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Analysis of Gas-Liquid Intermittent Flow Sub-Regimes by Pressure Drop Signal Fluctuations

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Abstract – This work is devoted to pressure drop signals analysis to characterize the sub-regimes of intermittent flows. Experiments were carried out using air-water mixture in a horizontal 30 mm ID pipe. The sub-regimes observed are classified as Plug flow, Less Aerated Slug flow (LAS flow) and Highly Aerated Slug flow (HAS flow). Thus, a flow sub-regime map, based on the gas and liquid superficial velocities, is proposed. At first, the visual observation of the pressure drop signals showed peaks and a relatively constant pressure drop region. Furthermore, a gas and liquid superficial velocity surge induces an increase of the values of the pressure drop standard deviations. The gathered frictional pressure drop values are analysed using the Lockhart-Martinelli method. The best results are obtained for a coefficient C = 10. Finally, the comparison between the measured slug frequencies with some existing models showed that the correlations of Fossa et al. (2003) and Wang et al. (2007) predict well the experimental results.

***Keywords*:** Gas-liquid two-phase flow; Intermittent flow; Plug flow; Less Aerated Slug flow; Highly Aerated Slug flow; Pressure drop fluctuations.

1. Introduction

Among the flow pattern encountered in gas-liquid two-phase flow, the intermittent flow is the most complicated. The flow appears as the intermittent passage of elongated bubbles flowing above a liquid film and liquid slugs which bridge the pipe section area. The passage of these two structures leads to important fluctuations of flow parameters such as void fraction, pressure and velocity. In the industry, the presence of the intermittent flow induces an increase of erosion-corrosion phenomena and acceleration of pipe damage [1]. Thus, it is important to study the intermittent flow behaviour for a better understanding of this type of flow, and for a development of most accurate predictive models.

The study of two-phase flow at a laboratory scale has an advantage of controlling flow parameters such as pipe diameter, phasic flow rates including their physical properties. Transparent pipes are used for visualization purposes in addition to temporal flow parameters recordings to study the flow dynamics [2]. The important fluctuations encountered in the case of intermittent flows make the recourse to these tools very interesting. Due to its simplicity, the pressure signal (absolute or differential) is widely used in the industry to characterize the parameters of intermittent flows.

Weismann et al. [3] reported that the pressure drop signature of each horizontal flow regime is different. In case of slug flow the authors noted large amplitude fluctuations. Lu et al. [4] studied the absolute and differential pressure fluctuations behaviour in case of slug flow in a 40 mm ID pipe. The authors found that an increase of gas and liquid superficial velocities induces a raise of the standard deviation of absolute and differential pressure. Arabi et al. [2] used the pressure drop signal to study the behaviour of slug flow upstream and downstream of a sudden expansion. The study was carried out using notably the standard deviation and also the Probability Density Function (PDF). It was found that the dissipation of the slug flow downstream the singularity leads to the unimodal distribution disappearance of PDF. More recently, Torres et al. [5] acquired a pressure signal for different conditions using an air-glycerine mixture and 76.2 mm ID pipe. The study concerned the PDF, the mean and the standard deviation of the pressure drop and included the Root Mean Square (RMS) pressure drop, which is calculated from the mean and standard deviation of the pressure drop. In Ref. [6], our group have studied the stratified/intermittent flow transition. In addition to photographs of flow regimes, a pressure drop signal was used to identify the onset of intermittent flow, which correspond to the zone when the liquid slugs begin to appear.

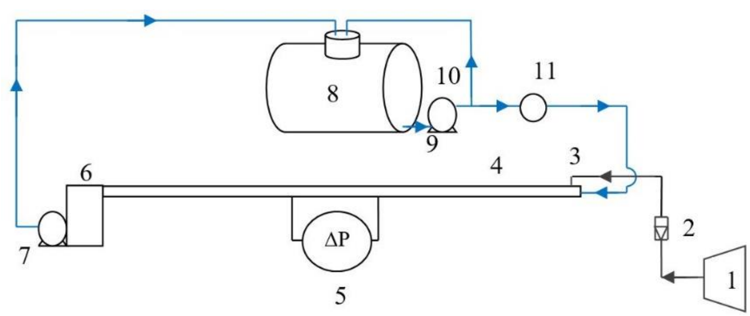
In addition to study of the flow behaviour using statistical tool, the pressure drop signal can be used to quantify the slug frequency and the frictional pressure drop. Unlike to single phase flow, the frictional two-phase flow pressure drop is not well predicted, as demonstrated by the large and various number of exiting models in the literature [7, 8]. The slug frequency refers to the number of liquid slugs passing by a point of the pipe through a period of time [9]. The slug frequency can be used as input parameter for slug flow model [10]. This parameter is also complicated to estimate.

The intermittent flow can be classified into sub-regimes. Some authors used the mechanism of formation of slugs as criterion to classify the sub-regimes [9]. In 2015, Thaker and Banerjee [11] used the shape of liquid slugs/gas interface and the presence of aeration inside the liquid slugs as tool to classify the sub-regimes. In other work [1], the same authors proposed to consider three sub-regimes: plug flow, Less Aerated Slug flow (LAS flow) and Highly Aerated Slug flow (HAS flow). In plug flow, the liquid slugs are unaerated, while in the LAS and HAS flow, they transport a small and large quantities of gas bubbles within them, respectively. The behaviour of flow parameters and the erosion-corrosion phenomena due to the flow of the two structures of the intermittent are found different for each sub-regime by the authors.

If the pressure drop fluctuations, the pressure drop and slug frequency have been largely studied in the literature, the study carried out by taking out the nature of the sub-regimes are still scarce. In order to contribute in this area, a series of acquisitions were carried out on 30 mm ID pipe. The air and water was used as working fluids. The influence of the nature of the sub-regimes as well as the gas and liquid superficial velocities on the fluctuations of pressure drop are studied. The obtained frictional pressure drop and the slug frequency, for each sub-regime, are compared with some existing models in the literature.

2. Experimental Setup

The experiments were performed using air-water mixture and horizontal 30 mm ID pipe using air-water test facility illustrated in Fig.1. The detail of this experimental setup can be found in our previous works [8, 9, 12, 13]. The air flows in an open circuit while the water is re-used after separation. The air and liquid flow rate are measured using rotameter and ultrasonic flowmeter respectively. The accuracies are 1.57 l/mn and 0.66 l/mn, respectively. A differential pressure transducer type Freescale MPX-2010DP, with a relative uncertainly of 2%, is used to measure the pressure drop. These terminals are connected to lower part of the pipe at distance of 173.33 and 193.33 D from the input mixer. The obtained signal of pressure drop is filtered and digitalized using an acquisition card and a portable PC.



(1): compressor; (2): gas flowmeters; (3): two-phase flow mixer; (4): 30 mm ID pipe; (5): differential pressure transducer; (6): decantation tank; (7): pump; (8): liquid tank, (9): pump; (10): by-pass; (11): ultrasonic flowmeter.

Fig. 1: Diagram of the experimental setup used in this study.

3. Results and Discussion

3.1. Sub-regimes and Flow Map

This experimental investigation was performed over forty (40) couples of phasic's superficial velocities as follows: $0.786 \leq V_{SG} \leq 3.537$ m/s and $0.141 \leq V_{SL} \leq 0.778$ m/s. For these conditions, the three sub-regimes reported in the literature were observed. The plug flow, when the liquid slugs were free of gas bubbles, was observed for the case of $V_{SG} = 0.786$ m/s. The LAS flow was present for $1.179 \leq V_{SG} \leq 1.965$ m/s, while the HAS flow was reported for high values of gas superficial velocities. The presence of large quantities of small gas bubbles and eddies in the nose of liquid slugs allows to distinguish HAS flow from LAS flow [1, 9, 11]. Thus, only gas superficial influences the transition between the three sub-regimes as it was reported previously in the literature [1, 8, 9, 12, 13]. The plot of experimental conditions of the present study using V_{SL}-V_{SG} plane, in Fig. 2, has allowed to obtain the flow regimes map. A photography of an example of the liquid slugs observed for each sub-regime is showed. The stratified/intermittent flow transition line obtained in our previous work [6] is also represented in Fig. 2.

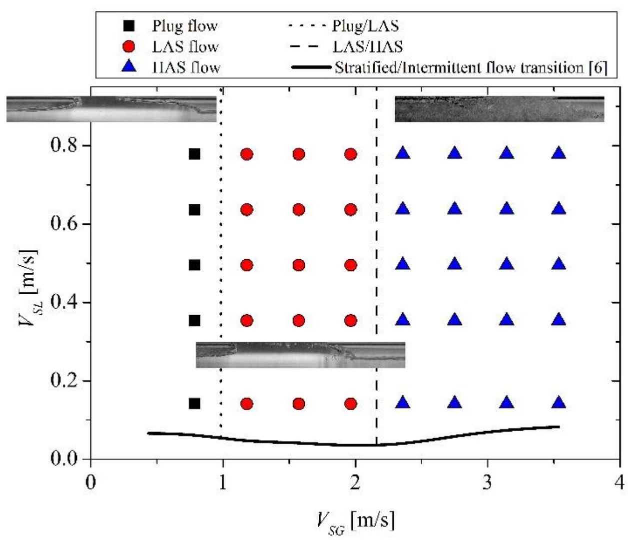


Fig. 2: Proposed sub-regime flow maps.

3.2 Pressure Drop Signals

Fig. 3 represented a portion of collected signals of a duration of 15 s for a case of $V_{SL} = 1.572$ m/s and $V_{SL} = 0.495$ m/s. It can be seen clearly that the signal is composed of peaks and passive region when the pressure drop is relatively constant. According to Refs. [2, 3, 6], two zones represent the passage of liquid slugs and gas pockets flowing on film liquid, respectively.

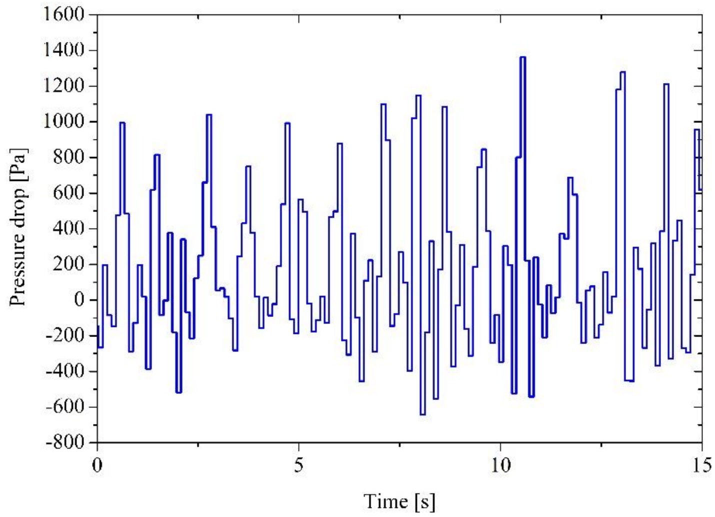


Fig. 3: Example of pressure drop signal collected.

3.3 Standard Deviation

The standard deviation is a statistical tool used to measure the dispersion of a set of values. The standard deviation (*Std*) of the recorded values of the pressure drop gradient for each signal (ΔP_i) is calculated using Eq. (1) and represented as function of V_{SG} in Fig. 4. We can see clearly that an increase of gas and liquid superficial velocities leads to a raise of standard deviation, as found previously [2, 4].

$$Std = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Delta P_i - \overline{\Delta P})^2} \tag{1}$$

Where N the number of sample and $\overline{\Delta P}$, the mean pressure drop gradient, given by Eq. (2).

$$\overline{\Delta P} = \frac{1}{N}\sum_{i=1}^{N}\Delta P_i \tag{2}$$

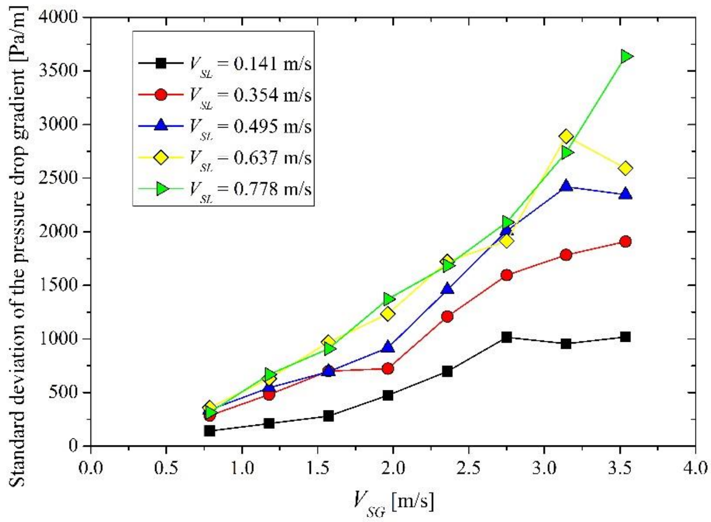


Fig. 4: Evolution of the standard deviation of the pressure drop gradient in function of gas superficial velocity.

3.4 Frictional Pressure Drop

The mean value of the pressure drop signal recorded, in each case studied, represent the value of the frictional pressure drop. Indeed, in the case of horizontal adiabatic flow, the acceleration and gravity term of pressure drop is neglected and equal to zero, respectively [8, 14]. The present data obtained for the three sub-regimes are analysed using the Lockhart-Martinelli approach. For this purpose, the data are represented using the two-phase frictional multiplier (ϕ_L^2) as function of the Lockhart-Martinelli parameter (X) in Fig. 5. These two dimensionless numbers are given by Eqs. (3) and (4), respectively.

$$\phi_L^2 = \frac{\left(\frac{dP}{dL}\right)_{f,TP}}{\left(\frac{dP}{dL}\right)_L} \tag{3}$$

$$X = \sqrt{\frac{\left(\frac{dP}{dL}\right)_L}{\left(\frac{dP}{dL}\right)_G}} \tag{4}$$

Where $\left(\frac{dP}{dL}\right)_L$ and $\left(\frac{dP}{dL}\right)_G$ are the frictional pressure drop for liquid and gas single phase. The latter are defined by the Eq. 5.

$$\left(\frac{dP}{dL}\right)_i = \frac{f_i G_i^2}{2D\rho_i} \tag{5}$$

Where the indice (i) refer to liquid (L) or gas (G) phase. D, G, ρ and f are respectively the pipe diameter, mass flux, density and Darcy-Weisbach friction factor. The latter is calculated using Eqs. (6) and (7) for the case of laminar and turbulent flow, respectively.

$$f_i = 64/Re_i \quad (6)$$
$$f_i = 0.3164/Re_i^{0.25} \quad (7)$$

Where Re_i, the Reynolds number of the phase i, given by:
$$Re_i = \frac{G_i D}{\mu_i} \quad (8)$$

Chisholm [15] has proposed to correlate the two-phase multiplier and the Lockhart-Martinelli parameter using the following equation:
$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (9)$$

The Chisholm parameters (C) takes the value of 10 or 20 according to the fluids state laminar/turbulent or turbulent/turbulent. Based on its experimental results obtained in 30 mm ID pipe, Sassi et al. [16] proposed recently to consider C = 21.
In addition to the present results, the data obtained by Thaker et al. [17] using air-water mixture and 25 mm ID pipe are displayed in the fig. 5. We can observe from this figure that values of Chisholm parameters of 20 and 21 overestimate the experimental values. The large dispersion observed for the case of C = 10 highlights the limit to correlate the data for the three sub-regime using a single value of this parameter.

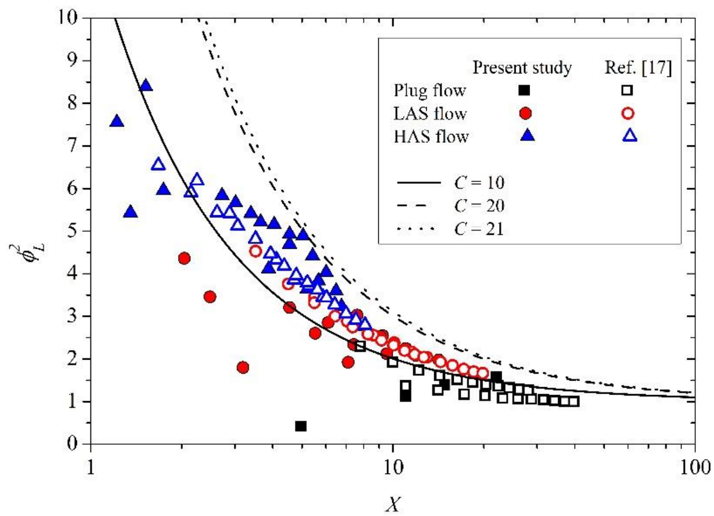


Fig. 5: Representation of the frictional pressure drop results using the two-phase multiplier and Lockhart-Martinelli parameter.

3.5 Slug Frequency

According to Arabi et al. [9], the Power Spectral Density (PSD) is employed to pressure drop signals recorded in order to extract the dominant frequency, considered as the slug frequency. The recorded slug frequency in the present study, as well as with those obtained by Thaker and Banerjee [1] using air-water and 25 mm ID pipe, are represented together in Fig. 6 using gas Strouhal number (St_G) and input liquid fraction (λ_L). The two dimensionless number are given by the Eqs. 10 and 11, respectively. The existing predictive models to slug frequency which used these dimensionless numbers [18-20] are also displayed in the Fig.6. It appears clearly that the correlation of Abdulkadir et al. [20] overestimates the experimental slug frequencies recorded in both studies. The two others correlations give better predictions.

$$St_G = \frac{f_S D}{V_{SG}} \tag{10}$$

$$\lambda_L = \frac{V_{SL}}{V_{SL} + V_{SG}} \tag{11}$$

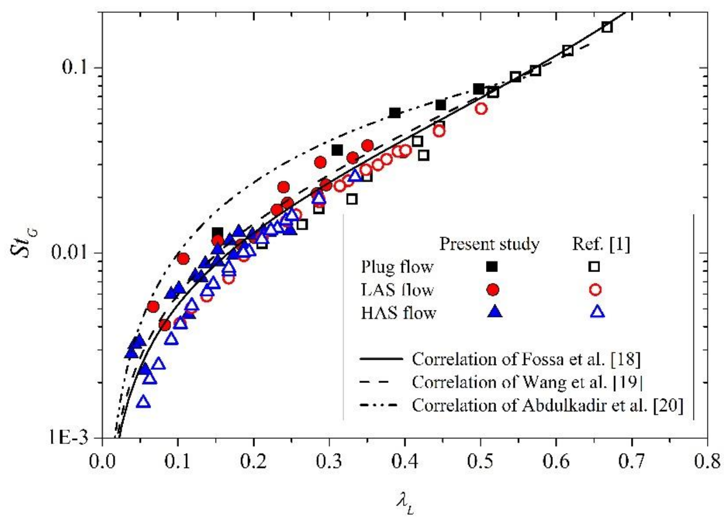


Fig. 6: Representation of the slug frequency results using the gas based Strouhal number and input liquid fraction.

4. Conclusion

An experimental characterization of the horizontal sub-regimes using the pressure drop signals were performed using a 30 mm ID pipe. The sub-regimes were identified by observations of the liquid slugs/gas pocket interface and the aeration of the liquid slugs. It was found the presence of Plug flow, Less Aerated Slug flow (LAS) and Highly Aerated Slug flow (HAS flow). The plot of the experimental conditions of each sub-regime on the flow map allowed to demonstrate that only gas superficial velocity plays on the role of Plug-to-LAS flows and LAS-to-HAS flows transitions.

As pointed out in many works, the pressure drop signals in the case of intermittent flow were composed of peaks of large amplitude and zone where the pressure drop was relatively constant. For each case, the standard deviation of the collected pressure drop was quantified. It was found that for each value of liquid superficial velocity, the increase of gas superficial velocity induces an increase of the values of this parameter

In addition, the frictional pressure drop and the slug frequency are extracted from the signals. The obtained values were compared with some existing models. The analysis of the frictional pressure drop results using the Lockhart-Martinelli approach showed that the Chisholm parameter value of 10 gives the best results. The correlation of Fossa et al. [18] and Wang et al. [19] predicted well the slug frequency results.

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