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Experimental Investigation of the Transition from Segregated Flow Regime to Intermittent Flow Regime in a Horizontal Pipe

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Abstract - The importance of two-phase flows in the industry is well established. The prediction of the flow regimes is of paramount importance. For instance, in the transport of hydrocarbon, the flow along the pipe often involves instabilities that can cause transitions between flow regimes, such as the transition from segregated to intermittent flow, resulting in pressure oscillations that can cause significant pipe damage. Understanding and studying the parameters influencing this transition is important for correct regime forecasting and pipe design. This study aims, firstly, providing a classification of sub-regimes in a 40 mm pipe, knowing that flow regimes are essential and useful for modelling hydrodynamic parameters and heat transfer in two-phase gas-liquid flows. Moreover, the present work will be focused on the intermittent regime in which oscillations generated by the passage of liquid slugs may cause pressure oscillations that can lead to pipe leaks. Thus, accurate prediction of the onset of intermittent flow and a better knowledge of the conditions under which it occurs are of great importance.

Keywords: Horizontal gas-liquid two phase flow; flow map; stratified flow; intermittent flow; sub-regimes; pressure drop fluctuation.

1. Introduction

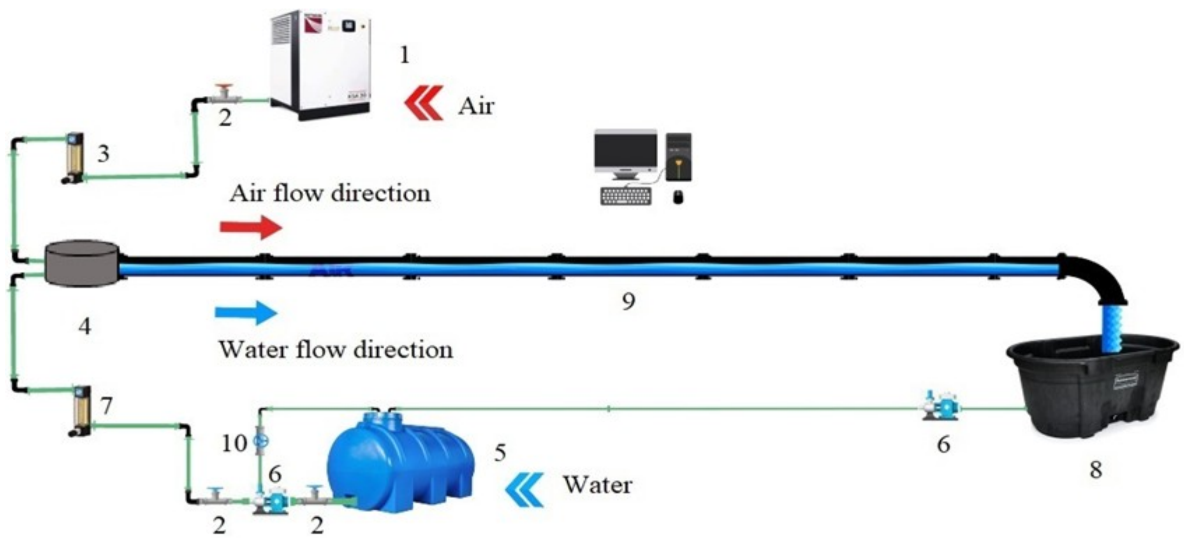
Two-phase gas-liquid flows are commonly observed in various industrial sectors, including petroleum industry, chemical engineering, nuclear engineering, heat exchangers. In horizontal pipes, such flows are generally classified into four distinct regimes: stratified, intermittent, bubbly and annular. Each flow regime is further subdivided into sub-regimes. Several researchers have taken a particular interest in the stratified regime [1-3]. Based on the observation of these sub-regimes, various flow maps have been developed [4-5], including the analysis of the transition to intermittent flow. However, the classification of flow regimes remains complex due in particular to the influence of pipe geometry and the properties of the fluids involved [6].

Although abundant studies have been devoted to the transition from flow patterns to intermittent flow, there are many differences between individual flow pattern maps, depending on experimental conditions and other independent parameters. Further study is therefore required to determine the reference for piping system design[7].

In the present work, a flow map of the intermittent and segregated flow regimes is built from experiments carried out in a two-phase air-water loop with an internal diameter of 40 mm. Besides, the onset of the intermittent flow line is compared to other lines found in the literature for other diameters. It was found that dimensionless mean pressure drops can be used to detect the transition from segregated flow to intermittent flow.

2. Materials and method

The experiment of this study was carried out at the Laboratory of Theoretical and Applied Fluid Mechanics (LMFTA) in the Faculty of Physics at the University of Science and Technology Houari Boumediene (USTHB). Data acquisition are ensured through the use of a Honeywell 26PC01SMT differential pressure sensor and a pico Technology ADC-20 acquisition card. The pipe is constituted of several 2 m long sections, entirely made of transparent acrylic resin (PMMA).



1: Air Compressor; 2: Valve, 3: Air flow meter; 4 : Two-phase flow mixer; 5: Water tank;
6 : Pump; 7: Liquid flow meter; 8: Decantation tank;9: 40 mm ID pipe;10 :By pass;

Figure 1 : Experimental setup.

3. Results and discussion

Experimental data collection was conducted by varying the value of the superficial Froude number of liquid and gas, these are represented on a flow regime map, as shown in Fig. 2. The dimensionless values of liquid and gas phase (Fr_{SG} and Fr_{SL}) are represented as abscissa and ordinate of the flow regime map, based on the superficial velocity of liquid (V_{SL}) and gas (V_{SG}) respectively.

$$Fr_{SL}=\frac{V_{SL}}{\sqrt{gD}}\sqrt{\frac{\rho_L}{\rho_L-\rho_G}} \tag{1}$$

$$Fr_{SG}=\frac{V_{SG}}{\sqrt{gD}}\sqrt{\frac{\rho_G}{\rho_L-\rho_G}} \tag{2}$$

This dimensionless parameter (Fr) captures the ratio of inertia to gravity forces, a low Fr value indicates that the force of gravity is greater.

Different colors are used to distinguish the flow patterns, black lines are transition lines between different sub regimes of flow, red line represent transition from stratified sub regimes to intermittent regime. The classification is based on visualization, observation sub-regimes: smooth laminate (SS), two-dimensional waves (2D), three-dimensional waves (3D), roll waves (RW), Entrainment droplet (ED) and pseudo-slug (PS). These sub-regimes are the same as those observed by [5] and [8], who used a 26 mm internal diameter pipe, or [1] and [9] in 77.9 and 51 mm pipes respectively. Note that these last two studies did not report the existence of PS.

For a fixed liquid Froude number, the first waves appearing with an increasing gas Froude number are small amplitude, the interface of two-dimensional (2D) waves is basically flat without curvature at the interface, the waves are regular in appearance. After that three- dimensional (3D) waves are observed, the interfacial wave structure changes into irregular, the increase of Fr_{SG} causes coalescence of 3D waves to induce the appearance of roll waves (RW) which are large but not sufficient to block the pipe. Entrainment droplets (ED) are present simultaneously with the roll waves, some of the liquid from the RW is pulled off in the form of droplets on the upper wall of the pipe due to the gas acceleration. The deposition of droplet on the pipe wall is one of the initial mechanisms for the occurrence of the annular flow ([10]).

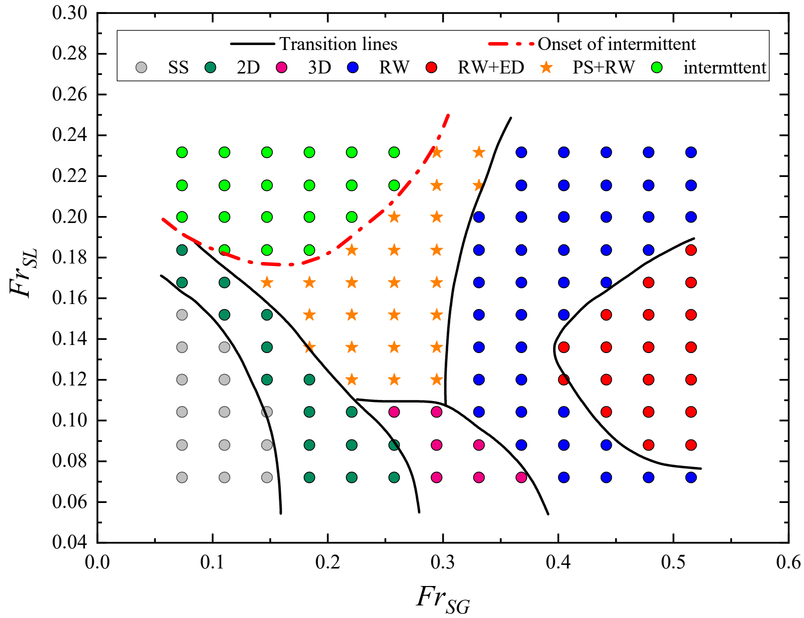


Figure 2. Proposed flow pattern.

The increase in liquid Froude number announces the transition to intermittent operation, passing through a zone of PS, in which ephemeral slugs are formed. These slugs are driven out as quickly as they are formed, and the increase in Fr_{SG} does not support their stability. Under these conditions, the flow pattern is not clearly distinguishable between roll waves and slug, and thus is called as pseudo slug flow.

Temporal fluctuation of pressure drop signal depends on the two-phase flow pattern [11]. Conversely, the zone occupied by each phase and their dynamic characteristics specify and impact the intensity of pressure fluctuations [12,13]. Instantaneous pressure drop signals recorded by the pressure transducers for different regimes of two-phase flow are illustrated in Figure 3. Stratified smooth and 2D waves shows negligible fluctuation. For RW pressure drop signal fluctuates around a higher average than 3D waves. the signal shows small peaks when the droplets are pulled out. Intermittent flow represents more pressure pulsations as compared to stratified sub regimes except PS, and this is due to the chaotic behavior of the two phases. When the droplets are pulled out the signal is characterized by a higher average of pressure drop and shows small peaks.

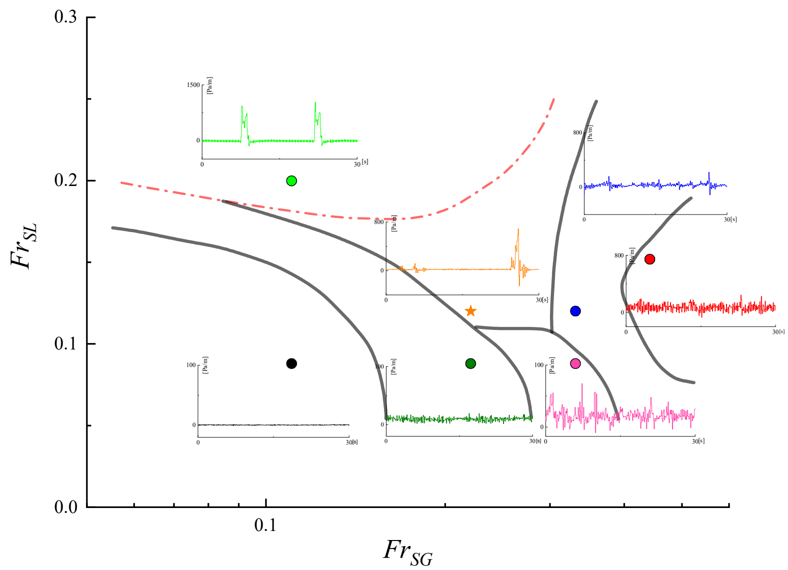


Figure 3. Pressure drop signal on flow pattern.

The transition lines from segregated to intermittent flow, obtained in the present study, are plotted with those obtained by different authors using an air-water mixture. the onset of the intermittent flow in this study occurs at higher Fr_{SL} when $Fr_{SG} < 0.17$, above this value, the effect of diameter seems difficult to determine.

Representing the onset of intermittency using the dimensionless Froude numbers makes it much easier to locate the stratified-to-intermittent flow transition interval. As it is presented on Table 1. Transition from segregated to the intermittent flow.

	$Fr_{SL} < 0.076$	$0.076 \leq Fr_{SL} \leq 0.2$	$Fr_{SL} > 0.2$
$Fr_{SG} < 0.17$	Segregated zone	Onset zone	Intermittent zone

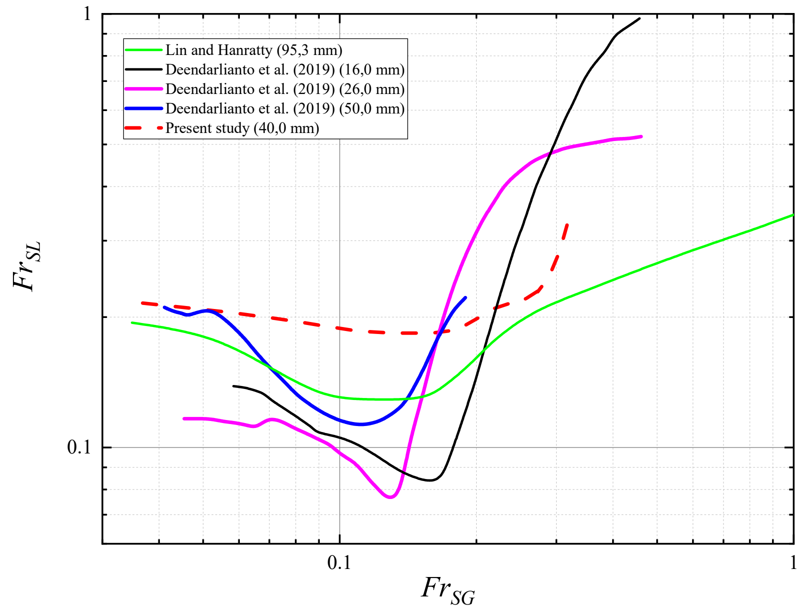


Figure 4. Transition line from segregated to intermittent flow.

To confirm and verify that this is an onset and a transition to the intermittent regime, we have chosen to represent our data in the dimensionless group proposed by [14] for the correlation of segregated regimes. The representation of normalize pressure drop gradient for liquid phase (PL^*) as function of the ratio of modified Froud number for liquid and gas phases (X^*) Figure 5. These parameters allow to align the different stratified flow sub regime as suggested and correlated by [14]. The SS, 2D, 3D, RW and ED are presented as stratified flow, and are well aligned. The Al-Sarkhi and Sarica correlation (5) is valid for $X^* < 0.5$. When the onset of the intermittent flow occurs, the data deviates from the correlation of [14], as well as PS+RW considerate as structure of initiation of Intermittent flow.

$$PL^{¿}=D\frac{\frac{dP}{dL}}{\frac{1}{2}\rho_L V_{SL}^2} \quad (3)$$

$$X^{¿}=\frac{Fr_{SL}}{Fr_{SG}}$$

$$X^{¿}=\sqrt{\frac{\rho_L}{\rho_G}}\frac{V_{SL}}{V_{SG}} \quad (4)$$

$$P^{¿}=0.075\,X^{¿(-1.808)} \quad (5)$$

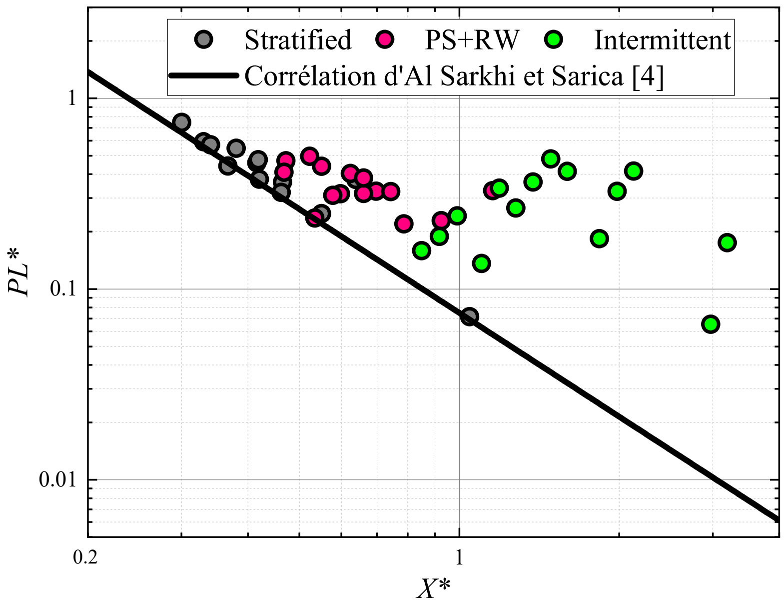


Figure 5. Detection of transition to intermittent flow using the PL* vs X* representation.

4. Conclusion

In this work, an experimental study of transition from the segregated flow regime to the intermittent flow regime in a horizontal pipe was presented. Based on experimental observations, a new flow map of stratified and intermittent flow for a 40 mm pipe has been proposed.

The following conclusion may be drawn:

- The pressure drop signals have a specific signature for each sub-regime of the stratified flow.
- The progressive increase in liquid superficial velocity V_{SL}, for a given gas superficial velocity V_{SG}, enables the first intermittent structures to be observed.
- The dimensionless representation of normalized pressure drops using PL^* vs. X^*, enables the transition to intermittent flow to be detected. The segregated regime data are in good agreement with the correlation of [14].
- The transition to intermittent flow is accompanied by a deviation in the data from this model, Pseudo slug and Roll waves are transitional structures.

Acknowledgements

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