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Characterization of slug initiation for horizontal air-water two-phase flow

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ABSTRACT

Two-phase gas-liquid slug flow is the prevailing flow regime in many processes in the petroleum and chemical industries. This flow regime is the result of the growth of wavelike instabilities at the gas-liquid interface. The main characteristic of slug flow is the presence of liquid slugs that span the entire pipe diameter separated by gas bubbles. The rear end of these gas pockets can exhibit a staircase shape (also known as plug flow) or a hydraulic jump that reaches the top of the pipe when the flow rate is increased. In this paper, an experimental investigation of the statistical properties of slug flow is presented for flow initiation. A gas-liquid circuit made of acrylic tubes with a 26 mm ID was used to make these measurements. The test facility was composed of two sections: the first corresponded to a downward flow of −3 degree inclination where the prevalent flow regime was stratified flow, and the second was a horizontal section where the prevalent flow regime was slug flow. Resistive sensors located at three different positions in the horizontal section were used to acquire the liquid holdup, and the time series were processed and analyzed. Statistics for slug initiation position, slug and bubble lengths, bubble velocity, slug and unit-cell frequencies are presented. Further, the length and probability of occurrence of the bubble tail were also analyzed in the cases where the bubbles exhibited a staircase shape. Ultimately, data are provided for the validation and development of mathematical models and numerical codes for the simulation of two-phase slug flow.

1. Introduction

Systems exhibiting two-phase gas-liquid flow are abundantly observed in various industries such as petroleum, chemical, nuclear, geothermal, and others. The spatial configuration occupied by the gas and liquid phases in two-phase flow is called the flow regime. One such flow regime, called slug flow, often occurs in pipelines and is characterized by intermittent pockets or 'slugs' of liquid separated by long gas bubbles. Slugging can be caused by different mechanisms in a pipeline. Hydrodynamic slugging arises from instabilities in the gas-liquid interface, leading to the interaction and growth of small waves at the interface to ultimately bridge the pipe to form a slug [24,14]. Terrain slugging and severe slugging are caused when changes in the elevation of pipelines lead to liquid accumulation and a subsequent build-up of pressure [30,40].

The main theoretical approach to predicting the onset of slug flow in a horizontal or near horizontal pipe has been to consider the Kelvin-Helmholtz stability analyses. The inviscid Kelvin-Helmholtz (IKH) theory [32,22,25] considers a finite amplitude wave on stratified inviscid flow. This wave can grow and may form a slug whenever the suction pressure generated over the wave by the Bernoulli effect overcomes the stabilizing effect of gravity. The viscous Kelvin-Helmholtz (VKH) analysis takes into account the shear stresses and inertia terms, applying a long wavelength disturbance to linearize the one-dimensional two-fluid model equations [24,2,3]. The inclusion of these extra effects causes the instability to occur at a lower gas velocity than would be predicted by IKH since the inertia terms become destabilizing [24].

An interesting point about the Kelvin-Helmholtz stability analyses is that the VKH analysis generally gives better predictions for the onset of slug flow than IKH analysis for low liquid viscosity whereas the inviscid theory becomes more accurate as the liquid viscosity increases [2,4,15]. As another approach for stratified to slug flow transition, some wave generation theories have been proposed based on the transfer of energy from the gas to the liquid phase by pressure variations versus the energy dissipated by liquid viscosity [20,21,7,23]. Fan et al. [14] have observed that for low gas velocities, slugs evolve by the bifurcation of short-wavelength

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gravity waves whereby they have the possibility of doubling in wavelength. The authors have also observed another mechanism for the evolution of slugs through the coalescence of waves.

A newly formed slug grows when the liquid taken up at the front of the slug is greater than the liquid shed at its back, reaching a stable condition when these fluxes become equal. This kind of analysis introduces a condition for the establishment of stable slug flow [13,28,6,17]. Once the slug flow has been established, the rear end of the bubble can exhibit a hydraulic jump which may or may not reach the top of the pipe, depending on the Froude number and gas flow rate [29]. When the hydraulic jump does not span the pipe cross section, i.e., the bubble exhibits a staircase-like shape, the flow is called plug flow. Netto et al. [26] studied solitary air bubbles in a horizontal tube and proposed that the existence of a bubble tail depends on the Froude number and bubble length.

There have been several experimental studies dedicated to studying various aspects of slug flow [8,35]. These studies usually analyze stable or developed slug flow. However, studies dedicated to the analysis of slug initiation in horizontal pipes are less common. Nydal et al. [27] investigated the mean values and statistical distributions of slug characteristics such as length, holdup and velocity for air-water slug flow in 53 mm and 90 mm ID horizontal pipes. They observed that the initial developing length for slug flow increased with increasing gas velocity and decreased with increasing liquid velocity. They also observed that the slug lengths and in most cases the slug holdups exhibited a lognormal distribution, while the slug bubble velocity exhibited a normal distribution.

Woods et al. [38] studied the generation of slugs for air-water flow in horizontal 0.0763 m and 0.095 m ID pipes. They only considered superficial liquid velocities above 0.5 m/s for which slugs were formed close to the pipe entrance. They indicated that the process for forming slugs at large superficial liquid velocities was stochastic. They also defined a condition for fully developed slug flow, and based on their observations, suggested that the distributions of slug length and bubble length could be reasonably represented by a lognormal function.

Ujang et al. [34] conducted a series of air-water experiments at varying pressures to study the initiation and subsequent evolution of hydrodynamic slugs in a horizontal pipeline with a length of 37 m and an internal diameter of 0.078 m. They presented new data for the distributions of time intervals between slugs and slug length distributions and the evolution of these distributions along a pipeline in slug flow. Their statistical analysis of slug time intervals and lengths indicated that they were best represented by a lognormal distribution. They also showed that the slug time intervals measured very close to the inlet were well-represented by an exponential distribution, leading to the conclusion that slug initiations can be considered as uncorrelated events. According to the authors, only the mean frequency is needed for a stochastic representation of slug initiation. Their results also revealed that the mean values of slug time intervals and slug lengths increased along the pipe, while the standard deviation of time intervals decreased and that of slug lengths did not vary systematically along the pipe. They also observed that the standard deviation of time intervals increased with superficial velocity and pressure.

Gu and Guo [16] performed experiments in a 5 cm ID, 16 m long horizontal pipe to study slug initiation and subsequent evolution along the pipe. They observed that slugs were initiated by a deterministic process consisting of replenishment and depletion of liquid near the inlet for gas superficial velocity (J_G) < 3 m/s and by a stochastic process consisting of wave coalescence for J_G > 3 m/s. They also observed that the suppression of pressure oscillations near the pipe inlet significantly dampened the interfacial disturbances, hence moving the slugging onset further downstream and reducing the peak frequency. However, this did not affect the slug frequencies near the outlet.

Adibi et al. [1] studied the effect of gas and liquid superficial inlet velocities and the effect of liquid holdup on the slug initiation position for three liquid holdups in a horizontal channel with dimensions of 5 cm × 10 cm and 36 m long. Their experiments revealed that for a liquid holdup of 0.25, the slug initiation position increased with liquid and gas superficial velocities (J_L and J_G), for a liquid holdup of 0.75, the slug initiation position decreased with J_L and J_G, while for a liquid holdup of 0.5, the slug position was almost constant. They also proposed empirical correlations for the slug initiation positions at the different holdups considered.

A number of studies have also been dedicated to modeling slug flow, of which the two-fluid model [18] stands out in the literature. In this model, averaged equations are used to model each phase to capture in a natural way the development of slug flow from the growth of instabilities in stratified flow [19]. The slug tracking model [5,40] is another widely used model, exclusively dedicated to simulate slug flow. In this case, the conservation equations are applied in the region of the "unit-cell", a concept used by Wallis [36] to define a region occupied by a slug and an elongated bubble. Information about the flow characteristics (such as bubble and slug lengths, velocities and volumetric fractions), usually obtained from empirical correlations or experimental tests, are needed as an input to these models or to validate them.

The experimental studies presented above focus on the understanding of phenomena involved in initiation and evolution of slug flow, for which, there is a lack of experimental data available in the literature, in particular for cases where the bubbles show a staircase shape. In the current work, an experimental investigation of the statistical properties of slug flow is presented for the beginning of the flow. Resistive sensors were used to acquire the liquid holdup at three different locations, and the time series were processed using two different methods. The slug initiation position, slug and bubble lengths, bubble velocity, slug and unit-cell frequencies were analyzed, and in the cases where the bubbles presented a staircase shape (plug flow) the length and probability of occurrence of the tail bubble was measured. Data are provided for the validation and development of mathematical models and numerical codes for the simulation of two-phase slug flow. The measurements were performed at the two-phase circuit at NUEM – UTFPR for air-water flow at ambient conditions (~96 kPa and 20 °C).

2. Experimental methodology

The geometry of the test facility was chosen in order to ensure that the liquid slugs initiated from stratified flow, eliminating the external influences (e.g. air-water mixer) that could disrupt the flow and affect the formation of slugs. Therefore, an inclined section was added before the horizontal section, as shown in Fig. 1. The disturbances arising due to the mixer are attenuated on the inclined section where the flow is stratified, and slugs are generated on the horizontal section leading to a transition to slug flow.

The fluids used for the experiments were air and water at ambient conditions. The test facility was made of acrylic tubes with 26 mm ID. Two sections of different inclinations joined by a smooth elbow were used. The first section corresponded to a downward flow of −3 degree inclination. In the second (horizontal) section there were three measurement stations, each consisting of a pair of resistive sensors and a pressure well. The positions of the measurement stations and geometric characteristics of the test facility are summarized in Table 1.

Fig. 2 shows a schematic representation of the experimental apparatus. The air was compressed and stored in the pressure vessels to ensure a constant flow to the test section. The gas flux was measured using three different calibrated orifice plates, selected