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# Slug Frequency in Horizontal Pipeline Subject to a Sudden Contraction: State of the Art and Laboratory Testing Data

**Ibtissem Belgacem[1], Reda Mekhlouf[2]**

[1]Hydraulic Department, National Polytechnic School, Algiers, Algeria
[2]Shimadzu Software Development, Montréal, Canada

**Email address:**
ibtissem.belgacem@gmail.com (I. Belgacem)

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**Abstract:** Liquid-gas two-phase flows are widely encountered in industrial applications including chemical processes, petroleum engineering and energy manufacturing units systems. Of all flow patterns encountered in field operations, slug flow is the dominant one in horizontal and near horizontal pipelines, and is also the most complicated one. Of all flow topological configurations, slug flow is the most concerning from the operational perspectives. It is characterized by an alternate flow of liquid slugs and gas pockets, resulting in an inherently unsteady hydrodynamic behavior. Frequency of the slug has important significance on gas-liquid two-phase flow. This paper presents the results of experimental study of gas-liquid slug flow in a horizontal pipe subjected or not to a sudden contraction. The first objective of this study is to present a state -of -the art of correlations concerning slug frequency; an analysis on the accuracy of these correlations is performed based on direct comparison against experimental data. It has been found that none of the slug frequency correlation was able to produce accurate prediction. In this study, the effects of sudden contraction on slug frequency regime were also investigated experimentally through the analysis of slug persistence and frequency, it has been found that: i) the slug flow prevails before and after the contraction, ii) frequencies of the structures persist across the contraction.

**Keywords:** Two-Phase Flow, Slug, Frequency, Closure Equations, Contraction

## 1. Introduction

Two-phase gas-liquid flows in horizontal pipes are widely exists in industrial processes and in the petroleum industry in particular. In horizontal and near horizontal pipelines, the transportation of gas and liquid in conducts can lead to several topological configurations, flow patterns are usually categorized into the following six type: stratified, wavy, slug, elongated bubbles , annular, and dispersed bubble. As it is demonstrated by classical flow-pattern maps [1-2] and recently by [3], of all flow patterns encountered in field operations, slug flow is the dominant one in horizontal and near horizontal pipelines, and is also the most complicated one. The slug flow is characterized by an alternate flow of liquid slugs and gas pockets, this kind of flows can cause several damage, like poor oil –water separation, large - scale installations instabilities, loss of production can reach up to 50% [4] and also fatigue problem. In gas-oil industry, slugging is a major flow assurance challenge, the most significant parameter associated with the slug flow is the frequency that is defined as the number of slugs passing a stationary observer per unit time [3], knowledge of the slug frequency is essential to ensure correct sizing of pipelines, developing mitigation procedures and also for fatigue calculations.

Over the past five decades, many experimental and theoretical studies have been performed by several researchers [4, 6, 7] some representative works are summarized in table 1.

***Table 1.*** *Summary of slug frequency studies and closure correlations reported in the literature.*

| Reference | | | |
|---|---|---|---|
| [4] | Channel configuration<br>Circular<br>D=19 mm<br>Correlation<br>$f_b = 0.0226\left[\frac{J_{ls}}{g\,d}\left(\frac{19.75}{J_m} + J_m\right)\right]^{1.2}$ | Fluid<br>Water-carbon dioxide | Major findings/Remarks |
| [5] | Channel configuration<br>D=30mm and 38mm<br>Correlation<br>$f_b = 0.0226\left[\lambda_l\left(\frac{2.02m}{D} + Fr_M\right)\right]^{1.2}$<br>$\lambda_l$ : no-slip holdup $\lambda_l = \frac{J_L}{J_M}$<br>$Fr_M$ Froude number of du mexture<br>$Fr_M = \frac{J_M^2}{gD}$ | Fluid<br>Water-air | Major findings/Remarks |
| [6] | Channel configuration<br>Correlation | Fluid | Major findings/Remarks |
| [8] | Channel configuration<br>D=42mm<br>Correlation<br>$f_b = 0.0364\,\lambda_l\left[\frac{2.02}{d} + \frac{V_m^2}{gd}\right]^{1.06}$ $\lambda_l = \frac{J_l}{V_m}$ | Fluid<br>Air-water | Major findings/Remarks<br>calculated the probability density function and power spectral density of the hold-up in order to estimate the average slug frequency |
| [9] | Channel configuration<br>Data from the literature<br>Correlation<br>$f_b = 0.61\,\frac{\rho_g}{\rho_l}\frac{J_g}{h_g}$ | Fluid | Major findings/Remarks<br>-assumed that the slug frequency is one half of the frequency of the unstable<br>waves precursors of slugs. He used linear stability analysis and the concept of a<br>"most dangerous wave" to identify the frequency of the unstable wave responsible for initiating a slug. |
| [10] | Channel configuration<br>$31 < D < 90$ mm.<br>Correlation<br>$f_b = 0.088\,\frac{(J_l+1.5)^2}{g\,D}$ | Fluid<br>air–water | Major findings/Remarks<br>-Correlation can only be expected to give reasonable predictions in low viscosity liquid–gas flow systems where the liquid flow rate is so high that gas velocity has negligible impact on slug frequency. |
| [11], [12] | Channel configuration<br>Authors collected a large database on slug flow characteristics in both low pressure test rigs and field production flow lines.<br>Correlation<br>$\frac{f_b d}{V_m} = 0.275 * 10^{2.68H_{le}}$<br>$\frac{f_b d}{(J_g - J_l)} = 2.74 * \frac{H_{le}}{1-H_{le}}$ | Fluid | Major findings/Remarks<br>based on :<br>-The equilibrium film height<br>-The mechanics of slug formation from a horizontal stratified flow |
| [13] | Channel configuration<br>D=78mm<br>Correlation<br>$f_b = 0.0037\,\frac{J_l}{gd}\left(\frac{J_{m,min}^2 + J_m^2}{J_m}\right)^{1.8}$ $J_{m,min}$ =5m/s | Fluid<br>Air-water<br>Air-oil | Major findings/Remarks<br>-investigated the relationship between pressure and slug frequency<br>-it was found that the pressure had little effect on slug frequency. |
| [14] | Channel configuration<br>D=76.3 mm<br>L=23m<br>Correlation | Fluid<br>air-water | Major findings /remarks<br>- The results reveal that the mechanisms responsible for the formation of a slug, and thus the slug frequency, depend on the liquid Froude number of the wavy stratified flow, the gas velocity, and the location in the pipeline at which the slugs form. |
| [15] | Channel configuration | Fluid | Major findings /remarks |

| Reference | | | |
|---|---|---|---|
| | 1 to 8 inches. inclinations from $0^0$ to $11^0$ above the horizontal | air-water | -Correlation include the effect of inclination angle, which is not included in any of the published slug frequency correlations. |
| | Correlation | | |
| | $f_b = 0.0226\left[\frac{J_l}{gd}\left(\frac{212.6}{J_m} + J_m\right)\right]^{1.2} [0.836 + 2.7sin^{0.25}(\theta)]$ | | |
| [16] | Channel configuration | Fluid | Major findings/Remarks |
| | Correlation based purely on data from an oil field | | |
| | -The first correlation to make slug frequency a function of pipe length. In addition to pipe length, the slug frequency correlation is also a function of pipe diameter and superficial liquid velocity. | | |
| | Correlation | | |
| | $f_b = \frac{0.47 J_l^{0.75}}{d^{1.2} L_c^{0.55}}$ | | |
| [17] | Channel configuration | Fluid | Range |
| | D=95mm L=20m | air–water | -At varying flow rates, slug frequency is found to behave similar to the frequency of Oscillations in the gas phase. However, the scale of frequency is dominated by the liquid momentum. |
| | Correlation | | |
| | $f_b = 0.088\,\frac{(J_l+1.5)^2}{g\,D}$ | | |
| [18] | Channel configuration | Fluid | Major findings/Remarks |
| | D=50.8mm L=42,7 m | Air-oil | |
| | Correlation | | |
| | $ln(f_b)$=0.8+1.53 $Ln(J_l) + 0.27\frac{J_b}{J_m}$ -34.1 | | |
| | $J_l = \frac{J_{sl}}{H_{le}}$ | | |
| | $J_s = \frac{J_{sg}}{(1-H_{le})} - \frac{J_{sl}}{H_{le}}$ | | |
| | $J_m = J_{sl} + J_{sg}$ | | |
| | $0.084m/s < J_l < 2,82m/s$ | | |
| | $1.29m/s < J_b/J_m < 6.86m/s$ | | |
| | 0.025m<d< $2,203m$ | | |
| [19] | Channel configuration | Fluid | Major findings/Remarks |
| | $38 < D < 67$ mm | air-water | |
| | Correlation | | |
| | $f_s = 0.8428\left[\frac{J_{sl}}{gD}\left(\frac{19.75}{J_m} + J_m\right)\right]^{0.25}$ | | |

In most cases to ensure the distribution of the fluids in the industrial installations, the two-phase flows systems often exhibit complex geometry comprising singularities such as expansions, contractions, orifices, bends etc. Among these singularities, the abrupt contraction is relevant in many applications and has significant effects on the two-phase flow behavior as well on flow pattern. However no report is found in the open literature concerning the development of slug in the presence of sudden contraction, although they are popular in industrial application, the literature survey (see table 1) indicates the major part of previous laboratory experiments were not directed toward studies of flow in conduits of uniform cross-section. Although very few studies such as [20], have been carried out to study the effect of singularities on the slug redistribution and parameters. Using electrical capacitance tomography (ECT) [20] examine characteristics of structure across 0.32 sudden contraction using air/silicone oil flows; they reported that frequencies of the slug persist across the contraction.

Once literature is surveyed, it is evident that much experimental work is still important to attain understanding of slug flow and provide guidance to the design and operation of flow line. In the current study, an experimental investigation has been conducted for two test section (with and without contraction). The purpose is to examine the influence of liquid and gas superficial velocities on slug presence. In addition, using the previous research founding done by the authors [21-22], measuring slug frequency data was compared against empirical correlations published in the open literature. This also involves analysis of contraction on slug behavior and frequency. In what fellows in this paper, the experimental test loop are described, results and discussions are presented. Finally, the major observations from the present work are highlighted in the conclusion.

## 2. Experimental Apparatus and Procedure

The experiments were conducted for air-water two-phase flow at atmospheric pressure in a horizontal pipe with and without a sudden area contraction. A schematic diagram of the test flow loop is shown in Fig. 1. The experimental loop was adapted to generate gas-liquid two-phase flow concurrently. It operated in closed circuit for the liquid phase, open for the gas component. The liquid flow was provided by a centrifugal Noryle pump, with a nominal flow-rate of $10m^3/h$ for a nominal delivery head of 9m. Air was provided by a compressor. Both fluids air and water arrived in a cylindrical mixing chamber feeding the cylindrical pipe made in Polymethyl Methacrylate (PMMA) to allow optical access. Prior to the experiments, the horizontality was set to avoid any transition due to the effect of pipe inclination. Air was filtered to remove all traces of oil and impurities and to maintain good experimental conditions. Visualization of the flow regime without the singularity was achieved at 7m from the inlet of the pipe while in the presence of the contraction this was done at 1m upstream and downstream the singularity using a high resolution camera. Gas flow measurements were performed by two Rotameters VMRP010092 and VMRP010083 type. Liquid flow was measured by an ultrasonic flow meter type PT878. The estimated incertitude on liquid and gas flow rates were lower than ±2% and ±1% respectively. The test section, as shown in Fig. 1, had inner diameters of 0.04m and 0.03m upstream and downstream the contraction respectively leading to a contraction area ratio of 0.567.

The working fluids were air and water delivered at a total mass flux G ranging from 37.16 to 240 kg/m²s at a temperature of 25°C with a flowing quality $x$ range of $0.008 \leq x \leq 0.22$. The deduced superficial velocities were respectively for the liquid and gas as: $0.011 m/s \leq J_l \leq 0.24$ m/s and $0.54 m/s \leq J_g \leq 5.5$ m/s.

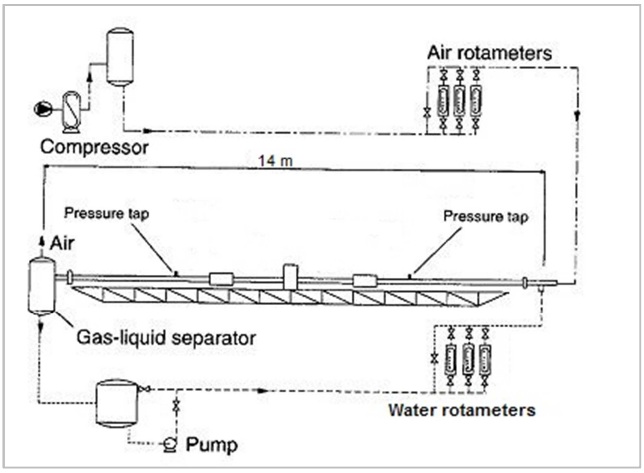



***Figure 1.*** *Description of the experimental loop.*

## 3. Results and Discussions

The experimental test matrix was chosen in order to have slug flow on the two configurations.

### *3.1. Slug identification*

Slug pattern in the tube were observed by treatment of the electric signal tension delivered by the piezoelectric pressure pick-up, together with visual observation for air water in the transparent tube[21]. A typical time wave form spectrum is presented in figure 2. It was noted under slug flow regime that the entire movement of the slug through the pipe was seen as increasing and decaying AE level which could be correlated with the slug head and tail respectively [22]. The slug flow data identified have been plotted in Figures 3, 4.a and 4.b for horizontal pipe of uniform diameter, upstream and downstream contraction, respectively together with the transition lines of Mandhane flow map. In our experimental work, at the transition from stratified-wavy flow to slug flow, which happens at very low superficial [21] liquid velocities (around $j_l$ =0.1 m/s) and relatively high gas velocities ( $j_g$ >2 m/s), slugs appear rarely and only at long distances from the inlet, e.g. not before 120D. As the superficial liquid velocity increases, slugs form closer to the inlet between 17D and 52D from the inlet.

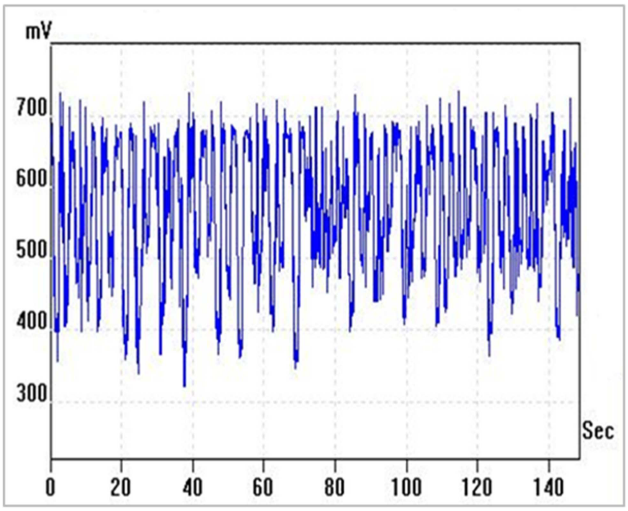



***Figure 2.*** *Typical signal from fully developed slug flow.*

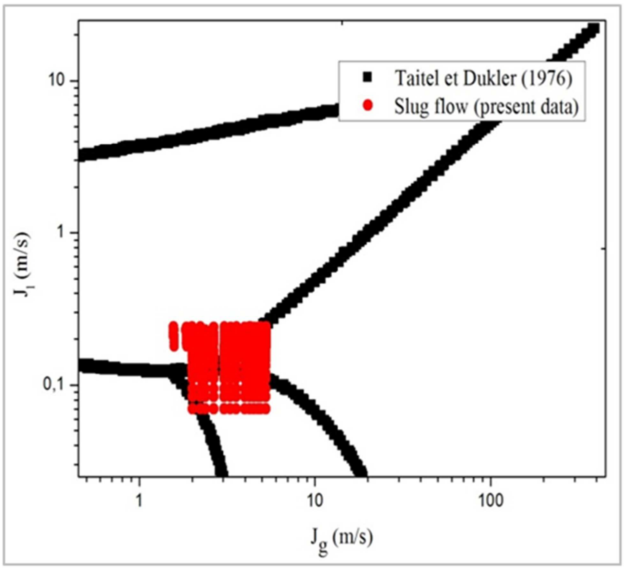
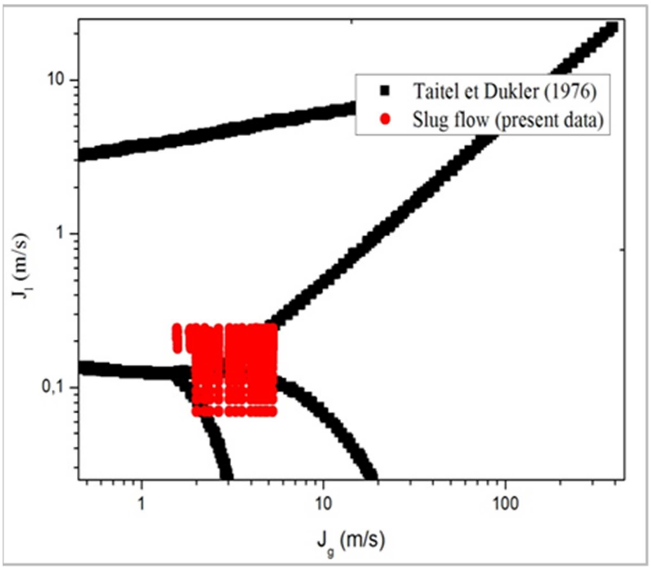
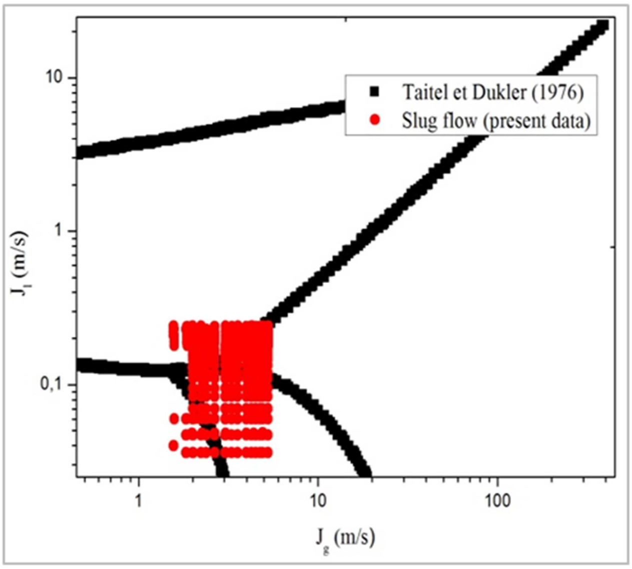



***Figure 3.*** *Data distribution in Taitel et Dukler (1976) flow map for configuration 1 (Horizontal pipe without contraction).*




(a) upstream contraction




(b) downstream contraction

***Figure 4.*** *Data distribution in Mandhane flow map for configuration 2 (Horizontal pipe with contraction).*

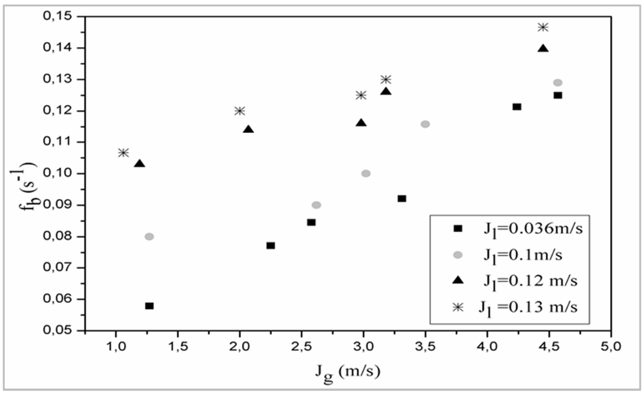
### *3.2. Slug Frequency*

#### *3.2.1. Pipe Without Contraction*

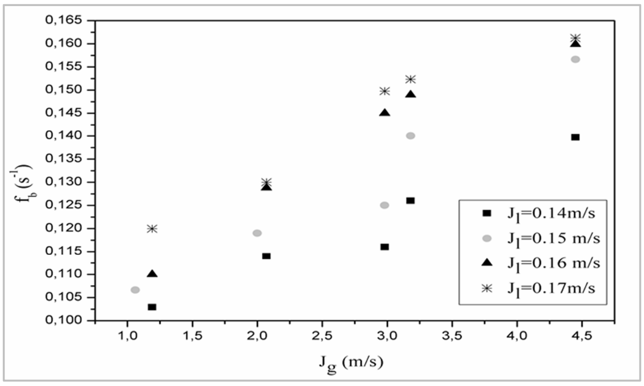
Slug frequency is estimated by counting the number of peaks and then dividing it by the measurement time [3-21]. Slug frequency was plotted against superficial gas velocities for different liquid velocities.

Field data suggests that for horizontal pipelines, the slug frequency is usually in the range of 1 to 20 slugs/minute depending on the liquid velocity. However, if the pipe is inclined, the slug frequency can increase to values much greater than these. In our experimental work and for the range of gas and liquid studied the frequency is in the range of 3 to 16 slugs/ minute.

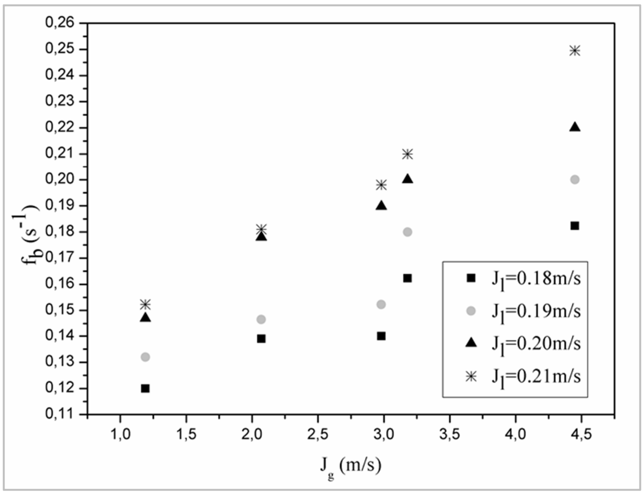
Figure (5. a. b. c) illustrates the dependence of slug frequency on superficial gas velocity. The superficial liquid velocities were kept constants in these figures.




(a)




(b)

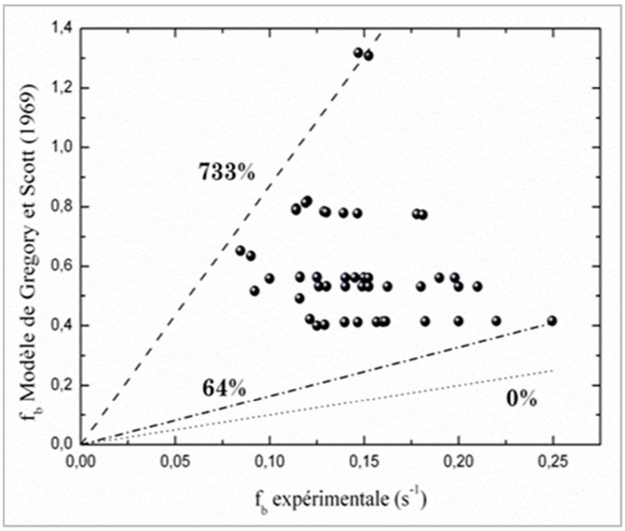



(c)

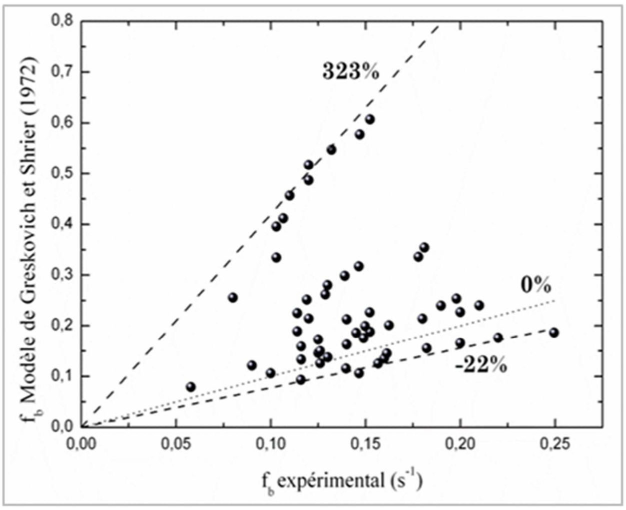
***Figure 5.*** *Frequency of the slugs according to the superficial gas velocity for various superficial liquid velocities.*

Experimental slug frequency was compared with predicted results of six empirical correlations; the slug frequency models selected for comparison are based on experimental data. Although these models are easy to use (i.e. a simple algebraic equation) their usefulness may be restricted in new scenarios [23].

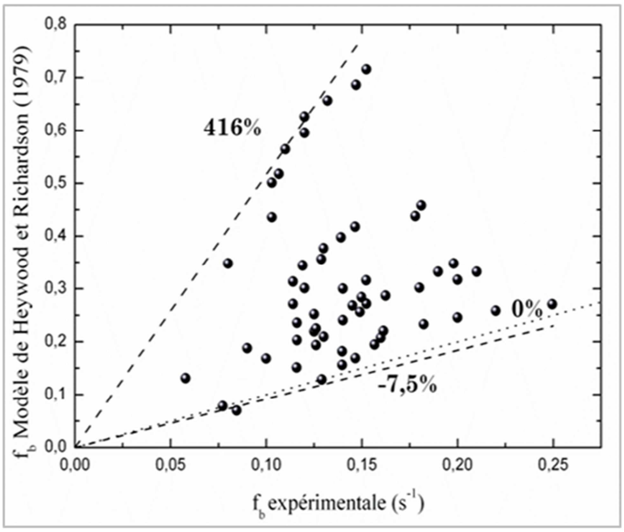
From figure.6, it is obvious that none of the slug frequency correlations were able to produce predictions of reasonable accuracy. The majority of the correlations grossly overestimate the slug frequency, results generated from that it were far away from the reality observed in the experiments. In the literature we can find many approaches to explain the results, [18] reports that slug frequency model revealed important dependency on slug initiation mechanism and development conditions, he suggests that the slugs generated under a hydrodynamics slugging mechanism have lower frequency than those generated under a terrain slugging mechanism for high Froude number, experimental condition parameters including pipe diameter, liquid velocity and the ratio of slip to mixture velocities were found to linearly correlate relate to slug frequency correlations.



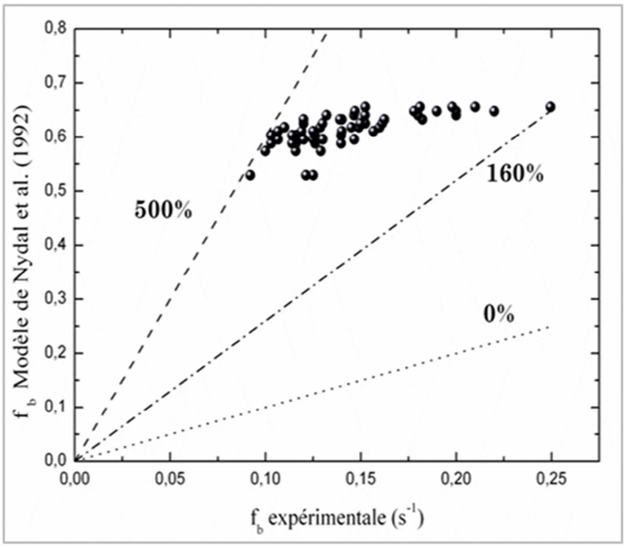

a/ [4]



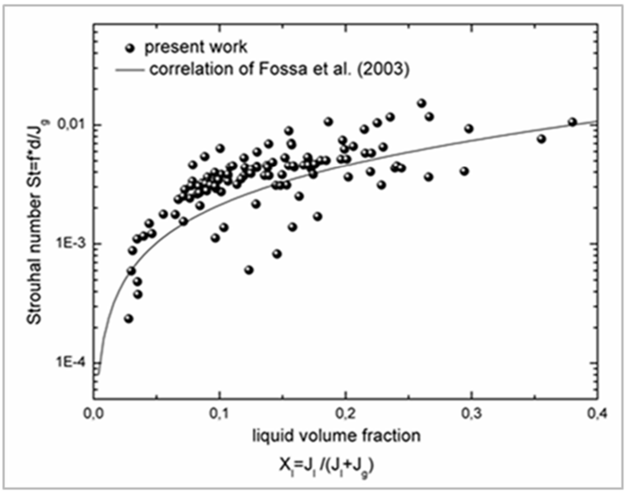

b/ [7]



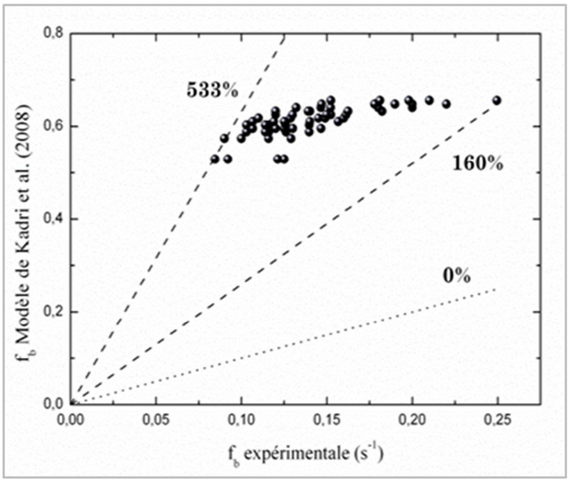

c/ [8]




d/ [10]




e/ [9]



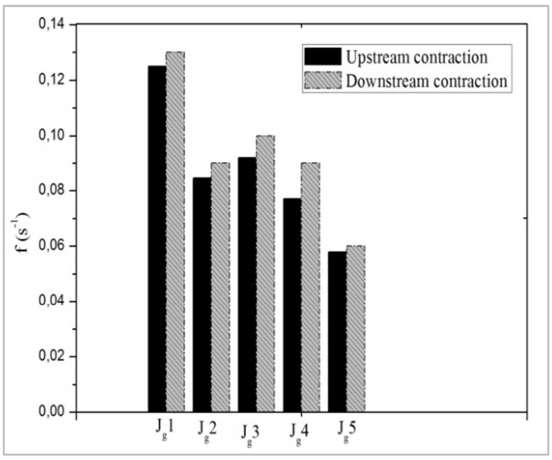

f/ [17]

***Figure 6.*** *Comparison between experimental slug frequency data and theoretical prediction.*

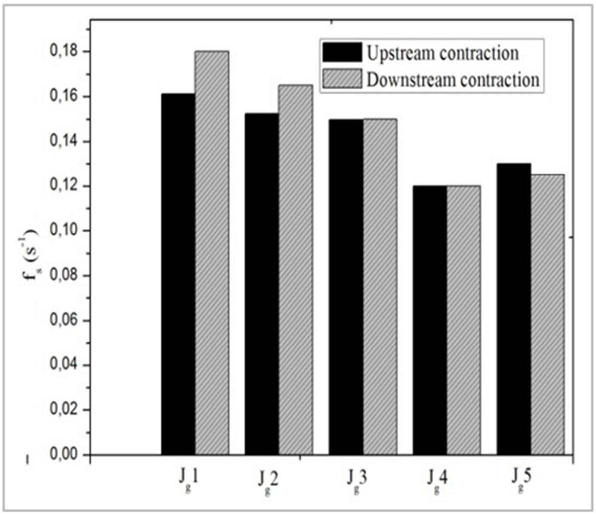
### *3.2.2. Pipe with Contraction*

As part of this work, measurements were conducted upstream as well as downstream the contraction allowing then to examine the frequency due to the singularity. Figure 7 shows twelve cases of slug frequency variations with superficial gas velocity for different liquid velocities, upstream and downstream pipe contraction. When examined individually, the dominant tendency across most of the twelve cases is for slug frequency to increase as superficial liquid velocities are increased upstream as well as downstream the sudden area change. In the most of the case studied the slug frequency remains constant upstream and downstream the contraction. There are remarkable cases where the slug frequency variation downstream the contraction is rather complicated. In one such case, slug frequency remains constant at first before increasing. In other such cases, the slug frequency initially increases and then decreases.

This is in agreement with earlier report by Azzopardi et al. (2014)




a/ $J_l$=0.1 m/s
$J_g$1=4.57m/s $J_g$2=2.58m/s $J_g$3=3.31m/s
$J_g$4=2.25m/s $J_g$5=1.27m/s




b/ $J_l$=0.21 m/s
$J_g$1=4.45m/s $J_g$2=3.18m/s $J_g$3=2.98m/s
$J_g$4=1.19m/s $J_g$5=2.07m/s

***Figure 7.*** *Slug frequency data upstream and downstream contraction.*

# 4. Concluding Remark

This work sets out to provide new experimental data on slug flow in horizontal pipe subjected or not to a sudden contraction. Based on results from the experimental measurements and visual observations, the following conclusions are made:

Considering the preliminary study carried out, the dominant tendency is for slug frequency to increases linearly with the superficial liquid velocities and it is weakly affected by the superficial gas velocity. On the other hand, none of the slug frequency correlations tested against experimental slug frequency data was able to produce predictions of reasonable accuracy.

The main part of this work, however, is concerned with the characterization of intermittent flow in the presence of sudden contraction. First the presence of slug flow is shown on a flow map upstream and downstream sudden area change, the intermittent flow prevails before and after the contraction, In addition, it has been found that frequencies of the structures do not vary across the contraction. Ultimately, data are provided for the validation and development of mathematical models and numerical codes for the simulation of two-phase slug flow.

# References

[1] Mandhane, J. M., Gregory, G. A., & Aziz, K. (1974). A flow pattern map for gas—liquid flow in horizontal pipes. International Journal of Multiphase Flow, 1(4), 537-553.

[2] Taitel, Y., & Dukler, A. E. (1976). A model for predicting flow regime transitions in horizontal and near horizontal gas‐liquid flow. AIChE Journal, 22(1), 47-55.

[3] Belgacem, I., Salhi, Y., SI-Ahmed, E. K., Legrand, J. (2105). Development and statistical characterization of slug in two-phase flow along horizontal pipeline “. Mechanics & Industry.

[4] Gregory, G. A., Scott, D. A., 1969. Correlation of liquid slug velocity and frequency in horizontal cocurrent gas–liquid slug flow. AIChE J. 42, pp. 901–907.

[5] Greskovich, E. J., & Shrier, A. L. (1972). Slug frequency in horizontal gas-liquid slug flow. Industrial & Engineering Chemistry Process Design and Development, 11(2), 317-318.

[6] Taitel, Y. and A. E. Dukler, 1977. A Model For Slug Frequency During Gas-liquid Flow in Horizontal and Near-Horizontal Gas-Liquid Flow, Int. J. of Multiphase Flow, Vol. 19, No. 5, pp. 829-838.

[7] Heywood, N. I., & Richardson, J. F. (1979). Slug flow of air—water mixtures in a horizontal pipe: Determination of liquid holdup by γ-ray absorption. Chemical Engineering Science, 34(1), 17-30.

[8] Tronconi, E., 1990. Prediction of slug frequency in horizontal two-phase slug flow. AIChE J. vol. 36, pp. 701–709.

[9] Nydal, O. J., Pintus, S., Andreussi, P., 1992. Statistical characterization of slug flow in horizontal pipes. Int. J. Multiphase Flow 18, pp. 439–453.

[10] Hill, T. J., & Wood, D. G. (1990). A new approach to the prediction of slug frequency. In 65 th Annual Technical Conference and Exhibition of SPE, September (pp. 23-26).

[11] Hill, T. J., & Wood, D. G. (1994). Slug flow: Occurrence, consequences, and prediction (No. CONF-940879--). Society of Petroleum Engineers, Richardson, TX (United States).

[12] Manolis, I., Mendes-Tatsis, M., Hewitt, G., 1995. The effect of pressure on slug frequency on two-phase horizontal flow. Presented at the 2nd International Conference on Multiphase Flow, Kyoto, Japan (cité par El safran 2009).

[13] Woods, B. D., Hanratty, T. J., 1999. Influence of Froude number on physical processes determining frequency of slugging in horizontal gas–liquid flows. Int. J. Multiphase Flow vol. 25, pp. 1195–1223.

[14] Zabaras, G., 2000. Prediction of slug frequency for gas/liquid flows. SPE 65093. SPE J. 5 (3).

[15] Shea, R., Eidsmoen, H., Nordsveen, M., Rasmussen, J., Xu, Z., Nossen, J., 2004. Slug frequency prediction method comparison. BHRG Multiphase Production Technology Proceedings, Banff, Canada.

[16] Kadri, U., Mudde, R. F., Oliemans, R. V. A.(2008). A growth model for dynamic slugs in gas/liquid horizontal pipes. In Proc. BHR Conf., Banff, Canada, pp. 241–254.

[17] Al-Safran, E. (2009). Investigation and prediction of slug frequency in gas/liquid horizontal pipe flow. Journal of Petroleum Science and Engineering, 69(1), 143-155.

[18] Hernandez Perez, V., Azzopardi, B. J., & Morvan, H. (2007). Slug flow in inclined pipes. In Proceedings of 6th international conference on multiphase flow (pp. 9-13).

[19] Azzopardi, B. J., Ijioma, A., Yang, S., Abdulkareem, L. A., Azzi, A., & Abdulkadir, M. (2014). Persistence of frequency in gas–liquid flows across a change in pipe diameter or orientation. International Journal of Multiphase Flow, 67, 22-31.

[20] Al-Lababidi, S., Addali, A., & Mba, D. (2012). Upstream Multiphase Flow Assurance Monitoring Using Acoustic Emission. INTECH Open Access Publisher.

[21] Belgacem, I., Salhi, Y., SI-Ahmed, E. K., Legrand, J., &Rosant, J. M. (2013). Experimental investigation of slug pattern in a horizontal two-phase flow. Computational Methods in Multiphase Flow VII. Wit transaction on Engineering Sciences, 79, 423-433.

[22] Rodrigues, H. T., Morales, R. E., Mazza, R. A., & Rosa, E. S. (2007). A comparative study of closure equations for gas-liquid slug flow. In international congress of mechanical engineering- COBEM (Vol.19).