{u_{ls} + u_{gs}\} + 0.35\sqrt{gD} \tag{1}$$

Where u_{ls} and u_{gs} are respectively liquid and gas superficial velocities, g is the gravitational-acceleration, D is the diameter of the tube and C_0 is the constant, for turbulent flow its value is 1.2.

The velocity of a small bubble in slug flow is given by;

$$u_{g,small} = C_0\{u_{gs} + u_{ls}\} + C_1\left[\frac{(\rho_l - \rho_g)\sigma g}{\rho_l^2}\right]^{0.25}[1 - \varepsilon_g]^m \tag{2}$$

where ε_g is the mean void fraction, ρ is the density (l and g refer to liquid and gas respectively) and σ is the surface tension.

Taitel et al. (1980) found that (when $C_0 = 1.2, C_1 = 1.53, m = 0$) and for small diameter pipe ($D < 0.05$ m), small bubbles moved faster than Taylor bubbles so that the bubbles in liquid slug could be absorbed by the proceeding Taylor-bubble, making the liquid slug region free of bubbles. This in turns creates non-aerated-flow when Bond number, Bo (a dimensionless number defined as; $D^2 g[\rho_l - \rho_g]/\sigma$) is less than 361.

Sylvester (1987) reported that the void fraction in the wake region (i.e.in the liquid slug) can be varied from 0 to about 0.8. Three different regions in two-phase slug flow were identified by Mori et al. (1999) who studied air-water two-phase slug flows at 2 bar using the following flow conditions; $D = 0.026$ m, $u_{gs} = 0.2$–5.0 m/s and $u_{ls} = 0.1$–3.0 m/s. The first region is called 'swelling region front-zone' (an area where the gas is entrained just at the end of the Taylor bubble). The length of this region varied from 0.15D to about 5D which is followed by the wake region whose length was approximately, 0.8D to 10D. They also showed that both the liquid slug and the wake zones increased, approximately, linearly with increasing the gas superficial velocity but they are quite independent on liquid superficial velocity, u_{ls}. The second zone is the Taylor bubble which takes a bullet-shape and occupies almost the entire pipe-cross sectional area. The third region reported by Mori et al. (1999) is the low-void fraction region. Brauner and Ullmann (2004), comprehensively, investigates the wake region and the low void fraction region. Azzopardi (2006) reported that the Taylor bubble flowing upward in a vertical pipe is symmetric in shape, but for inclined pipelines, the nose of the Taylor bubble tends to move towards the wall of the tube. The same observation was reported for Taylor bubble in downward flow (Bouyahiaoui et al., 2018).

Lengths of the Taylor bubbles and liquid slugs are usually extracted from the time series of the void fraction. Khatib and Richardson (1984) used an analytical approach to estimate the lengths of both liquid slug as well as Taylor bubbles. They carried out experimental work on air-water mixture using a conductance technique with a pipe diameter of 38.8 mm. Lengths of liquid slug and Taylor bubbles increase with increasing gas superficial velocity (Azzopardi et al., 2015, Pioli et al., 2012). Akagawa and Sakaguchi (1966) and Fernandes (1981) reported that due to bubbles coalescence at the wake region, the liquid slug's length increases with increasing gas superficial velocity, u_{gs}.

The thickness of a thin liquid film falling down around Taylor bubbles depends on the liquid amount flowing downwards (Shara et al., 2018). The effect of various physical parameters on the liquid film thickness in slug flow was investigated by Llewellin et al. (2011). They studied the relationship between film thickness and its flow rate and found that it depends on the flow type (i.e. laminar or turbulent (oscillating) flow). The variation of the film thickness in slug flow was also, extensively, investigated by Nusselt (1916) whose model is applicable for thin film and by others such as Goldsmith and Mason (1962) and Chang (1994).

Radovcich and Moissis (1962) developed a model to determine the collision-frequency of the bubble. They reported that this frequency increased sharply when the void fraction lies within 0.2–0.3, resulting in forming plug flow. Heywood and Richardson (1979) proposed a first slug frequency correlation mathematical model in horizontal flow using a test section. The model of the latter for vertical slug flow is given by the equation below;

$$f = 0.0543\frac{u_{ls}}{u_m}\left\{\frac{2.02}{D} + \frac{u_m^2}{gD}\right\}^{1.02} \tag{3}$$

Omebere-Iyari (2006) studied the effects of gas/liquid superficial velocity and system pressure on the structure frequency. He found that for low-pressure system, structure frequency is dependent on u_{ls}.

Although the previous studies on slug flow led to better understanding of its dynamic behavior, almost all such studies depend on a single point measurement. In other words, these studies focus only on a single axial location and ignore the progression/evolution of the slug flow along the pipe. In this work, we study the dynamic behavior of the slug flow at nine different axial locations along the pipe. Such work is also of interest to the modelers who need to validate various slug flow models at different locations and different inlet conditions.

2. Experimental setup and methodology

The experimental facility (Fig. 1) used in the present study was built at the Laboratory of Multiphase Flows and Porous Media of the University of Sciences and Technology Houari Boumedien, Algiers.

Transparent test section 6 m long, with pipe thickness of 4 mm and internal diameter, D of 34 mm was used. Tap water was forced by the pump to flow from a tank (acting also as a separator), through a PVC mixer, into a vertical test section. A compressed air was also fed into the mixer, as shown in Fig. 1.

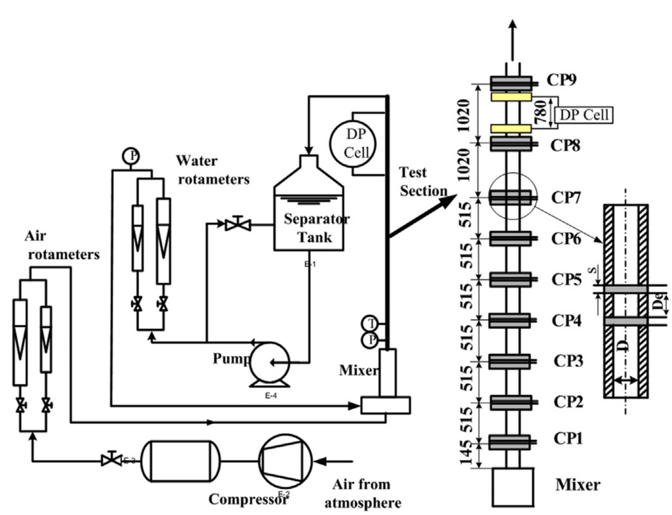

Fig. 1. A simplified diagram of the two-phase flow test facility.