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Detailed flow field measurements and analysis in highly viscous slug flow in horizontal pipes

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ABSTRACT

The flow field in the liquid phase of high viscous oil and air two-phase slug flow were experimentally studied under laminar flow conditions. The horizontal 50.8-mm (2-in.) inner diameter (ID) pipe and high viscous fluid properties (nominal viscosity values of 0.51, 0.68 and 0.96 Pa·s) yielded mixture Reynolds numbers less than 100. Particle Image Velocimetry (PIV) was used to analyze the flow field in the liquid phase. Slug characteristics were measured with a set of capacitance probes (CPs). Based on velocity field measurements, the liquid phase mass is shown to be conserved within the slug body despite local spatial variations in volumetric flow rate – flow accelerates at slug front and decelerates at slug tail. A low momentum region inside the liquid phase is identified beneath the mixing zone and close to the lower sections of the pipe. Furthermore, based on a frame of reference moving with the slug front, a pair of vortices is identified at the slug front. Accordingly, a continuous increase in velocity is observed at lower sections of the pipe. From CPs data, the flow coefficient is estimated to be between 2.11 and 2.20 for the elongated bubble flow, and 2.26 and 2.38 for the slug flow in laminar conditions investigated. From PIV data, the flow coefficient is estimated to be between 2.28 and 2.34 for the elongated bubble, and 2.31 and 2.44 for the slug flow, respectively. These slight differences in the obtained values of flow coefficient indicate the possible misunderstands of 1.13 multiplier.

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1. Introduction

Liquid-gas two-phase slug flow in pipes is a commonly observed flow during production and transportation of oil and gas. A simple schematic for the horizontal slug flow is illustrated in Fig. 1 for a typical slug unit. Based on the visual observations by Dukler and Hubbard (1975), the slug has higher kinetic energy than that of the liquid film. Therefore, the film penetrates a distance into the slug before it is finally assimilated at the slug velocity. This over-running phenomenon creates an eddy at the front of the slug which is essentially a mixing vortex. The distance of penetration constitutes the length of the mixing eddy. The rigorous identification of liquid slug body and film regions is described in the later section based on the experimental methodology.

Meanwhile, the two-phase slug flow has been expected to exhibit significantly different behavior for higher viscosity liquids. Several characteristics of slug flow, including bubble entrainment and slug mixing zones, might be affected by the liquid viscosity. For the design of a production system, it is crucial to predict the slug characteristics correctly based on different fluids properties.

It is commonly assumed that the flow in slug body is fully developed. This implies a constant wall shear stress in slug body. Whereas, Buitrago et al. (2017) presented the continuous increase of wall shear stress in the slug body and decrease in the liquid film for a highly viscous liquid. Additionally, they reported that some of the liquid near the pipe wall at the slug front was moving as it were still part of the liquid film region. This phenomenon led a delayed movement of liquid phase near the pipe wall at the slug front. This may indicate that a longer length is required to scoop the upstream liquid film, possibly inducing a relatively longer mixing zone at the slug front for higher liquid viscosity. Then, this liquid was dragged by the mass of liquid slug body, resulting in the continuous increase of wall shear stress. Similar to this accelerated flow, the wall shear stress decreased from the end of slug body owing to the deceleration of the flow. Despite all these observations, a complete flow field information in the pipe, such as the velocity field, has not been studied well in detail for highly viscous liquids.

Several researchers studied the viscosity effects on two-phase slug flow characteristics in the horizontal pipe. For example, recent

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Nomenclature

C_o	Flow coefficient (Distribution parameter), -
C_1	Ratio of the maximum to the mean velocity in profile, -
$\dot{m}_L$	Liquid mass flow rate, kg/s
μ_L	Liquid viscosity, Pa·s
$\mathrm{Re_M}$	Mixture Reynolds number, -
ρ_L	Liquid density, kg/m^3
ρ_G	Gas density, kg/m^3
σ	Standard deviation of samples, -
θ	Pipe inclination angle, °
v_D	(***u***-direction) Drift velocity, m/s
v_e	Erosion velocity, m/s
v_L	(***u***-direction) Liquid velocity in PIV window, m/s
$v_{L,Maxi}$	(***u***-direction) in-situ maximum liquid velocity, m/s
v_{Li}	(***u***-direction) in-situ liquid velocity in PIV window, m/s
v_M	(***u***-direction) Mixture velocity, m/s
v_{Sg}	(***u***-direction) Superficial gas velocity, m/s
v_{SL}	(***u***-direction) Superficial liquid velocity, m/s
v_{SLi}	(***u***-direction) In-situ superficial liquid velocity, m/s
v_T	(***u***-direction) Translational velocity, m/s

experimental results by Gokcal (2005, 2008), Kora (2010), Brito (2012), and Kim (2015) elucidated that slug length decreases and slug frequency increases as the liquid viscosity increases. Thus, the slug lengths might not be long enough to reach a fully developed velocity profile in the slug body resulting in the non-linear pressure drop. Gokcal (2005) indicated that high oil viscosity has a significant effect on the pressure gradient and liquid holdup, and previous models do not yield accurate predictions for this high viscosity range. Therefore, the current slug flow models may need to be modified or re-developed for highly viscous fluids to improve predictions. Later, Gokcal (2008) described that an increase in liquid viscosity might cause a decrease in Reynolds number and the turbulence in the mixing zone at the front of the slug. Accordingly, the slug length can be decreased with the decrease of mixing length for increasing liquid viscosity. This conclusion of the reduced mixing length could be against to the one expected by the results of Buitrago et al. (2017). A more rigorous comparison of the slug length and the mixing zone from the different liquid viscosities needs to be considered. Experimental results of Brito (2012) with relatively medium and high liquid viscosity (0.039–0.166 Pa·s) also indicated shorter slug lengths, as well as non-homogeneous bubble distribution in the slug body. Accordingly, the author reported that these phenomena might not allow the velocity profile to develop fully in the slug. From this point of view, the methodology of the existing mechanistic models such as Dukler and Hubbard (1975), Gomez et al. (2000) and Zhang et al. (2003a, b) needs to be reconsidered to apply for slug flow of highly viscous liquids.

Furthermore, many mechanistic models such as Dukler and Hubbard (1975) and Taitel and Barnea (1990) require several slug characteristics as the input parameters. However, most of the slug characteristics such as the slug liquid holdup and the translational velocity have been estimated by closure relationships.

It was reported that the amount of entrained bubbles increases at higher liquid viscosity and lower surface tension, decreasing the slug liquid holdup (Nädler et al., 1994; Kora, 2010; Brito, 2012). Based on the fluid properties such as density, viscosity, surface tension, etc., however, the travel routes and deformations of entrained bubbles can vary significantly. The bubbles can be dragged more at higher liquid viscosities and more inclined to float at higher liquid density with higher buoyancy. Moreover, their path-lines and deformations are affected by the shear and streamlines of neighboring liquid phase in slug body. As a result, it may be difficult to properly predict the slug liquid holdup, as well as the other slug characteristics, without understanding the inner flow field of liquid slug body.

In the literature, the various values of flow coefficient, which has been regarded as the ratio of maximum velocity to average velocity at a given pipe cross section, have been applied, such as 2.27 for laminar, 1.2 for turbulent flows and 2.27–1.2 for transition conditions. Undoubtedly, these values are valuable and reasonable for low viscosity vertical upward flow to predict the translational velocity since the phase distribution is near axi-symmetric with relatively longer slug lengths. Whereas, much shorter slug length with non-symmetrical phase distribution is expected with slug flow of high viscosity liquid and gas in horizontal pipes. The development of the flow in such short slug lengths and therefore the applicability of existing models and related closure relationships are very much in question. The inappropriate understanding of the flow coefficient leads to the incorrectly calculated translational velocity and, then, decreases the accuracy of the slug flow mechanistic models.

The elongated bubble and its effect on the upstream local liquid velocity profile have been studied intensively. The flow behavior of slug and elongated bubble patterns is the same with respect to the flow mechanism. The elongated bubble pattern is considered the limiting case of slug flow when the liquid slug is free of entrained bubbles. This occurs at relatively lower gas rates when the flow is calmer (Shoham, 2006). The flow coefficient (or distribution parameter), C_o, reflects the liquid velocity profile near the end

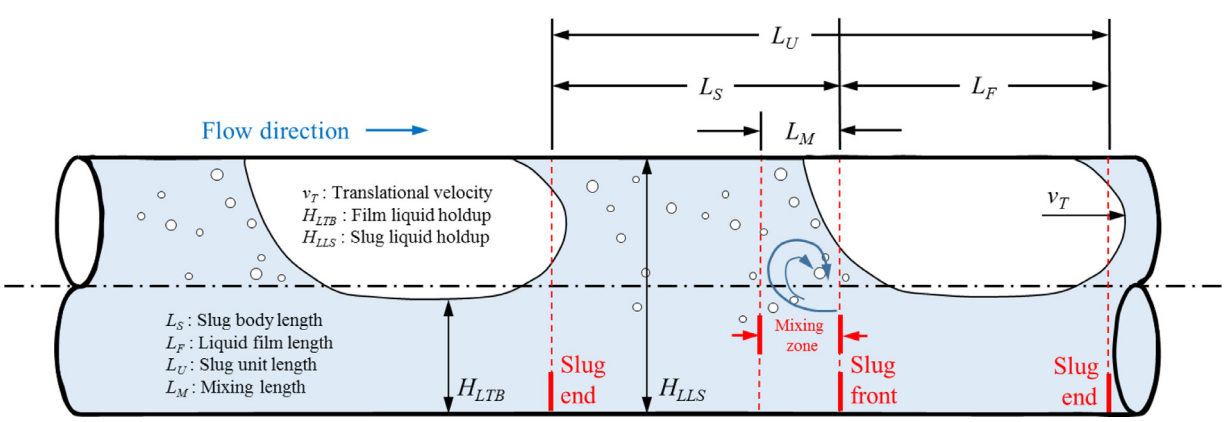

Fig. 1. Illustration of slug flow.

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