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On intermittent flow characteristics of gas–liquid two-phase flow ☆

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HIGHLIGHTS

- Unified correlations for intermittent flow characteristics are developed.
- Influence of inflow conditions on intermittent flow characteristics is analysed.
- Developed correlations can be used for effective design of piping components.

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ABSTRACT

Flow visualisation experiments are reported for intermittent regime of gas–liquid two-phase flow. Intermittent flow characteristics, which include plug/slug frequency, liquid plug/slug velocity, liquid plug/slug length, and plug/slug bubble length are determined by image processing of flow patterns captured at a rate of 1600 frames per second (FPS). Flow characteristics are established as a function of inlet superficial velocity of both the phases (in terms of Re_{SL} and Re_{SG}). The experimental results are first validated with the existing correlations for slug flow available in literature. It is observed that the correlations proposed in literature for slug flow do not accurately predict the flow characteristics in the plug flow regime. The differences are clearly highlighted in this paper. Based on the measured database for both plug and slug flow regime, modified correlations for the intermittent flow regime are proposed. The correlations reported in the present paper, which also include plug flow characteristics will aid immensely to the effective design and optimization of operating conditions for safer operation of two-phase flow piping systems.

1. Introduction

Intermittent type gas–liquid flow is observed in piping systems of various industrial applications includingpetroleum industries, nuclear power plants, chemical industries, geothermal industries, and desalination and process plants (Sun and Jepson, 1992; Jepson and Taylor, 1993). Such flow is common in long distance pipelines carrying natural gas and oil and air–water mixture in the form of steam. Presence of intermittent flow causes material degradation or wall thinning due to erosion-corrosion in piping components including tees, elbows, downstream of control valves, flow elements, reducers or orifices (Sun and Jepson, 1992). Wall thinning due to such erosion-corrosion had led to catastrophic failures in nuclear industries (Ahmed, 2012). In extreme conditions, intermittent flow is harmful to the structure of the piping systems due to (Ahmed, 2012):

- Enormous deviations in the gas and liquid flow rates,
- Significant momentum of long liquid plug/slug,
- Huge pressure losses,
- Resonance problems.

Qualitative and quantitative description of intermittent type two-phase flow is thus an active area of research for the economic and effective design, optimization of operating conditions and assessment of safety factors for these applications. Intermittent type two-phase flow patterns are observed for a wide range of inlet flow rates in a horizontal two-phase flow configuration as is illustrated in the classical flow pattern maps of Baker (1954), Mandhane et al. (1974), Taitel and Dukler (1976), Ghajar and Tang (2007) and Vaze and Banerjee (2011). Intermittent flow regime consists of two sub-patterns, namely plug flow and slug flow patterns. These sub-patterns are characterised by intermittent

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Nomenclature

L	length (m)
V	velocity (m/s)
D	diameter (m)
A	cross-sectional area of the pipe (m^2)
g	gravitational acceleration (m/s^2)
t	time (s)
X	axial coordinates (m)
f	frequency (1/s)
$\dot{m}$	mass flow rate (kg/s)
Re	Reynolds number
Fr	Froude number
St	Strouhal number

Greek letters

λ	no-slip holdup
α	volume fraction
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/ms)

Subscripts

G	gas
L	liquid
s	slug
I	intermittent
S	superficial
b	bubble
M	mixture
mod	modified
t	translational
d	drift

appearance of liquid pocket occupying the entire area of the pipe. A large elongated gas bubble moving on top of the liquid layer separates the liquid pockets from one another. These sub-patterns (plug and slug flow) are similar in nature but different in their flow characteristics due to the presence or absence of small bubbles in the liquid pockets. Slug flow is different from plug flow based on the aeration present inside the liquid pockets shown in Fig. 1. In plug flow, liquid plug (pocket) is observed free of bubbles (see Fig. 1(a)) while in case of slug flow large amount of aeration (in form of small bubbles) exists inside the liquid slug as shown in Fig. 1(b).

Dynamics of flow structure inside the liquid plug and slug are quite different due to certain intermittent mechanisms occurring during the flow. These mechanisms involve continuous elongation and degradation of plug bubble rim; bubble detachment from plug bubble tail; coalescence, collapse and break up of small bubbles inside the liquid slug (reported in Thaker and Banerjee, 2015). Because of these incessant mechanisms, mathematical treatment of such intermittent flow sub-patterns towards establishment of closure relationship for erosion-corrosion models or design of plug/slug catcher (separator) is difficult. Empirical observations and correlations for main characteristics of such flows are extremely important to close the models and to validate the numerical results. The most significant parameters that characterize intermittent flow sub-patterns are: gas and liquid phase distribution (void fraction and liquid holdup), liquid plug/slug velocity and its fluctuations, liquid plug/slug frequency, and liquid plug/slug length (Sharma et al., 1998). These parameters are transient due to the intermittent and irregular nature of flow. Different techniques for the measurement of these flow parameters in horizontal pipe have been reported in literature. Details of these measurements along with the test fluid and test section used in these experiments are summarised in Table 1.

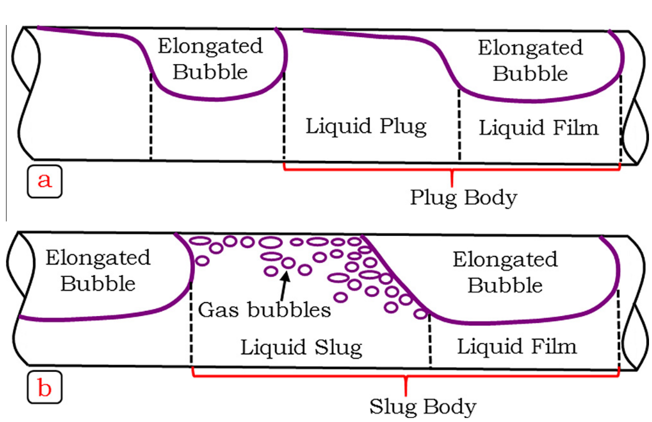

Fig. 1. Intermittent flow sub-patterns: (a) Plug flow; and (b) Slug flow.

Literature review reported in Table 1 shows measurements of statistical characteristics of slug flow. In addition, various models and correlations are proposed in literature for slug flow characteristics based on experimental measurements. However, these correlations for slug flow are not directly extendable to plug flow regime due to their distinct aeration characteristics. Towards establishing the flow characteristics for the entire intermittent flow regime (slug and plug flow), it is highly required to include the database for plug flow characteristics. The present work is an attempt in this direction. Two-phase air–water flow visualisation experiments are carried out on 25 mm inner diameter horizontal transparent pipe of 14 m length. Flow characteristics (including plug/slug frequency, liquid plug/slug velocity, liquid plug/slug length, and plug/slug bubble length) for intermittent regime are measured for 72 combinations of inlet flow conditions in terms of superficial Reynolds number of liquid (Re_{SL}) and gas (Re_{SG}). Flow characteristics are evaluated by processing the images captured at rate of 1600 FPS. Based on measured database, correlations are proposed for each flow characteristic in terms of inlet flow conditions. In what follows this paper, details of the experimental test facility are described in Section 2. Experimental flow conditions used for analysis and associated measurement uncertainties are reported in Section 3. Measurement procedure used for evaluating the flow characteristics are reported in Section 4. Detailed analysis of intermittent flow characteristics is reported in Section 5. Major observations of the present work are highlighted in Section 6.

2. Experimental flow facility for two-phase flow measurements

The experiments reported here are carried out on a *Two-Phase Flow Test Rig* (TPFTR) developed in Advanced Fluid Dynamics (AFD) laboratory at Department of Mechanical Engineering, Sardar Vallabhbhai National Institute of Technology (SVNIT), India. The test rig consists of various components: *Test Section*, *Air Circuit*, *Water Circuit*, *SCADA* (Supervisory Control and Data Acquisition), *Two-phase flow mixer*, and *High Speed Photography System*. The schematic diagram and actual images of different components for TPFTR are shown in Figs. 2 and 3 respectively.

Air is supplied in the TPFTR, using 'Atlas Copco' made industrial screw compressor. Air is filtered and condensates are removed

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