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Experimental study of the hydrodynamic behaviour of slug flow in a horizontal pipe

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HIGHLIGHTS

- Advanced instrumentation for slug flow measurement, namely ECT, under laboratory conditions, is used on a horizontal pipe
- In this study, oil with viscosity five times higher than water is used, as it is more relevant to industry
- Comparison with void fraction in the liquid slug and slug frequency data available in literature shows similar trends.
- Use of plots of average slug frequency against axial distance, probability density function (PDF) of void fraction and comparison of slug front and slug tail to establish flow development.

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ABSTRACT

This paper investigates the unsteady hydrodynamic behaviour of slug flow occurring within an air–silicone oil mixture, within a horizontal 67 mm internal diameter pipe. A series of slug flow regime experiments were performed for a range of injected air superficial velocities (0.29–1.4 m s−1) and for liquid flows with superficial velocities of between 0.05–0.47 m s−1. A pair of Electrical Capacitance Tomography (ECT) probes was used to determine: the slug translational velocities of the elongated bubbles and liquid slugs, the slug frequencies, the lengths of elongated bubbles and the liquid slugs, the void fractions within the elongated bubbles and liquid slugs. The pressure drop experienced along the pipe was measured using a differential pressure transducer cell (DP cell). A comparative analysis of the current experimental data and that previously published experimental confirms good agreement.

1. Introduction

Slug flows are the most prevalent and complex flow patterns experienced in multiphase transportation pipelines due to the long transport distances involved, and large pipeline diameters and uneven elevation profiles experienced in pipelines both onshore and offshore. As offshore production moves into deeper waters farther offshore, the cost of constructing and operating fixed platforms with separation facilities becomes increasingly challenging. An alternative solution is to utilize subsea production systems which entail minimum offshore processing. The presence of long, high density, fast moving liquid slugs within transport pipelines can cause significant variations in oil and gas flow rates entering downstream processing facilities, and result in mechanical damage to pipeline connections and supports (Bagci, 2003). Thus, an accurate prediction of the multiphase flow characteristics that may be experienced within these pipelines is therefore required to affect the safe and economic design and operation of these transportation systems. For this reason, it is of major interest within many industrial processes, including: upstream and downstream oil and gas processes, geothermal production of steam, chemical plants and refineries, and the handling and transport of cryogenic fluids (Bagci, 2003).

The literature is awash with large experimental data concerned with air–water flow in horizontal pipes and such data have been

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used extensively in the development of many of the available models and correlations. Expectedly, engineers dealing with fluid typical of industrial applications complain that water has inappropriate values of physical properties, particularly a viscosity that is much smaller than many of the materials they deal with. The range of viscosity of oils in real systems is 2.63×10^{-3} to 1000×10^{-3} Pa s, respectively.

In addition, detailed descriptions of the flow phenomena for this flow regime are sparse. New developments in flow measurement and instrumentation are a way to move forward. For instance, Abdulkadir et al. (2014) carried out a detailed experimental investigation to study the hydrodynamics of slug flows in a 67 mm internal diameter vertical riser. They employed electrical capacitance tomography (ECT) transducer to determine: the translational velocities of the Taylor bubbles and liquid slugs, the slug frequencies, the lengths of the Taylor bubbles and the liquid slugs, the void fractions within the Taylor bubbles and liquid slugs and the liquid film thickness. Their study also used a differential pressure (DP) transducer cell (DP cell) to measure the pressure drops experienced along the length of the riser.

1.1. *Slug flow characterization*

The principal features of slug flow are well explained by the model proposed by Dukler and Hubbard (1975). Their model is based on the observation that the slug behaves as a kinematic wave. Here, a fast moving liquid slug overruns and picks up a slow moving liquid film in front of it. The liquid scooping mechanism is due to the pressure drop that occurs during the acceleration of the liquid from the liquid layer by the front of the liquid slug body, Fig. 1. The kinematic wave velocity is actually higher than the actual velocity of the liquid particles inside the liquid slug body. Therefore, using a reference frame that moves at the wave velocity, the liquid moves across the liquid slug body. From a stationary reference frame, the liquid velocity decreases due to friction. The force due to the frictional pressure drop is the mechanism for the liquid shedding from the tail of the liquid slug body.

This Hubbard and Dukler (1975) model serves as a basic reference to the hydrodynamic behaviour of the slug flow pattern. A brief synopsis of the different methods to determine the characteristics of slug flow is presented, below:

1.1.1. *Slug velocity*

The slug front translational velocity, U_T, is often approximated using the approach known as the drift flux model, also suggested by Nicholson et al. (1978).

$$U_T = 1.2U_S + U_D \tag{1}$$

Where, U_s is the average velocity of the liquid in the slug. For homogeneous, no-slip flow in the slug body, $U_s = U_M$. Where U_M is the mixture superficial velocity. Therefore, the term $1.2U_M$ is approximately equal to the maximum velocity that the liquid in the slug may achieve. The drift velocity, U_D, in Eq. (1) is the relative velocity between U_T, and the maximum velocity of the liquid in the slug, $1.2U_s$.

As reported in the literature, the drift velocity is clearly nonzero for inclined flows. Early works of Hubbard and Dukler (1966), Gregory and Scott (1969), as well as Heywood and Richardson (1979), proposed that the drift velocity, $U_D = 0$, for horizontal flows. In contrast, later other investigators, such as, Nicholson et al. (1978), and Kouba (1986), have noted significant drift velocities in horizontal pipes.

Davies and Taylor (1950) show that, the bubble drift velocity in vertical tube is:

$$U_{D_{vertical}} = 0.35\sqrt{gD} \tag{2}$$

For horizontal pipes, Benjamin (1968) proposes the following relation:

$$U_{D_{horizontal}} = 0.54\sqrt{gD} \tag{3}$$

Where, g and D are acceleration due to gravity and pipe internal diameter, respectively.

1.1.2. *Liquid holdup in the liquid slug body*

One of the primary variables required to characterize slug flows is the liquid holdup in the slug body, H_s. Table 1 presents a summary of the slug body liquid holdup models considered by this study.

1.1.3. *Slug length*

The determination of the slug length (or frequency) is a key characterization parameter within almost all of the proposed slug flow models. According to Hernandez-Perez (2008), the prediction of the slug length is perhaps the most difficult parameter to estimate. Slug length has been found to be strongly dependent on the diameter of the carrier pipeline. This can complicate the application of correlation models obtained on small diameter test facilities to scale-up of larger field scale facilities.

A series of investigators Taitel and Dukler (1977), Nydal et al. (1991) and Barnea and Taitel (1993), report stable slug lengths of 15–40 pipe diameters in horizontal and slightly inclined pipes. All of these studies concluded that the slug length is fairly insensitive to the gas and liquid flow rates, and depend principally on the pipe diameter.

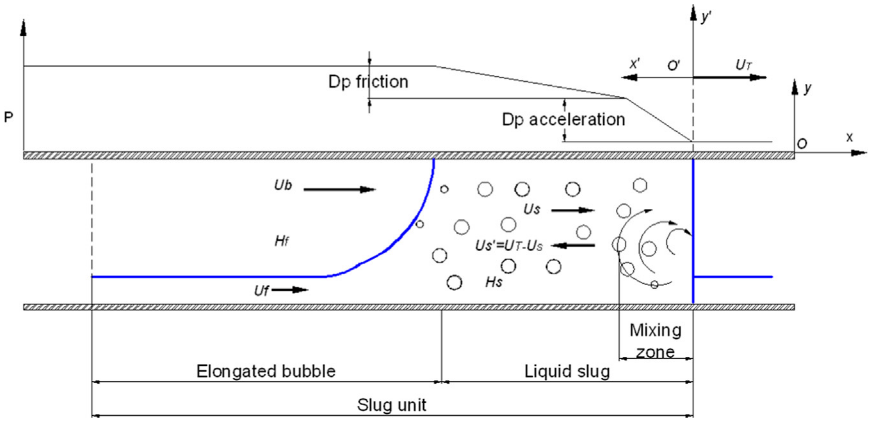

Fig. 1. Schematic representation of the Dukler and Hubbard (1975) slug flow model. Where, U_f, U_s, U_s' are the average liquid velocity in the film, average velocity of the liquid in the slug, difference between the slug front velocity and average velocity of the liquid in the slug, respectively. $U_b = U_T$, represents the slug front velocity, Hs and Hf are the liquid holdups in the liquid slug and liquid film, respectively. Dp is pressure difference.