INTERFACES OF LONG BUBBLES IN HORIZONTAL TURBULENT SLUG FLOW

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Abstract The present work discusses the manner in which long bubbles fill the space in horizontal turbulent slug flows. Particular emphasis is set on the description of the gas-liquid interface. The work shows that instability waves distort an otherwise smooth surface, giving rise to exposed areas that correspond to an excess of 10% over theoretical predictions. A Shadow Sizer system coupled with Particle Image Velocimetry is used to account for the properties of the flow.

INTRODUCTION

Horizontal turbulent slug flows are the predominant flow pattern in oil and gas production offshore fields. In fact, depending on the operational conditions, different flow configurations can be identified resulting in slug structure statistics that are observed to vary significantly.

Existing modelling practices normally consist of a combination of empirical correlations, mechanistic models and numerical models. Focused on the prediction of pressure gradients, mean phase velocities and mean volume fractions, these methods often do not provide information on the shapes of bubbles and other properties of the flow. However, to some applications, the correct characterization of the interfaces is of fundamental importance for the prediction of mean flow properties, including the pressure gradients. This typically occurs in flows with a soluble component (Magalhaes et al. 2013).

The present work discusses the shapes of long bubbles in slug flows. Previous authors have shown that the shapes of long bubbles depend on the mixture velocity and on the bubble length (Netto et al. (1999)). Arguing that the upstream flow is the chief responsible for the definition of the bubble shape, Netto et al. (1999) propose a model where the bubble is split into four regions: nose, main body, hydraulic jump and tail. Here, predictions provided by the theory of Netto et al. (1999) are compared with a very detailed experimental description of the gas-liquid interface area. A Shadow Size system and Particle Image Velocimetry are used to shown that theoretical predictions underestimate the interface area by more than 10%. The detailed experimental information allowed the construction of high resolution three-dimensional representations of the long bubbles.

For the first time, accurate relations are proposed to correlate the lengths, interface areas and volumes of long bubbles in horizontal slug flows. Netto el al. worked with a single isolate bubble. As a result, interface perturbations came about from the turbulent features of the single-phase flow ahead of the bubble nose. Here, an intermittent flow regime is established with alternating large bubbles and liquid slugs. The long bubbles are hence exposed to oncoming highly turbulent aerated liquid slugs.

LENGTH-AREA-VOLUME PROPERTIES OF LONG BUBBLES IN HORIZONTAL SLUG FLOWS

Interface effects can be incorporated to one-dimensional theories provided relations of the form $l = f(V^{1/3})$ and $A = g(V^{2/3})$ can be defined (Magalhaes et al. 2013), where l stands for length, A for area and V for volume. The theory of Netto et al. (1999) considers regular surfaces, deprived of wrinkles or further complications. In fact, in horizontal slug flows, the gas phase always moves faster than the liquid phase. As a result, pressure and friction forces perturb the equilibrium of the flow, generating waves at the gas-liquid interface that provoke sharp fluctuations on the bubble contour and give rise to a complex pattern. Figure 1 illustrates in two-dimensions (Fig. 1a) the contour of two long bubbles, together with predictions provided by Netto et al. (1999). The highly intermittent interface area of the bubbles is evident. A three-dimensional rendering of the bubble is presented in Fig. 1b.

Figure 1 was constructed from the Shadow Sizer data through a specially developed pattern recognition method. The procedure furnishes, in particular, accurate values of areas and volumes.

The statistics of the gas-liquid interface were obtained from the analysis of 72 bubbles, with flow conditions in the range, $0.13 < j_g$ ms^{-1} < 1.6 and $0.13 < j_f$ ms^{-1} < 1.3. The experiments were carried out with water and air in a 2"-pipe.

Figure 2 illustrates the relations between length-volume (2a) and interface area-volume (2b) for horizontal slug flows. Predictions furnished by the theory of Netto et al. (1999) are also shown. The agreement between experiments and theory in Figure 2a is very good. The length of isolate long bubbles can be correlated through relation

$$l_f = \alpha_1 (V^{1/3})^n, \quad (\alpha_1 = 299, n = 2.48, \text{ Experiments}; \ \alpha_1 = 316, n = 2.50, \text{ Netto et al.}). \tag{1}$$

Because the long bubbles approximate the forms of slender cylinders, the exponent n approaches 3, indicating an almost linear relation between l_f and V.

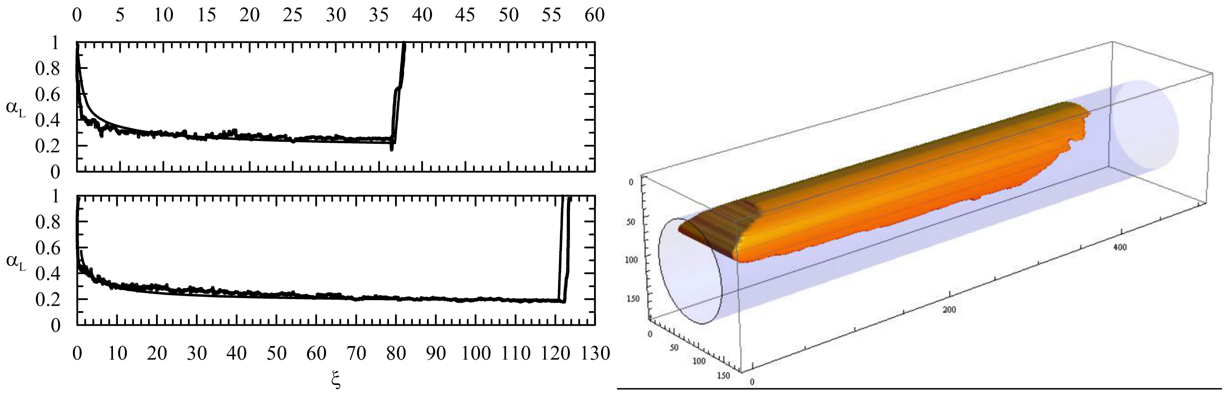

Figure 1. Typical shape of a bubble for horizontal slug flow, ξ = non-dimensional streamwise coordinate (=x/D), α_L = liquid volume fraction.

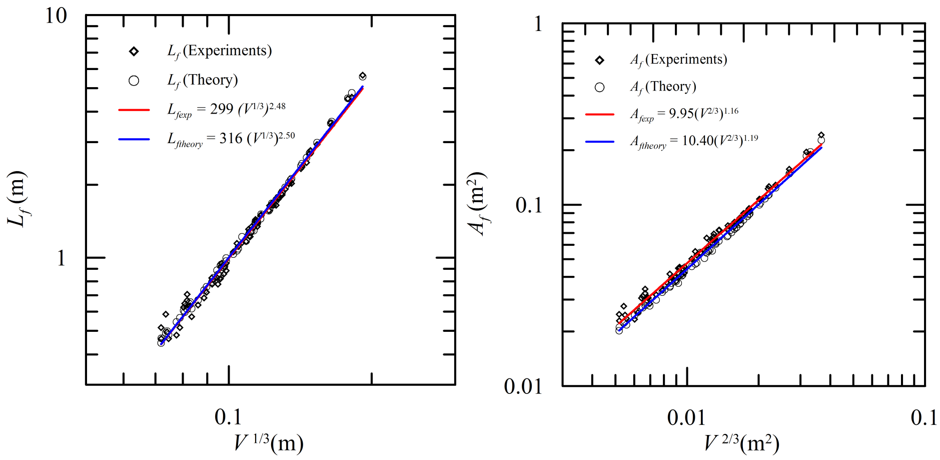

Figure 2. Length-volume and Gas-liquid interface area-volume for a horizontal slug flow.

For the interfaces, predictions are not good (Fig. 2b). Netto et al. (1999) show that for Froude numbers lesser than unity, the interface perturbations have a constant wavelength and a decreasing amplitude. For high Froude numbers ($F_r > 2$), the amplitude decreases. Irrespective of the range of Froude number studied in the present work, the agreement between experiments and theory for interface area prediction was not good.

The interface area can be described through

$$A = \alpha_2 (V^{2/3})^m, \quad (\alpha_2 = 9.95, m = 1.16, \text{ Experiments}; \ \alpha_2 = 10.40, m = 1.19 \text{ Netto et al.}). \tag{2}$$

CONCLUSION

The present work has experimentally identified the structure of gas-liquid interfaces in slug flows. The work shows that the mean position of the gas-liquid interface is well characterized by the theory of Netto et al. (1999), but that complexities resulting from wave instabilities make the theoretical area predictions present errors of the order of 10% of the actual values.

References

[1] G.R. Magalhães, G.F.N. Gonçalves, J.B.R. Loureiro and A.P. Silva Freire. An experimental investigation of the effects of gas solubility on the properties of horizontal slug flow. *International Journal of Multiphase Flow* **50**: 33–40, 2013.

[2] J.R. Fagundes Netto, J. Fabre and L. Peresson. Shape of long bubbles in horizontal slug flow. *International Journal of Multiphase Flow* **25**: 1129–1160, 1999.