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Modelling and statistical analysis of high viscosity oil/air slug flow characteristics in a small diameter horizontal pipe

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HIGHLIGHTS

- New experimental data on elongated bubble velocities and pressure drops are presented.
- Slug length statistics are analysed and the related PDFs are built from experimental data.
- A new slug length correlation for horizontal highly viscous oil/air flow is introduced.
- A mechanistic model is developed, which is able to predict the pressure drops along the slug unit.

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ABSTRACT

High viscosity oil/air slug flow is investigated both experimentally and theoretically. The behaviour with three different oils, whose viscosities range from 0.037 Pa s to 0.804 Pa s, is investigated in a horizontal pipe with 0.022 m I.D. and 9 m length. A statistical approach is adopted during the tests so to collect a meaningful amount of data and to build the probability density functions for slug lengths. A new correlation to model their dependence on superficial gas velocity is introduced. The length correlation along with a corrected version of the Nicklin (1962) correlation is used as an input into a developed mechanistic model, which is able to predict the pressure drops along the slug unit. The Modified Two Fluid model (Ullmann and Brauner, 2006) is used as closure relation for shear stresses in the stratified region. The model is validated against the pressure drop data obtained from performed experiments showing good accordance with them and providing detailed pieces of information about the mechanics of the flow regime.

1. Introduction

Two-phase liquid/gas flows are commonly encountered in many industrial processes, ranging from energy production to petroleum extraction. Among two-phase liquid/gas flow regimes, the most complex and thoroughly studied is slug flow and many efforts have been done to model this regime for water/air mixtures.

Dukler and Hubbard (1975) and Nicholson et al. (1978) are among the first available examples. In these two pioneering works, slug cell unit concept is introduced along with the differential problem, which rules the variable film thickness at the rear of a slug. Pressure drops along the unit are obtained considering only the frictional pressure drops and a mixing contribution due to the acceleration of the liquid at the slug front. Kokal and Stanislav (1989) further developed the previous works extending their application to all the range of intermittent flows. None of these works takes into account pressure drops along the film region of the slug unit.

In Taitel and Barnea (1990) several simplified submodels are formulated and compared against the complete one. Pressure drops are obtained by a force balance over the unit and pressure drops along the film region are introduced integrating the liquid and gas wall shear stresses along the length of that region.

Andreussi et al. (1993) introduced some simplifications in the momentum equations and analysed each single contribution to the pressure drops along the slug unit, dividing it into different sections.

More recently, Orell (2005) proposed a simplified model, similar to one by Taitel and Barnea (1990), to calculate pressure

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drops, but the model does not solve the hydrodynamic problem along the film region, assuming a constant film height.

Although these works focused on water/air slug flow, new demands from industry, especially petroleum industry, have moved the interest towards very viscous liquid/air flows.

Studying the effect of viscosity on slug flow characteristics has been attracting a growing interest. Some works investigated the role of viscosity in regime transitions, see Barnea (1987), Andritsos et al. (1989), and Matsubara and Naito (2011), and its influence on slug flow characteristics, such as frequency, see Gockal et al. (2009), holdup – see Nädler and Mewes (1995), Kora et al. (2011), Farsetti et al. (2014), Khaledi et al. (2014), and Zhao et al. (2013) – and bubble velocity, see Foletti et al. (2011) and Losi and Poesio (2016). However, there is still a limited amount of information about the influence of viscosity on slug lengths and velocities, although they are input parameters required by most of the mechanistic models, as the ones briefly mentioned earlier.

Recently, the work of Al-Safran et al. (2011) pointed out the role of viscosity on shortening slugs, providing also an empirical correlation to predict their lengths. The accordance of the correlation with experimental data is good, even with experimental results reported in this work. The functional structure of the correlation (developed for viscosity in the range from 0.017 Pa s to 0.580 Pa s) does not however include the dependence of the slug length on the superficial gas velocity. A new set of experiments and a statistical approach for data analysis is presented here. Based on those data, a new correlation to describe slug lengths in horizontal flow for high viscosity liquids is formulated and tested against experimental observations.

The new correlation, along with a corrected Nicklin (1962) correlation for bubble velocity in two-phase flow, is used as an input into our mechanistic model. The developed model is built on the mass and momentum conservation equations for separated flow, as it is done in Andreussi et al. (1993) and Cook and Behnia (2000) but, unlike the recent works by Khaledi et al. (2014) and Zhao et al. (2015), the hydrodynamic of the liquid film in the stratified region is solved. The Modified Two Fluid model (Ullmann and Brauner, 2006) is used to provide the closure relations for shear stresses in the same region, avoiding the use of empirical correlations. Calculated pressure drops by the model show an overall good agreement with experimental results.

2. Experiments

2.1. Experimental set-up and procedure

The experimental facility, especially designed to study multiphase flows, consists of a $L = 9$ m long glass pipe with an inner diameter of $D_i = 0.022$ m. The pipe is formed by six 1.5 m long sections. A sketch of the set-up is given in Fig. 1. The pipe inclination is set at 0°. The inclination angle is periodically checked with an electronic level sensor, which offers an uncertainty of ±0.1°.

Three different paraffin oils are used in these experiments. Their densities are measured by a hydrometer, their viscosities are measured with a rotational rheometer (Ultra Programmable Rheometer LV-DV III+, Brookfield, Middleboro, USA) while their surface tensions are measured by a Wilhelmy plate tensiometer; the values are all reported in Table 1.

The oil is initially stored in a tank and it is pumped into the pipe through a gear pump. Air is directly supplied by the University network.

Oil flow rates are measured, before entering the mixing section, by a screw-spindle flow-meter, especially designed for high-viscosity liquids. Air mass flow rate is measured by a thermal mass flow meter. At the same spot, air pressure is imposed at 4 bar by a pressure safe valve. Oil and air flow rates are measured with a 5% of uncertainty on their reading value.

The oil/gas mixture is discharged into a receiver tank where the air is subsequently vented to the atmosphere and the oil is pumped back to the storage tank, see Fig. 1.

The experimental campaign is performed following the procedure outlined below:

1. oil is introduced at the lowest value of superficial velocity j_l;
2. air is introduced at the highest value of superficial velocity j_g;
3. visual observations and data acquisitions for the (j_l, j_g) pair are performed for a period of time of 45 min, so to collect statistically meaningful data – at least 1000 slugs are observed;
4. air flow-rate is decreased and acquisitions for the new (j_l, j_g) pair are carried out;
5. step 4 is repeated from the highest to the minimum air flow-rate;
6. oil flow-rate is increased and the procedure is started again from the highest air flow-rate until the minimum is reached.

Oil and air superficial velocities are in the ranges $j_l = 0.1 - 0.3$ m/s and $j_g = 1.3 - 2.2$ m/s, respectively.

The multiphase flow set-up is equipped with a capacitance probe, see Section 2.2, which is used to measure oil slug velocities and is placed 6.5 m downstream the inlet, on the fifth pipe section. A differential pressure probe is placed across the same pipe section, the pressure taps being 1.5 m apart.

2.2. Capacitance measurements and data post-processing

Capacitance probes take advantage of the difference in dielectric permittivity between oil and air, so, when a bubble passage occurs, it is detected by capacitance variations between two copper electrodes flush-mounted on the external surface of the non-conductive pipe. The probe is made up of two electrodes, three guarding sections, and one polarizing electrode. The distance ΔX between the two electrodes is 197.8 ± 0.5 mm; such distance is used to compute the bubble velocity. Each electrode, which is the sensitive area of the probe, has an opening angle of 179° to ensure a full coverage of the test section and an axial extension of 10 mm. For more details on the capacitance sensor refer to Strazza et al. (2011). The electric outputs of the probes are acquired at 100 Hz sampling frequency and they are stored in a PC for further post-

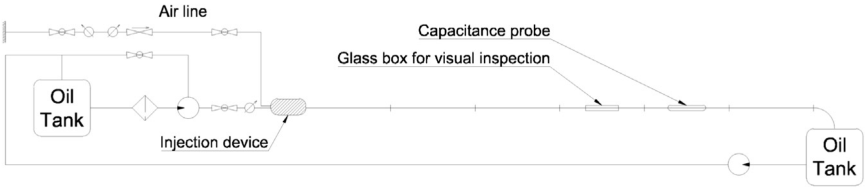

Fig. 1. Experimental multiphase flow set-up.