Using Differential Pressure Signal for Slug Frequency Measurement in Two-Phase Flow within Horizontal Configuration

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Abstract- The purpose of this work is to make a comparative of the existing methods for the slug frequency' measurement of the slug flow in the case of gas-liquid two-phase flow within an horizontal configuration; using the differential pressure signal between two points of the pipe.
An experimental investigation on a 30 mm internal diameter pipe was carried out. The frequencies were obtained by adopting various methods; such as the Counting, the Wilkens & Thomas, and the Power Spectral Density (PSD) one. Summarizing the obtained results, using the PSD approach was more required to get a clear measurement of the slug frequency, regarding the complex nature of the slug flow.

Keywords— Two-phase flow, slug flow, differential pressure.

Nomenclature

D	Pipe Diameter	[M]
f	Faning Friction Factor	[-]
F	Slug Frequency	[Hz]
J	Superficial Velocity	[m/s]
L	Length	[m]
N	Number of Slugs	[-]
Re	Reynolds Number	[-]
t	Time	[s]
STD	Standard Deviation of Frequency Measurement	[Hz]
T	Time Series Duration	[s]
V	Velocity	[m/s]
ΔP	Pressure Differential	[Pa]
ρ	Density	[Kg/m^3]
μ	Viscosity	Pa.s

Subscript

g	Gas
l	Liquid
M	Mixture
S	Slug

I. Introduction

Two-phase gas-liquid flow co-current found applications in many fields of engineering; such as nuclear and chemical engineering, as well as the oil and gas industry. There were several ways to classify the two-phase flows, in particular as a function of the flow pattern. Among the flow pattern present in the horizontal pipes, the slug regime is considered to be the most complex pattern. The latter is characterized by an intermittent behaviour: A gas pocket flowing on a liquid film follows a liquid slug which touches the top wall of the pipe. This intermittence of the flow causes large fluctuations in pressure, which leads to erosion and therefore premature aging of the pipes. The complexity of slug flows is such that there is not a complete theoretical model which describes this phenomenon. To predict the intrinsic parameters for such type of the flow (such the frequency, the speed and the length of the liquid slug mainly), experimental studies are very important.

The slug frequency, where the number of liquid slugs passing into a time interval, is a very important parameter for the design of industrial installations. Today, industrialists use correlations with input parameters such as the superficial velocities of the two phases. These correlations can be empirical [1-3] or theoretical [4, 5].

This work aims at a comparative investigation between several methods to measure the slug frequency, based on the time signal obtained from a differential pressure sensor, which has several advantages; as the non-intrusive, low cost, simply implemented and widely used in industry.

II. Experimental Setup

The study was carried out on an experimental setup specially designed to generate a two-phase water-air flow within a horizontal configuration (*see for instance* Fig. 1). The pipe has a total length of about 12m and an internal diameter of 30mm. A compressor is used to generate the air while a system composed of a reservoir and a pump is used to circulate the liquid phase. The flow rates of the air are measured using a rotameters. The water flow rate is measured with an ultrasonic flowmeter. The two phases are contacted using a Y-mixer. The gas is injected horizontally while the liquid is injected diagonally.

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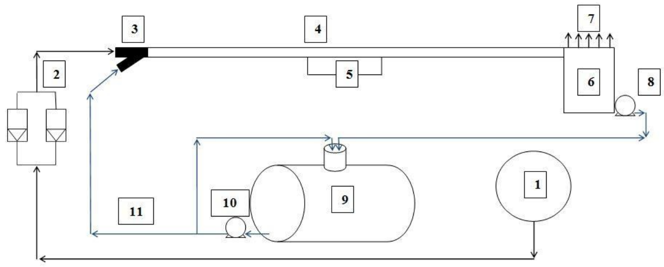
A differential pressure sensor type Freescale MPX-2010 DP range 0-10 kPa was connected to the remote points of 173.33D and 193.33D with respect to the input mixer. A total of 35 acquisitions were carried out with liquid flow rates of 360 to 1260 l / h. The flow rates of the gas phase varying from 3000 to 9000 l/ h. This range of flows corresponds to the cases where one is in the presence of the slug flow. For each pair of flows, a signal with duration of 30s with an acquisition frequency of 500 Hz was collected.



1: compressor; 2: gas flowmeters; 3: two-phase flow mixer; 4: measuring pipe; 5: differential pressure transducer, 6: decantation tank; 7: air outlet; 8: pump; 9: liquid tank, 10: pump; 11: ultrasonic flowmeter

Fig. 1 Schematic of the experimental system.

III. Methods Used

As reported by Weisman et *al.* [6], the passage of a liquid slug through the terminals of a differential pressure sensor is accompanied by an increase in the pressure drop, hence the appearance of the peaks in the time series. The counting method, as the name suggests, relies on counting the number of peaks, the frequency is obtained by dividing the number of peaks by the duration of the signal.

It should be noted that this method can be used for the signals of the pressure drop, for the signals of the absolute pressure as well as for the void fraction.

Figure 2 displays a part of the signal of the pressure drop of a slug flow with a duration of 15s in the case J_l = 0.141 m/s and J_g = 2.358 m/s. It can be clearly seen in the figure that there are 19 peaks, the frequency is:

$$F = N/t = 19/15 = 1.26 \text{ Hz} \qquad (1)$$

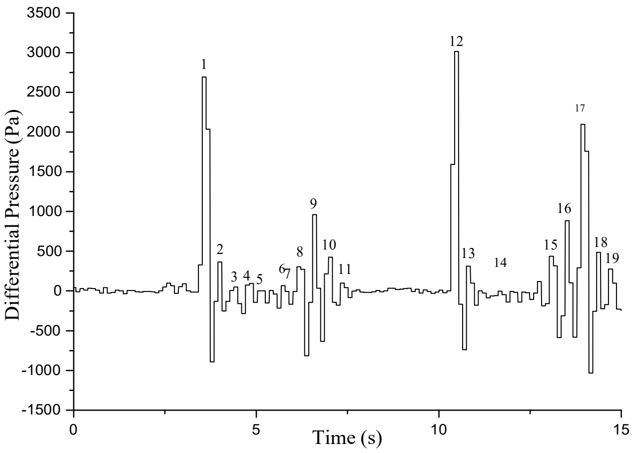


Fig. 2 Example of differential pressure signal for the slug flow (J_l= 0.141m/s and J_g= 2.358 m/s)

In many cases, in the intermittent flow, there are not only slugs; we can find roll waves that do not touch the top of the pipe. The passage of these structures through the terminals of the pressure sensor leads to an increase in the differential pressure, which leads to the appearance of the peaks, distorting the results obtained with the counting method [7]. To remedy this, Wilkens and Thomas [8] proposed a method for the calculation of the frequency of the passage of liquid slugs by calculating the pressure drop generated by a single slug. The Wilkens and Thomas method relies on the following steps :

a) Calculate of the velocity of a slug which is considered equal to the gas-liquid mixture velocity.

$$V_S = V_M = J_l + J_g \qquad (2)$$

b) Calculate the slug Reynolds number.

$$Re_S = \rho_S D V_S / \mu_s \qquad (3)$$

with ρ_s et μ_s the density and viscosity of the liquid phase respectively.

c) Calculate the slug friction factor.

$$f_s = 0{,}0014 + 0{,}125 / Re_s^{0{,}32} \qquad (4)$$

d) Estimate the minimum stable slug length.$L_{smin} \geq D\,(10\,V_{sl} + 5)$ (5)

If the minimum stable length is greater than the differential pressure tap spacing (20D or 600 mm in our case), use the differential pressure tap spacing.

e) Calculate the pressure drop required for one slug.

$$\Delta P_{one\ slug} = 4\, f_S\, (L_s\, \rho_S\, V^2_m) / 2D \qquad (6)$$

f) Representation of the pressure drop required for one slug to the base line differential pressure to establish the threshold differential pressure for a slug between the taps.

g) Counting only the slug's occasion where the differential pressure exceeds the threshold differential pressure.

Figure 3 shows the signal of Fig. 2 with the line representing the pressure drop generated by a single slug (calculed by eq. 6). It is clear that there are 8 peaks, the frequency is,

$$F = N/t = 8/15 = 0.533 \text{ Hz} \qquad (7)$$

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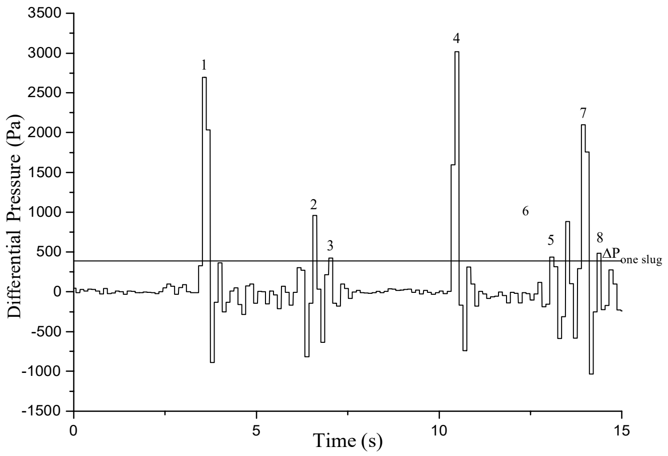

Fig.3 Example of differential pressure signal for the slug flow with a threeshold (J_l = 0,141m/s and J_g= 2,358m/s)

Spectrum Density (PSD) is a function used to extract the frequencies present in a time signal. In our case, it is used to extract the dominant frequency which is considered equal to the frequency of the passage of the liquid slugs.

Figure 4 shows the present energy spectrum of a pressure drop signal in the case J_l = 0.141 m/s and J_g = 2.358 m/s extracted from the PSD, it is clear that the energy is distributed especially in the frequency band below 12.5 Hz.

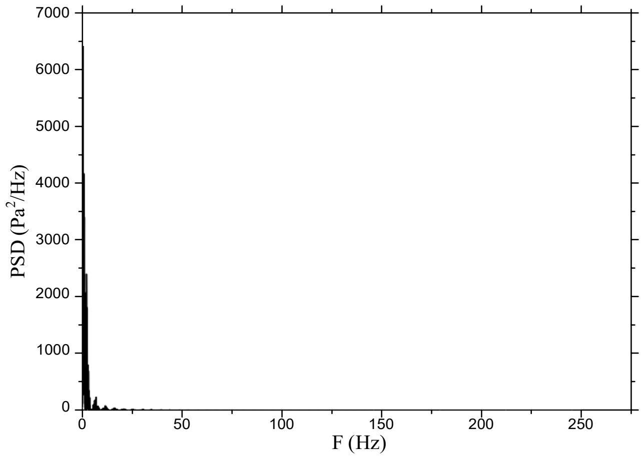

Fig.4 Example of frequency spectrum obtained by using the PSD (J_l= 0,141m/s and J_g = 1,179 m/s)

Figure 5 shows a zoom of the frequency spectrum of Fig. 4, a clear peak is clearly visible, corresponding to the frequency of 0.366 Hz, which corresponds to the slug frequency.

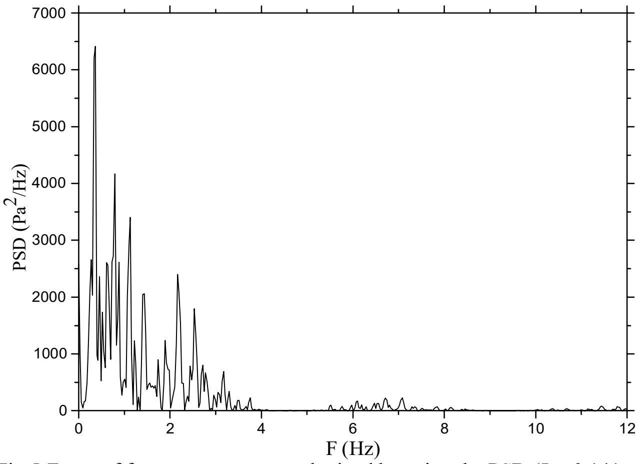

Fig.5 Zoom of frequency spectrum obtained by using the PSD (J_l= 0,141m/s and J_g = 1,179 m/s)

IV. Results and Discussion

In the first step, the results of the repeatability; found by the three methods; were discussed. Fig. 6 shows the standard deviation' values obtained by the adopted methods and that; for three pairs of the flow rates.

As we can see, the dispersion of the results is found to be more significative using the spectral analysis; compared to the other ones (i.e. the counting and Wilkens and Thomas methods), which allow us to say that the results given by the PSD are affected by the huge uncertainty, what makes it less inaccurate.

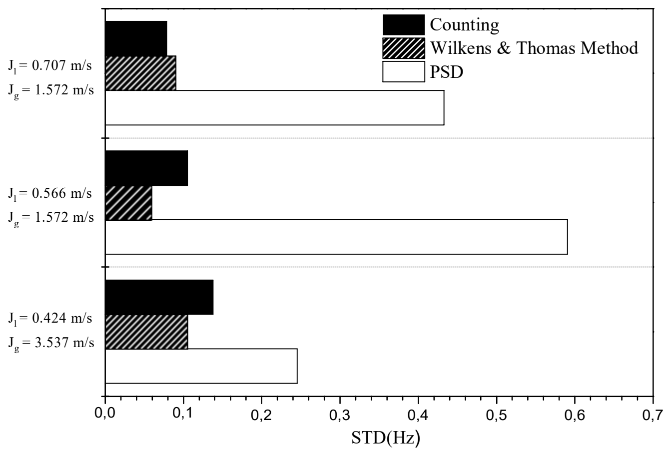

Fig. 6 Comparison between the standard deviation of the counting, the Wilkens & Thomas Method and PSD.

The results obtained from the three adopted methods were plotted as a function of the superficial velocities of the air, and that, for five superficial velocities of the Water liquid (*see for instance* Fig. 7). This kind of representation was previously used by Bertola & Cafaro [9].

The first thing that can be seen in Fig. 6 is that the counting method tends to overestimate the obtained results compared

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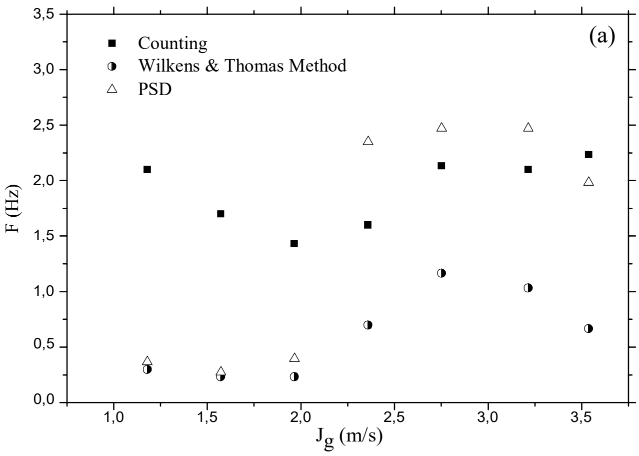
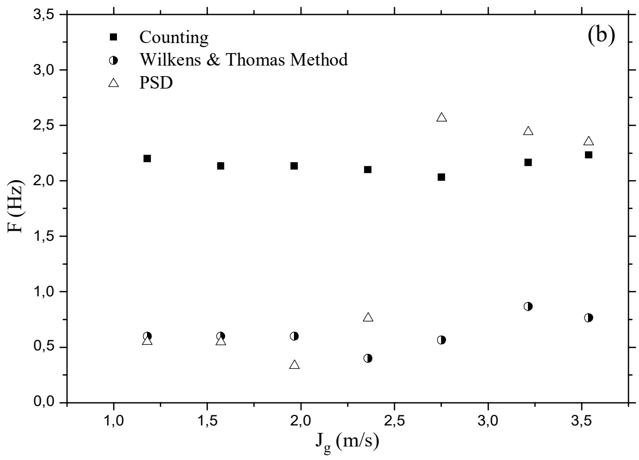
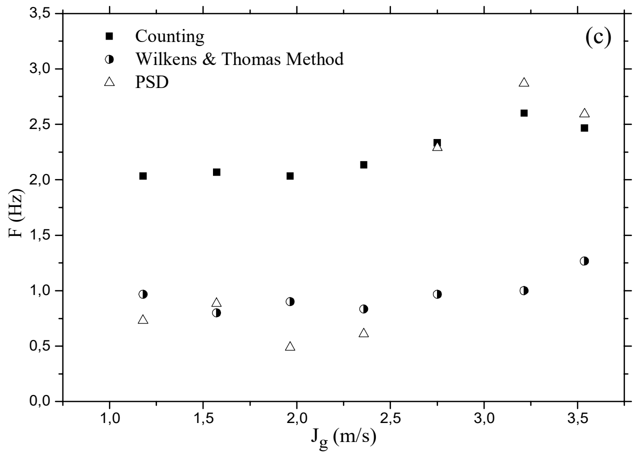
to Wilkens and Thomas method, which is logical as the latter takes into account the waves found into the slug flow.

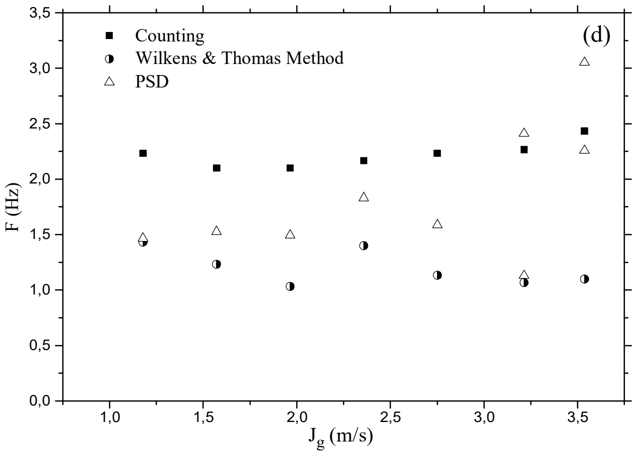
In addition to this, for the small values of the gas superficial velocity (in other words, Jg < 2.358 m/ s), the results obtained by the Wilkens and Thomas method and those using the PSD are very close to each other. By increasing the superficial velocity of the gas phase, the results given by the two methods disagree. This result can be related to the presence of several slugs in the space between the two pressure taps. In fact, the Wilkens and Thomas approach was developed on the basis of the presence of only one slug in the space between the two pressure taps and, as we know, there was no study which may prove the validity of the latter in the presence of several slugs [8].

With $J_l > 0.566$ m/s, and for a higher gas superficial velocity, PSD gives several values. In other words, the spectral analysis of the same signal yielded two or three results, which is due to the existence of two or three dominant frequencies in the frequency spectrum as shown in FIGS. 7 and 8.









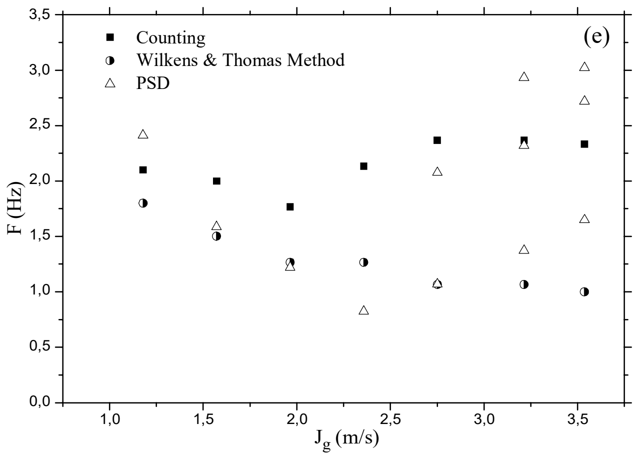


Fig.7 Comparative illustration of the slug frequency results obtained by the various adopted approach. $J_l = 0.141$ m/s **(a)**, $J_l = 0.283$ m/s **(b)**, $J_l = 0.424$ m/s **(c)**, $J_l = 0.566$ m/s **(d)**, $J_l = 0.707$ m/s **(e).**

From these figures, it is clearly seen that the spectrum is a bimodal and trimodal spectrum; composed of two peaks and three Peaks, respectively. Each peak illustrates a natural frequency. The existence of several natural frequencies is mainly due to the existence of several independent structures, the one with its own frequency, which is a clear proof that the

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system has been changed from the slug flow to another sub-regime of slug flow, such as the pseudo-slug [9].

At J_l = 0.566 m/s (see for instance Fig. 10), there was a bifurcation at J_g = 3.144 m/s at the occurrence of a second value for the frequency drawn from the spectrum of frequencies. At J_l = 0.707 m/s, there are two bifurcations: the first was found at J_g = 2.751 m/s, corresponding to a monodal spectrum to a bimodal one; or the transition towards a first sub-regime. The second at counted J_g = 3.144 m/s, which present the transition to a trimodal spectrum and thus; the transition to a second sub-regime. Either the same observation is presented by Bertola & Cafaro [9].

The fact that the spectral analysis may give us two or three values, it puts in the picture the complex nature of the slug flow regarding its non-periodicity and then; the slug frequency is not a standard periodic function as already reported by Woods et *al*. [11]. Both, the counting method and Wilkens & Thomas one can give only one frequency value, which informs us about their limit application; which making its less desired.

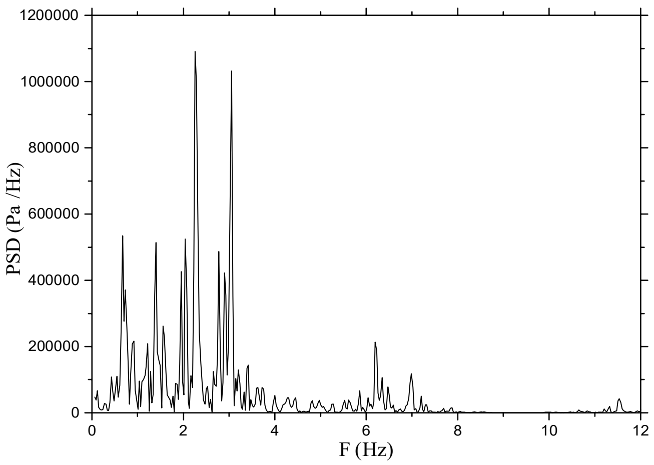

Fig.8 Exemple of bimodal spectrum (J_l = 0.566 m/s and J_g = 3.537 m/s)

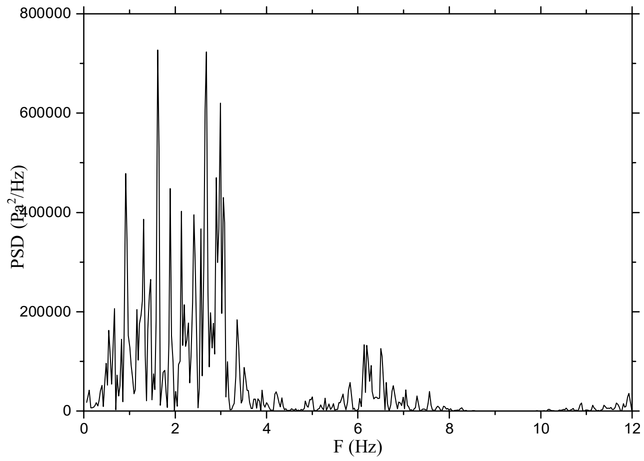

Fig.9 Exemple of trimodal spectrum (J_l = 0.707 m/s and J_g = 3.537 m/s)

V. CONCLUSION

The aim of this investigation is to compare the counting, the Wilkens & Thomas methods, based on the time series visualization, with the spectral analysis one, obtained using the PSD, to predict the frequency passage of liquid slugs in two-phase water-air flows within a horizontal pipe.

It has been found that the counting method tends to overestimate the results. For the low velocity flows, both the Wilkens & Thomas method and the PSD one give close results. When flow rates increase, the Wilkens and Thomas method tends to give unreliable results due to the presence of several slugs between pressure taps.

It appears to us that PSD is the most appropriate method for the slug frequency measurement. The latter gives results with a great uncertainty, but it is the only method that makes it possible to distinguish all the frequencies presented in the slug flow; as the slug flow can not be a standard periodic function. Thus, this approach can be used to distinguish the different transitions between the sub regimes of the slug flow.

REFERENCES

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

[2] Greskovich E.J and Shrier A.L., (1972), Industrial& Engineering ChemistryProcess Design and Development 11 (2), 317-318.

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

[4] Y. Taitel and A.E. Dukler, "A model for slug frequency during gas-liquid flow in horizontal and near-horizontal gas-liquid flow", *Int. J. of Multiphase Flow*, Vol. 19 (5), pp. 829-838, 1977.

[5] U. Kadri, "A Probabilistic Approach for Predicting Average Slug Frequency in Horizontal Gas/Liquid Pipe Flow", *Oil & Gas Science and Technology – Rev. IFP Energies nouvelles,* Vol. 69 (2), pp 331-339*, 2014.*

[6] J. Weisman, D. Duncan, J. Gibson and T. Crawford, "Effects of fluid properties and pipe diameter on two-phase flow patterns in horizontal lines", *Int. J. Multiphase Flow*, Vol. 5(6), pp. 437-462, 1979.

[7] M. Lin, Y. Liu, Y. Hu and D. Che, "Influence of the gas and liquid superficial velocity on slug frequency", 7th International Symosium on Multiphase Flow, Heat Mass Transfer and Energy Conversion, AIP Conf. Proc. 1547, 253-263. 2013.

[8] R.J. Wilkens and D.K. Thomas, "A Simple Technique for Detremining Slug Frequency Using Differential Pressure", *Journal of Energy Resources Technology*, Vol. 130, 2008.

[9] V.Bertola, E. Cafaro, "On the Measurement of Sug Frequency in the Horizontal Gas-Liquid Flow", *AIAA Paper* 2001-3035, 2001.

[10] P.Y. Lin and T.J Hanratty, "Detection of slug flow from pressure measurements". *Int. J. Multiphase Flow*, Vol. 13(1), pp. 13-21, 1987.

[11] B. D. Woods, Z. Fan and T. J. Hanratty, "Frequency and development of slugs in a horizontal pipe at large liquid flows" *Int. J. Multiphase Flow* , Vol. 32 (8), pp. 902-925,2006

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