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Void fraction and pressure waves in a transient horizontal slug flow

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ABSTRACT

The void fraction and the pressure waves in an air–water mixture flowing in the slug regime are experimentally investigated in a horizontal line. The test section is made of a transparent Plexiglas pipe with 26 mm ID and 26.24 m long, operating at ambient temperature and pressure. The flow induced transients are made by quickly changing the air or the water inlet velocity. The test grid has four operational points. This choice allows one to create expansion and compression waves due to the changes to the gas or to the liquid. Each experimental run is repeated 100 times to extract an ensemble average capable of filtering out the intrinsic flow intermittence and disclosing the void fraction and pressure waves' features. The slug flow properties such as the bubble nose translational velocity, the lengths of liquid film underneath the bubble and the liquid slug are also measured. The objective of the work is two-fold: access the main characteristics of the void fraction and pressure waves and disclose the mechanics of the transient slug flow as described through the changes of the slug flow properties.

1. Introduction

Theoretical aspects of void fraction and pressure waves occurring in gas–liquid flows cover several topics including, for example, flooding, shocks, density-wave instabilities and flow regime transition, which have applications on nuclear safety problems as well as on the crude production in petroleum fields. Typical nuclear safety problems are the loss of coolant, accident in nuclear reactors, choked flow after a postulated break of hot or cold leg of pressurized water reactors and the flow instability in parallel boiling channels. Complementary, transient flow applications in the crude oil production lines are usually associated to the start up and shut down of two-phase lines, artificial lift, flow assurance and flow in vertical risers where severe slugging is likely to occur.

The pressure and void waves are coupled through the mass and momentum equations: when pressure is perturbed so is the void fraction. Therefore, the features of void fraction and pressure waves are by themselves a way to typify gas–liquid flows. Furthermore, comparisons of wave velocity prediction offer an excellent means to test the ability of numerical models, such as those based on the mixture model (Masella et al. 1998; Evje and Fjelde 2002; Malekzadeh et al. 2012 and Santim and Rosa 2015), slug tracking models (Nydal and Banerjee 1996; Taitel and Barnea 1998; Al-Safram et al. 2004; Ujang and Hewitt 2006 and Rosa et al. 2015) and on different forms of the two and multi-fluid models (Larsen et al. 1997; Issa and Kempf 2003; Bonizzi et al. 2009; Carneiro et al. 2011; Kjeldby et al. 2013; Gourma et al. 2013; Simões et al. 2014), to capture transient features of slug flow.

Experimental studies on waves in gas–liquid flows motivated a large body of scientific works, but few devoted to slug flow regime, the focus of this work. Perhaps one of the reasons is the inherent difficulties to access wave properties in slug regime if compared with the more abundant wave studies in bubbly flow. The hindrances of the experimental approach are linked to the intermittent passage of liquid slugs trailed by elongated bubbles. To disclose the void fraction and pressure waves in flow transients one needs to use the ensemble average to filter the natural void and pressure perturbations.

A brief review on pressure and void waves follows. For clearness sake, we grouped the references into three categories: (i) articles which report only pressure waves in slug flow; (ii) articles which report only void fraction waves in slug flow and (iii) articles which report slug flow transients analyzing void and pressure waves simultaneously.

1.1. Pressure wave disturbance on slug flow

It is well known that the presence of small amounts of gas in a liquid reduces significantly the velocity at which pressure waves can travel through the mixture. The research on this topic emerged during the 1960s motivated by safety issues on nuclear reactors for power generation. A comprehensive study on the velocity propagation at various flow patterns was carried out by Henry et al. (1971). Specifically, the slug flow regime was idealized as a

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pattern which alternately liquid and gaseous elements are in line, taking the whole pipe cross section as plugs. The. lengths of the liquid slug and of the gas bubble are identified by L_S and L_f, respectively. Furthermore, the unit length, $L_U = L_S + L_f$. Considering that the pressure pulse crosses the liquid and the gas plugs with the corresponding acoustic velocities, c_L and c_G, the acoustic velocity of an unit is then an average of c_L and c_G weighted by the relative lengths of the liquid and gas plugs:

$$c_P = \left(\frac{\beta}{c_G} + \frac{1-\beta}{c_L}\right)^{-1}, \tag{1}$$

where β is the intermittence factor defined by the ratio between the lengths of the gas plug to the unit,

$$\beta = \mathrm{L_f}/\mathrm{L_U} \text{ where } \mathrm{L_U} = \mathrm{L_f} + \mathrm{L}_S. \tag{2}$$

However, a recognizable problem of this model is the severe attenuation when the pressure pulse is transmitted from the liquid to the gas plug due the mismatch of the phases' acoustic impedance. The accuracy of Eq. (1) was checked against experimental data taken in a vertical test section with 50.8 mm in diameter and 22 free diameter long. The working fluids were air and water operating at absolute pressure of 170 kPa. Compression or rarefaction pressure pulses were made by causing the rupture of a diaphragm. The test's initial condition was a static plug of air on top of a plug of water standing still in the test section, i.e., the test section had a single slug unit per test. The slug flow tests were taken for various levels of water inside the test section. The estimate of the acoustic pressure wave velocity compares favorably against the experimental data.

Martin and Padmanabhan (1979) studied numerically and experimentally the velocity propagation of the pressure pulse in slug flow. The work's objective was twofold: to compare the experimental data (i) against the acoustic model for a homogenous mixture proposed by Henry et al. (1971) and (ii) against the numerical values of the eigenvalues rising from the drift flux model. The experimental data was taken in 13.4 mm ID cooper tube with 102 m long. The working fluids were water and air. Once the slug flow was established, a pressure surge was introduced by closing the outlet valve. The transient slug flow was numerically solved employing the drift-flux model. The system of transport equations is hyperbolic with three real and distinct eigenvalues which were evaluated numerically. They show that a linear combination of the high speed eigenvalues matches the acoustic velocity of a homogeneous mixture, as proposed by Henry et al. (1971):

$$\frac{c_P}{c_G} = \left\{\sqrt{\alpha(1-\alpha)\frac{\rho_L}{\rho_G} + \alpha^2 + \left(\frac{c_G}{c_L}\right)^2\left[(1-\alpha)^2 + \alpha(1-\alpha)\frac{\rho_G}{\rho_L}\right]}\right\}^{-1}, \tag{3}$$

where α is the void fraction and ρ_G and ρ_L represent the gas and liquid phase densities. Considering the tests operational conditions: $\rho_G/\rho_L << 1$, $(c_G)^2 = \mathrm{k.P}/\rho_G$ and $(c_G/c_L)^2 << 1$ where k is the polytropic coefficient, the authors simplify Eq. (3) to:

$$c_P \cong \sqrt{\frac{kP}{\rho_L \alpha(1-\alpha)}}. \tag{4}$$

Furthermore, Martin and Padmanabhan (1979) also showed that the pressure pulse propagation velocity is much less than those predicted by Eq. (1), but are slightly greater than the values based on the homogenous adiabatic model given in Eq. (4), for k equals to1.4.

Matsui et al. (1979) employed the idealized slug flow pattern proposed by Henry et al. (1971) to model a slug train by means of a mass-spring analogy, taking into account the liquid inertia and the gas compressibility. The mass-spring analytical model disclosed that the pressure wave is dispersive with a characteristic velocity given by:

$$c_P = \sqrt{\frac{kP}{\rho_L \beta(1-\beta)}}. \tag{5}$$

Eq. (5) coincides with the acoustic speed for homogenous flow shown in Eq. (4) if the intermittence factor β is replaced by the unit void fraction, α. The experimental apparatus consists of a shock tube with 5 mm inside diameter operating with air and water. The lengths of the low and high pressure chambers are, respectively, 2040 mm and 1000 mm. The liquid and gas plugs are easily formed inside the low pressure chamber due to the small tube diameter. The compressibility effects were tested changing the number of gas–liquid units inside the low pressure chamber from 1 up to 20. The experimental results show a dispersive pressure wave. Furthermore, they propose a fast and a slow traveling pressure wave based on the experimental data. The fast wave follows the model proposed by Henry et al (1971), Eq. (1), but it is barely detectable because for an air-water system the wave speed spans from 340 m/s to 910 m/s. Furthermore, the acoustic impedance mismatch, when the wave crosses a liquid plug to a gas plug, strongly attenuates the acoustic intensity. On the other hand, the slow wave velocity is due to the gas compressibility and the liquid inertia. It travels with a speed estimated by Eq. (5), which is one order of magnitude less than the fast wave speed. It is symmetric for β with a minimum for $\beta = 0.5$.

Nguyen et al. (1981) proposed simple analytical expressions for propagation of pressure disturbances in gas–liquid flows using the well known physical behavior that the acoustic velocity in a single phase flow is influenced by the wall's elasticity. But for slug flow regime, the authors used the idealized pattern proposed by Henry et al. (1971) and the same expression for the acoustic velocity, see Eq. (1).

Legius et al. (1997) measured the pressure wave velocity in an upward slug flow pattern. They used a vertical line with 17 m height where in the last 10 m was positioned the test section with a 50 mm ID pipe. The pressure disturbance is made through a secondary air injection line assisted by a fast opening valve. The authors use the acoustic velocity expression for homogenous flow proposed by Nguyen et al. (1981) to estimate the pressure wave velocity as,

$$\frac{1}{c_P} = (1-\alpha)\sqrt{\frac{(1-\alpha)}{c_L^2} + \frac{\rho_L \alpha}{\rho_G c_G^2}} + \alpha\sqrt{\frac{(1-\alpha)\rho_G}{c_L^2 \rho_L} + \frac{\alpha}{c_G^2}}. \tag{6}$$

The model overestimates the experimental data by an offset of nearly 10 m/s, which represents roughly 50% of the experimental velocity.

Lee et al. (1998) based on the two-fluid model, introduced a new interfacial term which was capable of converting the system of equations into a hyperbolic type. Based on the analysis of the eigenvalues, the authors proposed for the slug flow an acoustic speed defined as:

$$c_P = \left(\frac{\alpha}{c_G} + \frac{1-\alpha}{c_L}\right)^{-1}. \tag{7}$$

A quick inspection discloses that Eq. (7) is similar to Eq. (1), the nonsimilarity is on the difference between the α and β. Nonetheless, it can be anticipated that the estimates given by Eq. (7) are close to the fast wave approximation which is one order of magnitude higher than the slow wave discussed in Matsui et al. (1979).

Xu and Gong. (2008) employed the two-fluid model and used a virtual mass coefficient expression capable of rendering the conservation equations into a hyperbolic system. The authors determined the real eigenvalues and associated them to the acoustic velocity. For the slug flow pattern, the author proposed an acoustic velocity