Escola de Primavera de Transição e Turbulência Blumenau 2020

ABCM Associação Brasileira de Engenharia e Ciências Mecânicas

12th Spring School on Transition and Turbulence
September 21st-25th, 2020, Blumenau, SC, Brazil

EPTT-2020-0082
ANALYSIS OF CHARACTERISTICS OF HORIZONTAL GAS-LIQUID INTERMITTENT FLOW USING HIGH-SPEED DIGITAL CAMERA

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Abstract. *Intermittent gas-liquid turbulent flows are characterized by the alternating passage between the elongated bubbles that occupy the upper part of the pipe followed by a piston of liquid that occupies almost the entire cross section of it. In horizontal flows, this flow regime occurs in a wide range of flow conditions and is therefore quite common in many industrial processes. The intermittent pattern is divided between plug and slug flow and they are inherently unstable and complex, which requires detailed knowledge of their characteristics. In this work experimental series of intermittent gas-liquid two-phase flows had been carried out in a 74 mm internal diameter transparent acrylic horizontal pipe. These experiments were performed in order to investigate topological characteristics of the passage of the intermittent flow structures in different operational conditions. Air and water were used as the test fluids. The flow behavior was recorded using a high speed camera that was installed at two axial position of the pipe to follow the flow evolution. The pressure signals were also acquired, both to support the observed phenomena, but also to analyze the effects of increased superficial velocities on pressure fluctuations. The intermittent flow was successfully recorded and characterized on the basis of the visualization study from different couples of test condition of superficial water and air velocities. Analyzing frame by frame, it is possible to extract structural parameters from different slug flow. In this way, it is possible to evaluate the influence of the increase or decrease in the superficial velocities of each phase on the flow characteristics such as frequency, length of the slug body, liquid level and velocity of travel of the slug in the pipe.*

Keywords: *Intermittent flows, flow structure, two-phase flow parameters, high-speed camera.*

1. INTRODUCTION

In several industrial processes there are simultaneous flow of gases and liquids inside pipes. These flows are called biphasic flows and they are classified according to the spatial distribution of the phases during their displacement inside the pipe, named flow pattern or flow regime. The occurrence of each flow pattern depends on several factors, such as flow-line geometry, size, and orientation, individual phase flow rates, and component transport properties (density, viscosity and surface tension) (Abbagoni and Yeung, 2016; Arabi et al., 2020; Mostafa Ghiaasiaan, 2007; Rajan et al., 1993; Shoham, 2006; Thorn et al., 2013). The flow patterns in horizontal pipes are basically divided in segregated (annular and stratified), dispersed (bubbly) and intermittent flow (plug and slug). This last mentioned pattern is considered the most complex due to its main feature: its unstable and random behavior. And the occurrence of random plug or slug structure can produce high fluctuation of the transient pressure gradient and vibration on the piping, among problems such as erosion-corrosion on several piping components (Deendarlianto et al., 2019, 2016; Dinaryanto et al., 2017; Thaker and Banerjee, 2016).

Intermittent flow is characterized by the alternating passage of liquid pockets, which can occupy the entire area of the tube, followed by elongated bubbles, moving along the top of the tube. As this flow occurs under a wide range of operating conditions, as shown by different classical flow pattern maps (Baker, 1953; Mandhane et al., 1974; Taitel and Dukler, 1976; Weisman et al., 1979), its occurrence is very common in several industry processes. Although they present similar shape, some authors differ the plug from slug by the absence of dispersed gas bubbles inside the liquid slug and by the shape of the elongated bubble tail, which are usually similar to the front or in the shape of stairs (Barnea et al., 1980; Kong et al., 2018; Ruder and Hanratty, 1990; Thaker and Banerjee, 2016). The presence of gas bubbles inside the liquid slug is the result of a higher level of turbulence inside the slug body (Arabi et al., 2020; Kesana et al., 2017). It is important to note that these physical differences are a consequence of the differences between the flow dynamic characteristics of this patterns such as pressure drop, local void fraction, gas-bubble shape, length and shape of the liquid slug, and local flow velocity (Arabi et al., 2020). In addition to the distinction between plug and slug, within intermittent flow, more specifically, in slug flow, over time, other distinctions have emerged as pseudo-slug (Hanratty, 2013; Kesana et al., 2017; P Y Lin and Hanratty, 1987; Soleimani and Hanratty, 2003) and roll waves (Hanratty and Hershman, 1961; Kadri et al., 2009). The roll waves, in fact, are a type of waves that occur in stratified wavy flow near the transition to slug flow. Including, slugs can arise from their coalescence (Hanratty, 2013; Lin and Hanratty, 1987).

The intermittent flow starts from the transition with the stratified pattern. The latter occurs at lower gas and liquid flow rates. As that flow rates increase, more unstable flows form, with the appearance of waves at the interface. As the liquid velocity increases, the plug flow is formed. If the gas flow rate increase, instead of the liquid, the wavy stratified pattern would occur. From this last pattern, with the increase in the liquid flow rate, or, from the plug flow, with the increase in the gas flow rate, finally, slug flow occurs. The mechanisms of emergence of these waves, which lead to the formation of plug or slug flow, have been extensively explained by several researchers.

One of the first theoretical predictions of this disturbances were based on the classic Kelvin-Helmholtz instability of a stratified flow which results from Bernoulli effect. This occurs when Bernoulli force exceeds the stabilizing effect of the gravity that attenuates the disturbance of the gas-liquid interface (Vaze and Banerjee, 2011). Kordyban and Ranov (1970) extended this theory to ideal inviscid fluids (Inviscid Kelvin-Helmholtz IKH). This theory explained that the formation of slug occurred from the growth of infinitesimal disturbances at the interface of a stratified flow and the authors obtained an instability criterion for the flow in a rectangular channel. Taitel and Dukler (1976), applied the same mechanism a solitary wave of finite amplitude in pipe flow and established a critical condition for the gas velocity for the slug flow transition to occur. Lin and Hanratty (1986) found that the classic Kelvin-Helmholtz approach incorrectly predicts the stability of stratified flows because it does not consider the effects of viscosity. So, they included the effects of the drag of the gas and the resisting stress of the wall on the liquid and better predictions for the onset of slug flow were obtained. These changes in theory made the air-water system more unstable, as the onset of long wavelength interfacial disturbances is expected to occur at lower gas velocities (Hanratty, 2013). With this, this theory came to be called Viscous Kelvin–Helmholtz (VKH) or Viscous large-wavelength instability (VLW). However, Andritsos et al. (1989) when evaluating the effect of liquid viscosity and their measurements agree with the VLW theory at viscosities of 16 cP or less. The results obtained for viscosities of 70 and 100 cP were quite different from that predicted by the theory. Another approach, complementing Kelvin-Helmholtzs instability, is to consider the stability of slugs (Bendiksen, 1984; Hurlburt and Hanratty, 2002; Ruder et al., 1989; Woods and Hanratty, 1996). A stable slug is one that the adjacent liquid rates are no less than the rates at which the liquid to shed in the rear region and when the flow reaches this condition it is considered to be fully developed (Kadri et al., 2009; Ruder et al., 1989). Ruder et al. (1989) developed conditions for the existence of stable slugs based on a critical height of the liquid layer. However, this prediction is independent of the gas density and requires the assumption that the effects of aeration and surface tension are negligible.

Hurlburt and Hanratty (2002) made a systematic comparison between the theories mentioned above. According to the authors, three different theories can be used to define the transition to slug flow: Viscous large-wavelength instability for air-water systems with low surface gas velocities, Kelvin-Helmholtz instability for viscous liquids and slug stability theory for flow with high gas velocities, high gas densities and in the other cases mentioned above. Ujang et al. (2006) evaluated statistically distributions of time intervals between slugs and their lengths and, mainly, the evolution of these distributions along the pipe. They showed that slug time intervals and lengths were best represented by a lognormal distribution and when measured very close to the inlet they were represented by an exponential distribution. The results also shown that the standard deviation of time intervals decreased and the slug lengths did not vary systematically, but their mean values increased along the pipe. According to Gu and Guo (2008) the slug initiation mechanism depends only on the superficial gas velocity and its increase leads to a great decrease in the peak frequency close to the entrance and in the frequency of fully developed slugs. Recently, Dinaryanto et al. (2017) investigated initiation and fully developed slug flow using in a pipe with 10 m length. Their results shown that the onset of the slugs occurred between 0-75 D and between 75-210 D the flow was considered to be fully developed. When superficial gas velocity increases with a constant superficial liquid velocity, slug flows were formed at the closer position to the inlet. The slug flow was formed from the following mechanisms: wave coalescence, Kelvin-Helmholtz instability and disturbance waves.

In addition to determining the mechanisms of slug formation, knowledge of how its characteristics change as it travels down the pipe is also important for its modeling. The purpose of this work is to investigate the evolution of slug flow characteristics inside a horizontal pipe by experimental flow visualization study using a High-Speed Camera. With the analysis of images captured in high resolution, in addition to providing a better understanding on the slug flow structure evolution, they can contribute to the development of theoretical models and the validation of CFD codes.

2. MATERIALS AND METHODS

A schematic representation of the experimental unit used in this work is presented in Fig. 1. The horizontal test section is made of transparent acrylic with inner diameter of 0.074 m and total length of $L/D \cong 95$. The water was fed by a centrifugal pump (model BTM-30, Bombetec) coupled to a 2 CV motor (WEG) and air was supplied by a radial compressor (model CJ4, Ibram) coupled to a 4 CV motor (WEG). Air and water were mixed at the entrance to the test section by a tee mixer and their flow rates were metered by a Venturi flowmeter and an orifice plate, respectively. After the experiment, two-phase mixture was separated in a gravitational separation tank where the air was exhausted into the atmosphere and the water returns to reservoir tank.

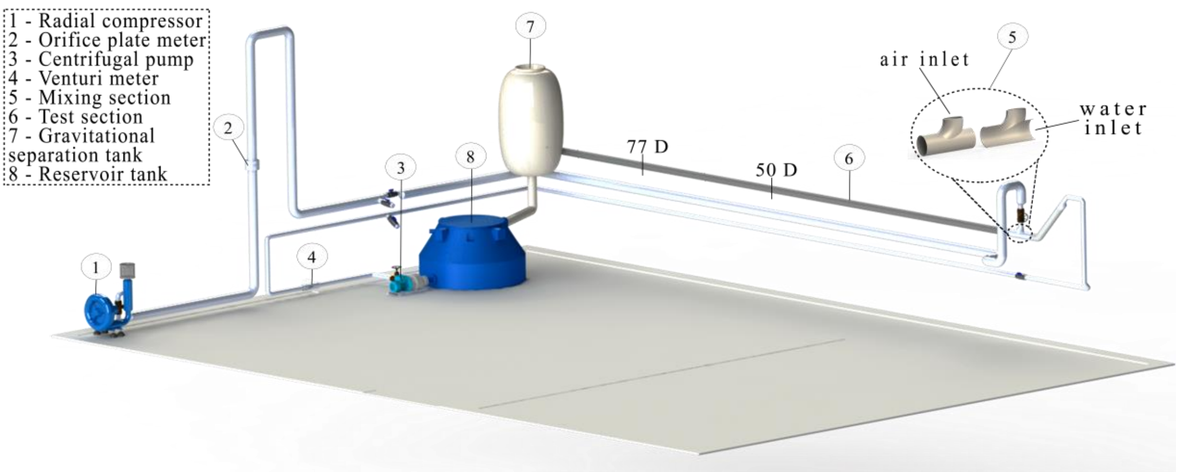

Figure 1 – Schematic representation of the experimental facility

The images of the intermittent flow structures were captured by a High-Speed Camera model IDT OS3-V3-S1 at a rate of 7790 FPS and at resolution of 1280 x 1024. The frame acquisition rate used is the maximum allowed by the equipment because, as it is an initial study, it was decided to obtain the largest possible number of flow details. For this same reason, no digital image processing was applied in this work. A continuous LED light source was placed in front of the measurement to accurately visualize the air–water interface. The camera was positioned at the level of the central line of the tube at a frontal distance of 35 cm, capturing profile images of the gas-liquid interface. The visualization studies were carried out in two different axial positions (at 50 D and 77 D) to analyze the characteristics of the slug flow in the formation and in the subsequent evolution.

To verify the visualization data pressure fluctuations measurements were carried out. A gauge pressure transmitter (RTP-420, Rücken with uncertainty of ± 0.20%), with a measuring range from 0 to 30 kPa, was installed in the horizontal test section at the axial position of 78.4 D (5.8 m) at the bottom of the tube. This sensor modulates their pressure range into a 4 – 20 mA linear output signal that was acquired with a USB-6211 National Instruments board. With the aid of a virtual instrument developed using LabView software, the output of the sensor was measured at a 1 kHz sampling rate.

As shown in Fig. 2, the range of water and air superficial velocities were J_L = 0.55–1.00 m/s and J_G = 2.25–5.50 m/s, respectively. The experimental conditions were plotted on the flow pattern map Mandhane et al. (1974), and it can be seen that the points are only in the slug flow pattern.

Experiments	J_L (m/s)	J_G (m/s)
1	0.55	2.25
2	0.55	5.50
3	0.85	2.25
4	0.85	5.50
5	1.00	2.25
6	1.00	5.50

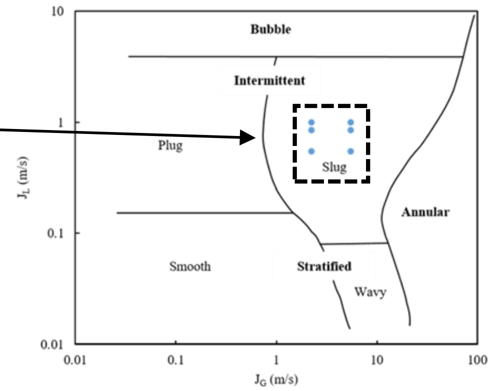

Figure 2 – Experimental matrix test and Experimental points on flow pattern map of Mandhane et al. (1974).

3. RESULTS AND DISCUSSION

Figure 3 illustrates the spatial and temporal evolution of slugs from 50 D to 77 D obtained in experiments 2, 4 and 6. In these experiments the superficial air velocity was of 5.50 m/s and the water superficial velocities vary from 0.55 to 1.00 m/s. The capture of the images was carried out between the passage of slugs, so the illustrated sequence starts after the passage of them. The observed characteristics are as follows:

1 – In the experiment 2 (JL = 0.55 m / s and JG = 5.50 m / s), at 50 D and t = 0, before the passage of the next slug, air and water flow are in a stratified manner (Fig. 3 (a)). In this case, the liquid level is restored, that is, in equilibrium, flowing with the air. Following the sequence of images, the interface becomes more unstable. Specifically, between Fig. 3 (e) and (g), it is possible to observe the passage of waves that can lead to the formation of slugs later (downstream), however, their evolution was not followed. The growth of these waves leads to acceleration of the air. Thus, due to the Bernoulli effect, the pressure in the air above the wave decreases, causing a suction of the liquid and increasing the amplitude of the wave until it forms a block in the cross section of the pipe. This can be seen in Fig. 3 (j) - (k), as the liquid level is slightly lower than what appears in Fig. 3 (a) and in the following illustrations there is the passage of the highly aerated slug, due to the high level of turbulence in the air flow. The liquid slug is accelerated by air and it sweeps the water ahead, which can increase its length. After the passage of the slug, as shown in Fig. 3 (m) - (o), water level immediately behind it drops significantly below the equilibrium level. As the liquid decelerates, after the passage of the slug, it rebuild to its original level and a new cycle begins.

2 – In this same operational condition, however, at the 77 D axial position, different characteristics can be observed in the flow. Starting with the liquid level before the passage of the slug, which does not return to the level of balance before its passage. The slug captured in this region has a higher degree of aeration than the one formed in 55 D. This occurs, because as the slug advances and the liquid is accelerated, more air entrainment occurs in the front of the liquid slug (Thaker and Banerjee, 2015). Bubbles are also observed in the region at the beginning of the liquid film.

3 - The topological characteristics of the flow, in experiments 4 and 6, are very similar to those of experiment 2. However, some differences can be observed. The interface stratified before the slug, at 50 D, is much more unstable and is it is possible to see small drops traveling detached from the front of it. The mechanism for detaching these droplets has not been explored in the present work. It can be seen that they travel a great distance from the front of the slug from which it comes at very high velocity. In experiment 4, this behavior is more pronounced than in experiment 6. Another characteristic about the stratified layer is related to the liquid level. In experiments 4 and 6, despite the increase in liquid flow, the liquid level is lower than in experiment 1. This is because the increase in flow can promote an increase in the frequency of slugs, reducing the time interval between their passages and consequently the stratified layer cannot decelerate and return to a level of equilibrium. In experiment 6, with the increase in the superficial liquid velocity to 1 m/s, at 50 D, it was possible to capture this behavior explained previously that is the passage of two slugs in a shorter time interval. At the position 77 D, in the same experiment, this was not observed, as these two waves formed at 50 D, later one can coalesce and result in only one slug or some of them may suffer viscous damping which means that they may not be able to support themselves until the end of tube.

In general, analyzing the three experiments (Fig. 3), the slugs formed at 50 D present different characteristics from the slugs observed at 77 D. At this position, the slugs observed have the frontal region or the liquid slug more aerated and with greater length. This is because, at the position of 50 D, the flow is not fully developed. There are no stable slugs, because as they moved along the tube their characteristics changed (Dukler and Hubbard, 1975). According to Thaker and Banerjee (2015), these three operational conditions are in the development region of highly aerated slugs and this makes it somewhat difficult to visualize the well-defined intermittent flow structure, such as a liquid slug, the region of the liquid film and the elongated bubble that accelerates the liquid ahead. Due to this "lack" of definition, it is difficult to identify, without a volumetric fraction measurement, if the cross section of the tube was blocked by the liquid, or if the high momentum air flow broke this block, i.e., broke the wave by overtaking it. The presence of aeration, mainly as shown in Fig. 3 (h) - (m) at 77 D, is still one of the main challenges found in studies of visualization of slug flow. This requires the implementation of image processing techniques to facilitate visual investigation (do Amaral et al., 2013; Widyatama et al., 2018)

Figure 4 shows the slugs formed in experiments 1, 3 and 5. It was not possible to evaluate the evolution of the slugs in these experiments since 50 D, because with a reduction in the superficial air velocity to 2.25 m/s, they only formed after this position. In these experiments, differences can be observed, in relation to those previously presented, in the intermittent structures formed:

1 – In experiment 1, at t = 0, before the formation of the slug, a high level of liquid can be observed. Because the gas velocity was reduced by half, the competition for the space between the phases is lower. In Fig. 4 (b) the wave begins to grow, which will result in the formation of the slug. In relation to the experiments presented in Fig. 3, the blocking of the cross section of the tube through the passage of the liquid slug is quite evident. The front of the slug still aerated, but the body of the liquid slug is well defined.

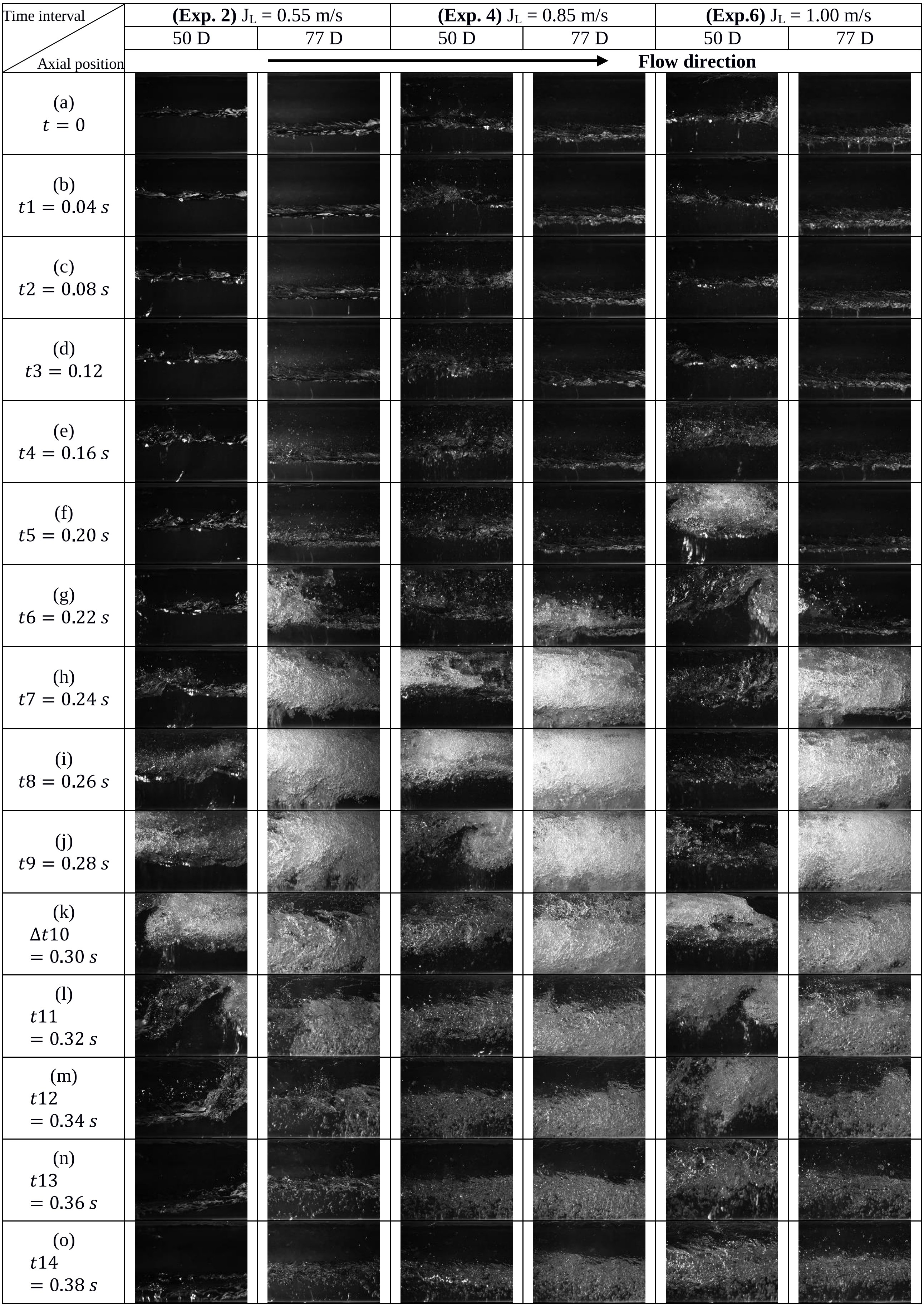

Figure 3 – Snapshot of the interfacial behavior of the slug flow at 50 D and at 77 D with the J_G = 5.50 m/s.

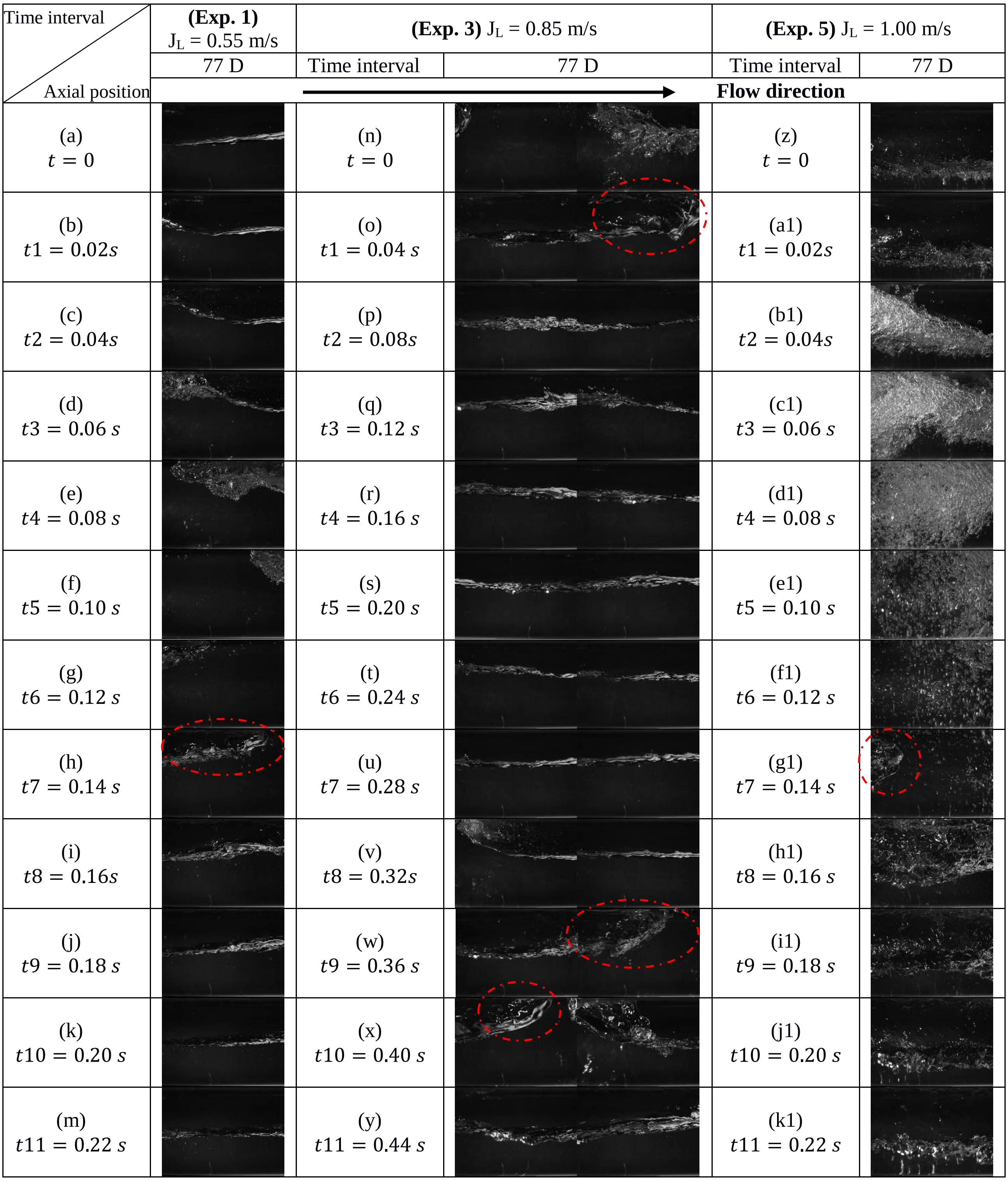

Figure 4 – Snapshot of the interfacial behavior of the slug flow at 77 D with the J_G = 2.25 m/s.

2 – With the increase in the surface velocity of the liquid, between Fig. 4 (n) - (y), two different slug structures are seen, longer intervals were applied in this sequence of images to be able to illustrate these two forms. In Fig. 4 (n), the slug has an aerated front and a well-defined liquid slug. After a time interval, in Fig. 4 (v) the passage of the second slug begins. This presents a liquid slug with a shorter length than the first one, and in a shorter time interval, the third slug occurs (Fig. 4 (x)). In this case, the increase in the superficial liquid velocity promoted irregular slug passages in both shape and frequency, and this is an inherent characteristic of intermittent flow.

3 – Increasing the liquid velocity to 1 m/s, although the superficial air velocity is lower, the captured slugs present high aeration in the frontal region (experiment 5). This demonstrates the role of the liquid in the gas entrainment into the

liquid slug. In addition to the presence of aeration, the length of the slug also increased and the liquid film had a much smaller thickness.

In these three experiments, the increase in liquid velocity played a dominant role in the slug formation. Visually, the changes in the flow were more incremental than in experiments with the superficial air velocity at 5.50 m/s. Here the captured slugs had a more defined shape allowing a clearer visualization of the cross section blocking and the elongated bubble nose (highlighted by the red dashed circle). Although an increase in the frequency of slugs has not been seen at the superficial liquid velocity at 1 m/s in the capture region, in previous axial positions smaller slugs may have coalesced and formed the captured slug that is longer than in other cases.

In addition to the captured images, pressure signals were also acquired to support the observed phenomena, but also to analyze the effects of increasing superficial velocities on pressure fluctuations. The pressure sensor used is positioned close to the 77 D axial position to be able to associate the images captured in this region. Figure 5 presents the pressure fluctuations from all experiments. Clearly, it can be seen that as the superficial velocities of the liquid and the air increase the greater is the amplitude of the pressure signal. As the slug reaches the pressure tap, the pressure at that point increases markedly due to obstruction of the pipe cross section. And, except in experiment 1, in the other experiments at most pressure peaks the pressure value remains high until the slug comes out of the pipe. This indicates that the slug maintained the cross section blockage until it left the pipe (Lin and Hanratty, 1987). Analyzing the expanded pressure series (Fig. 5 (a)-(b)), it can be seen that most peaks have a width that represents the time interval between the slug to pass through this pressure tap and to exit the pipe. In experiment 1, although the captured images showed the passage of a slug that blocked the cross section of the pipe, the pressure signal did not follow the signal pattern presented by the other experiments. In this experiment, the passage of the slug is represented by a sequence of oscillations that have a large time interval over and over. It indicates that after the slug has passed, there is a large period of time that the flow remains stratified until a new slug is formed.

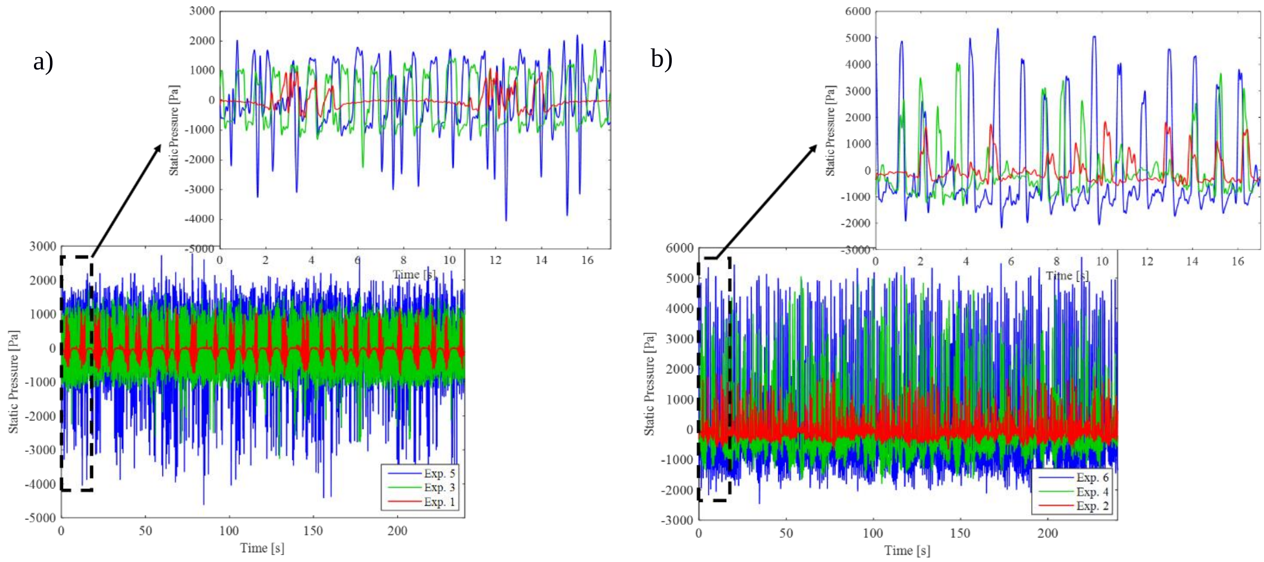

Figure 5 – Pressure fluctuations measurements: a) Experiments 1, 3 and 5, and b) Experiments 2, 4 and 6.

Still on the pressure fluctuations time series, analyzing each experiment in isolation, it is possible to observe that there are differences between the amplitudes and time intervals of the pressure pulses corresponding to the passage of the slugs. In experiments 2 and 4, this characteristic is more pronounced. It reflects the presence of slugs of different lengths (Drahoš et al., 1996) and with this information it is possible to analyze the flow stability or development. The formation of slugs with varying lengths can influence the frequency of their occurrence. When there is a slug with a shorter length, there will be less liquid to push the gas and less resistance to flow and more slugs can be formed quickly. Figure 6 illustrates power spectral density of pressure fluctuations. The dominant frequencies represent the higher energy oscillations that occurred in the flow periodically.

The dominant peaks of the power spectra provide the slug passage average frequency (Arabi et al., 2020; Drahoš et al., 1996). Except experiment 1, all the experiments shown the dominant peak around 1 Hz. Analyzing the detailed spectra images, some characteristics can be observed. In experiment 1, as expected by the behavior presented by the time series, the dominant peak was found at a low frequency value, 0.35 Hz. However, another peak can be seen at 0.81 Hz and it represents oscillations while the slug is passing through the pipe. Although the difference is very small, the experiment 3 showed a higher frequency than experiments 5. As seen in Fig. 4 (n) - (y), the experiment 3 presented the passage of more slugs in a shorter time interval, even if irregular in length. This may explain this small frequency in the spectral power. Between experiments 2, 4 and 6, experiment 2 showed a dominant peak with a lower value, 0.83 Hz. As noted in Fig. 3, this case had higher levels of liquid in the stratified layer between the passage of the slugs in relation to experiments 4 and 6, even with less liquid flow. This behavior can be associated with a lower frequency of slugs, since the stratified layer is able to return to an equilibrium level as the liquid decelerates after the passage of the slug. In the other cases, as the frequency of slugs is higher, the liquid cannot return to the level of equilibrium before the passage of the next slug. Similar to experiments 3 and 5, experiment 6 showed a lower frequency than experiment 4, which has less liquid flow. Normally, higher flows of liquid result in an increase in the frequency of passage of the slugs.

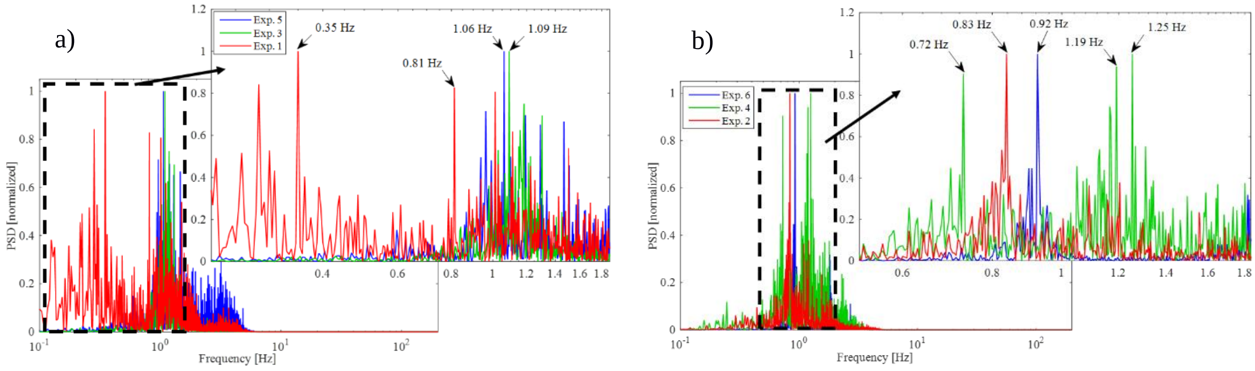

Figure 6 – Power spectral density of pressure fluctuations: a) Experiments 1, 3 and 5, and b) Experiments 2, 4 and 6.

This effect was observed when there was an increase in the superficial liquid velocity from 0.55 to 0.85 m/s, but, not happen with the liquid velocity increase to 1 m/s. The explanation adopted to describe this difference between experiments 3 and 5 can also be used for experiments 4 and 6, although among them the difference between the frequency values is greater. Observing the experiment 4 time series (Fig. 5 (b)), it can be seen that the pressure pulses have slightly irregular amplitudes and intervals, which, as previously mentioned, can be associated with slug passages with different characteristics and/or another greats disturbance at the interface. As a result, experiment 4 (Fig.e 6 (b)) presents more than one significant frequency peak, two significant frequency peaks closer at 1.19 and 1.25 Hz and one more distant at 0.72 Hz.

4. CONCLUSIONS

In this work, an experimental study was carried out on the evolution of slugs in a horizontal pipe with an internal diameter of 74 mm and air and water as working fluids. The range of water and air superficial velocities were J_L = 0.55–1.00 m/s and J_G = 2.25–5.50 m/s, respectively Images were acquired with a high speed camera, and pressure measurements were performed to analyze the flow. The results are summarized as follows:

1 – The increase in the superficial air velocity to 5.50 m/s resulted in the formation of slugs closer to the entrance and because of that, the evolution of the slugs was analyzed in two axial positions (50 D and 77 D) only in the experimental conditions with this superficial air velocity.

2 – In experiments with the J_G = 5.50 m/s and the J_L varying from 0.55 to 1 m/s it was found that the flow identified in 77 D had different characteristics from the slugs that passed in 50 D. The slugs captured in 77 D presented greater aeration in the frontal region and greater length. Thus, it can be concluded that in 50 D the flow was not yet completely developed. In these experiments, the main effects regarding the increase in the surface velocity of the liquid, refer to the liquid levels in the stratified layers adjacent to the passage of the slug. With the increase in the superficial liquid velocity, lower levels of liquid have been identified, this characteristic can be associated with the other effect, which is the increase in the frequency of slugs and, with this, the stratified layer cannot recover the level of equilibrium before the next slug.

3 – In cases with J_G = 2.25 m/s and the J_L varying from 0.55 to 1.00 m/s o, unlike previous experiments, the captured slugs presented well-defined shapes such as the evident cross section blocking by the liquid slug and the elongated bubble nose. As the superficial liquid velocity increased, an increase in the frequency of slugs and aeration in front of the slug was observed.

4 – Analyzing the pressure signals obtained in 5.8 m, as expected as the superficial velocities of the phases increased, the value of the pressure signal amplitude was higher. The time series of experiments 2 and 4 show irregular pressure pulses that can be associated with the passage of slugs with different lengths.

5 – With the power spectral density analysis of the pressure fluctuations it can be confirmed that the increase in the superficial liquid velocity promotes an increase in the frequency of slugs.

5. ACKNOWLEDGEMENTS

This work was supported by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES); Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq); and Petrobras [grant number 5850.0103010.16.9].

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