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Transition of plug to slug flow and associated fluid dynamics☆

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ABSTRACT

Transition of plug to slug flow is associated with bubble detachment from elongated bubble tail or bubble entrainment inside the liquid slug. The mechanism responsible for this transition was earlier identified by Ruder and Hanratty (1990) and Fagundes Netto et al. (1999) based on the shape of the hydraulic jump observed at elongated bubble tail region. The transition mechanism reported by Ruder and Hanratty (1990) and Fagundes Netto et al. (1999) was only based on their flow visualization study. Plug to slug transition and associated dynamics of bubble detachment from the elongated bubble is analysed in the present paper using flow visualization and local velocity measurements. Experiments are reported for 13 different inlet flow conditions of air and water phases. Images of plug/slug flow structures are captured at a rate of 4000 FPS using FASTCAM Photron camera and the local values of axial liquid velocity are measured using LDV system synchronised with a 3D automated traverse system. LDV measurement of local liquid velocity in the liquid slug and liquid film establishes the reason for detachment of bubbles from the slug bubble tail.

1. Introduction

Gas-liquid intermittent flow received special attention in context to petroleum, nuclear, chemical and geothermal industries during last two decades due to their intermittent and irregular flow structures (Oliveira et al., 2015). Such flows can cause serious erosion-corrosion and strong mechanical impact in various piping systems including tees, elbows, downstream of control valves, flow elements, reducers or orifices (Sun and Jepson, 1992; Thaker and Banerjee, 2016). Erosion-corrosion leads to wall thinning or material degradation in piping systems which has been responsible for large catastrophic failures in industrial applications (see Ahmed (2012) and Wood et al. (2013) for a review). Critical analysis of the interfacial dynamics of intermittent flow is required to avoid such failures.

Intermittent two-phase flow regime (demarcated by Mandhane et al., 1974; Taitel and Dukler, 1976; Ghazar and Tang, 2007; Vaze and Banerjee, 2011) is characterised by intermittent appearance of liquid pocket occupying the entire area of the pipe. The liquid pockets are separated from one another by large elongated bubbles moving on top of the liquid layer. This flow regime can be subdivided mainly into plug and slug flows as shown in Fig. 1. Plug flow is observed at low liquid and gas flow rates (Ghazar and Tang, 2007; Vaze and Banerjee, 2011). It is generally known as an elongated bubble flow without the appearance of dispersed bubbles (Barnea, 1987) or considered as un-aerated liquid plug followed by a long “Benjamin” bubble as shown in Fig. 1(a). On the other hand, slug flow is characterized by intermittent appearance of aerated liquid slugs separated from one another by elongated slug bubble shown in Fig. 1(b).

Although these two sub-patterns of intermittent flow regime show nearly similar appearance, their fluid dynamic characteristics such as plug/slug frequency, length of liquid plug/slug, elongated plug/slug bubble shape geometry, local liquid plug/slug velocity and pressure drops are distinctively different (reported in Thaker and Banerjee, 2016). The differences are due to the onset and growth of aeration inside the liquid pockets (Thaker and Banerjee, 2016) in slug flow. Aeration inside the liquid pocket (or liquid slug) leads to bubble breakup, collapse, agglomeration, coalescence and collisions which are responsible for asymmetric distribution of void fraction inside the liquid slugs and erosion-corrosion problems in industrial piping systems (Thaker and Banerjee, 2016). It is thus essential to identify the exact transition condition for plug to slug flow and analyse the flow dynamics responsible for onset of aeration inside the liquid slug for accurate modelling of void fraction inside the liquid slug. This will help in refinement of erosion-corrosion inhibitor programme for industrial piping systems.

Abbreviations: FPS, **F**rame **P**er **S**econd; TPFTR, **T**wo **P**hase **F**low **T**est **R**ig; LDV, **L**aser **D**oppler **V**elocimetry; MRD, **M**ean **R**elative **D**eviation.

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Nomenclature

t	Time (s)
V	Velocity (m/s)
D	Diameter of pipe (m)
$\dot{m}$	Mass flow rate (kg/s)
A	Cross-sectional area of the pipe (m^2)
l	Length (m)
r	Radial distance (m)
R	Radius of pipe (m)
Re	Reynolds number
Greek Letters	
ρ	Density of fluid (kg/m^3)
μ	Dynamic Viscosity of fluid (N sec/m^2)
Subscripts	
G	Gas
L	Liquid
S	Superficial
max	Maximum
e	Entrance

Baker, 1954; Govier and Omer, 1962; Weisman et al., 1979; Barnea et al., 1980; Lin and Hanratty,1987; Ruder et al., 1989; Hand and Spedding, 1993; Ghajar and Tang, 2007; Vaze and Banerjee, 2011 have reported the transition of plug to slug flow in terms of inlet flow conditions based on flow visualization. According to their developed flow pattern maps, for a given liquid superficial velocity, the transition from plug to slug regime is expected to occur above a threshold value of gas velocity. Some studies reported in literature emphasizes on the flow dynamics (in terms of elongated slug bubble shape geometry) associated with the transition (Barnea et al., 1980; Ruder et al., 1989; Ruder and Hanratty; 1990; Fagundes Netto et al., 1999; Hanyang and Liejin, 2015; Oliveira et al., 2015). Barnea et al. (1980) distingushed plug and slug regime in terms of the absence of dispersed gas bubbles inside the liquid plugs. In support of the results of Barnea et al. (1980), Ruder et al. (1989) based on their flow visualization, described plug flow as being an unaerated liquid slug followed by a gas bubble with characteristics similar to a "Benjamin bubble' ' (Benjamin, 1968). Later, Ruder and Hanratty (1990) using their photographic visualization included qualitative characteristics of the front and rear part of the bubbles into this definition. They suggested that the transition from plug to slug regime occurs when the tail of the bubble approximates the form of a single-stage hydraulic jump. Although they measured different parameters of the flow, their contribution to the definition of plug flows was derived from qualitative analysis of a restricted number of images. Based on the observations of different behaviours for these two sub-regimes of intermittent flow, Fagundes Netto et al. (1999) suggested the use of the characteristic shapes of the front and rear of elongated bubbles as a means of accessing transition. They suggested the angle of the hydraulic jump at rear of the bubble as a possible criterion to define the transition threshold. More recently, Hanyang and Liejin (2015) and Oliveira et al. (2015) applied quantitative visualization technique (synchronised with image analysis) to investigate the shape of the rear and front parts of the elongated bubbles during transition from plug to slug regime. They concluded that the criterion for transition from plug to slug regime as suggested in the works of Ruder and Hanratty (1990) and of Fagundes Netto et al. (1999) requires additional investigation.

In summary, there is no local measurement reported in literature for analysing the transition from plug to slug flow pattern. Present study is an attempt to establish the flow dynamics associated with bubble entrainment inside the liquid slug using flow visualization and local velocity measurements. It is to be emphasized here that flow visualisation can identify transition condition (in terms of inlet flow conditions) only, but local velocity measurements are required for estimating the dynamics associated with the transition. In what follows in this article, the details of the experimental test facility and measurement uncertainties are described in Section 2. Experimental flow conditions used for detailed analysis of plug and slug flow sub-patterns of intermittent flow regime are reported in Section 3. Interfacial dynamics for plug flow and its transition to slug flow is analysed using captured visual images of plug/slug flow structures in Section 4. Single phase flow measurements are reported in Section 5 for validating the LDV measurements with the classical laminar flow theory. Results for two phase flow are documented in Sections 6 and 7 in terms of the local axial velocity behaviour within the liquid plug/slug and liquid film (underneath the large plug bubbles) regions. Major observations from the present work are highlighted in Section 8.

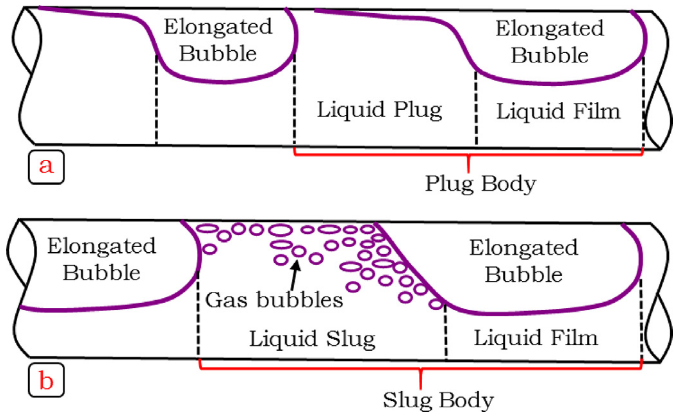

Fig. 1. Sketch of intermittent flow patterns: (a) Plug flow; and (b) Slug flow.

2. Experimental test facility

The experimental test facility mainly includes two-phase flow test rig (TPFTR), high speed photography system, and velocity measurement system. Detailed information on the TPFTR and high speed photography system are available elsewhere (Thaker and Banerjee, 2016). Velocity measurement system contains laser Doppler velocity (LDV) system synchronized with automated traverse. LDV system used for recording the local fluctuation in velocity consists of an argon-ion laser source of 5 W capacity, water chiller for maintaining a lower temperature for the laser, fiber light multi-colour beam generator which is used for splitting the coherent single laser beam from laser source into six beams, fibre optic single transceiver probe, photo detector module, frequency signal analyser, seeding particles, and data acquisition software. Moreover, fibre optic single transceiver probe is mounted on 3-dimensional (3D) automated traverse. This automated traverse has a resolution of 6.25 µm and unidirectional repeatability of ± 10 µm and is synchronized with data acquisition software. Actual photograph of LDV system with all mentioned components are shown in Fig. 2.

In the present work, single major component of local axial velocity is measured using higher intensity of two beams coming out from the multi-colour beam generator. These dual beams pass through an 80 mm diameter coaxial 5-beam three components fibre-optic single transceiver probe. This probe has a facility of combined transmitter and receiver unit which operates in back scatter mode and with the advantage of being permanently aligned for precise measurements. Moreover, transceiver probe focuses and