Slugging Frequency Correlation for Inclined Gas-liquid Flow

V. Hernandez-Perez*, M. Abdulkadir, B. J. Azzopardi

***Abstract*—**In this work, new experimental data for slugging frequency in inclined gas-liquid flow are reported, and a new correlation is proposed. Scale experiments were carried out using a mixture of air and water in a 6 m long pipe. Two different pipe diameters were used, namely, 38 and 67 mm. The data were taken with capacitance type sensors at a data acquisition frequency of 200 Hz over an interval of 60 seconds. For the range of flow conditions studied, the liquid superficial velocity is observed to influence the frequency strongly. A comparison of the present data with correlations available in the literature reveals a lack of agreement. A new correlation for slug frequency has been proposed for the inclined flow, which represents the main contribution of this work.

***Keywords*—**slug frequency, inclined flow

I. INTRODUCTION

PREVIOUS studies reported in the literature reveal that intermittent flow exists as the dominant flow pattern in upward inclined flow. Intermittent flow is characterised by the variation of the liquid holdup with time, mainly in the form of periodic structures, such as slugs. The slugging frequency, *f*, is in fact defined as the mean number of slugs per unit time as seen by a fixed observer; [11], [7]. To calculate this parameter, in practice, it is common to recourse to the use of empirical correlations.

A very much used correlation for slug frequency prediction was developed by [7] based on data by [11], [17]. Nydal [17] compared the correlation with experimental data and found a good fit within the original data range (U_{SG} < 10 m/s and U_{SL} < 1.3 m/s).

$$f_S = 0.0226\left[\frac{U_{SL}}{gd}\left(\frac{19.75}{U_m} + U_m\right)\right]^{1.2} \quad (1)$$

A correlation was suggested by [8]. This model is on the same form as the [7] correlation,

$$f_S = 0.0226\left[\frac{U_{SL}}{U_m}\left(\frac{2.02}{d} + \frac{U_m^2}{gd}\right)\right]^{1.2} \quad (2)$$

Heywood and Richardson [10] proposed the following correlation, being almost identical to the one from [7], but based on a much larger amount of experimental data,

$$f_S = 0.0434\left[\lambda_L\left(\frac{2.02}{d} + \frac{U_m^2}{gd}\right)\right]^{1.02} \quad (3)$$

Tronconi [18] presented a semi-mechanistic expression for the slug frequency, where the slug frequency was assumed to be half the frequency of unstable waves (slug precursors),

$$f_S = 0.305 Cw^{-1}\frac{\rho_G}{\rho_L}\frac{U_G}{h_g} \quad (4)$$

Where $U_G = U_{SG}/(1-H_L)$ and h_G is the height of the gas phase at the inlet, immediately upstream the point of slug initiation. C_w is the wave velocity of the waves growing to become slugs. Tranconi [18] postulated a linear relationship between the frequency of critical waves and the slug frequency, $f_w = C_w f_S$, with $C_w = 2$. This corresponds to observations in slug flow (by [4] and [13], where every second slug originating from these waves was unstable and disappeared. The [18] correlation does not directly take into consideration any change in slug frequency with changing liquid flow rate, but indirectly through the calculations of gas flow rate and height.

Nydal [17] argued that, at high liquid flow rates, the slug frequency should depend weakly on U_{SG}, but strongly on U_{SL}, and suggested a correlation based on the liquid flow rate alone,

$$f_S = 0.088\,\frac{(U_{SL}+1.5)^2}{gd} \quad (5)$$

Jepson and Taylor [12] published data from the 306 mm pipe diameter rig of the Harwell laboratory, and the effect of diameter was investigated by including 25.4 and 51.2 mm pipe

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data from [16]. A non-dimensional slug frequency was correlated against the superficial mixture velocity,

$$f_S = \frac{U_{SL}}{d}\left(7.59*10^{-3}U_m + 0.01\right) \quad (6)$$

Manolis *et al.* [15] developed a new correlation based on [7]. Taking $U_{m,\min}$=5 m/s and the modified Froude number

$$Fr_{mod} = \frac{U_{SL}}{gd}\left[\frac{U_{m,\min}^2 + U_m^2}{U_m}\right] \quad (7)$$

Where

$$f_S = 0.0037 Fr_{mod}^{1.8} \quad (8)$$

Zabaras [21] suggested a modification to the [7] correlation, where the influence of pipe inclination angle was included, equation (9). The data on which the modified correlation was tuned included positive pipe angles in the range of 0 to 11° relative to the horizontal.

$$f_S = 0.0226\left[\frac{U_{SL}}{gd}\left(\frac{19.75}{U_m} + U_m\right)\right]^{1.2} \bullet \left(0.836 + 2.75\ \sin\theta\right) \quad (9)$$

All the above correlations are for horizontal flow. As a result, it is expected that when applied to other inclinations, they will fail to predict the frequency. In an effort to provide a tool for frequency calculation in inclined flow, a new correlation is reported in the present work, based on experimental data.

II. EXPERIMENTAL FACILITY

All experiments were carried out on an inclinable rig in the chemical engineering laboratory of the department of Chemical and Environmental engineering at University of Nottingham. Figure 1 shows a schematic diagram of the experimental facility used which had been employed earlier for annular flow studies by [1], [6] and [5] have been employed for two phase flow in inclinable pipes by [9]. The experimental facility consists of an inclinable 6 m long rigid steel frame.

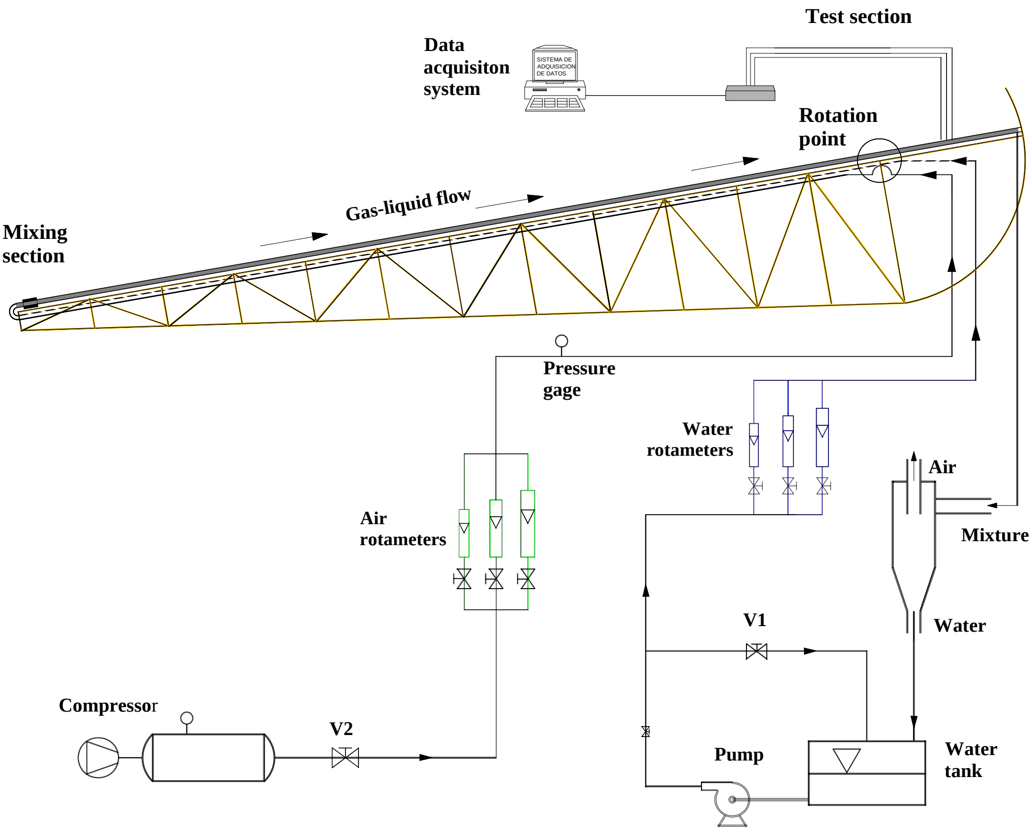

Fig. 1 Schematic diagram of inclinable rig

The test pipe is mounted on this frame and could be rotated between vertical to horizontal in 5° increments meaning the effect of different inclinations could be monitored. Two pipe diameters were studied, namely 38 mm and 67mm. This testing section is made up of shorter pipes. Each shorter pipe can be easily installed or replaced.

Air from the laboratory 6 bara compressed air main was used as the gas phase. It is fed into the facility through a 0.022 m internal diameter stainless steel pipe. A pressure regulating valve sets the maximum air inlet pressure and a pressure relief valve, set at 100% of the required feed pressure protects the facility against overpressure. Both the airflow rate and gage pressure are measured prior to entering the mixing section using a set of rotameters that covered a wide range of flow rates as well a pressure gage meter respectively. Inlet volumetric flow rates of water are determined prior to entering the mixing section with a set of rotameters that cover the range from 0-0.73 m/s of superficial velocities. The two separate phases are then mixed at the gas liquid mixing section. From the mixing section, the two-phase mixture flows along the inclined pipe before reaching the test section where the capacitance sensors are located. The pipe outlet is connected to the separator tank open to the atmosphere.

In the separator air is released to the atmosphere from the top of the separator and liquid is settled under the influence of gravity and flows through the bottom to return to main liquid tank.

This rig used an air-water mixture to examine the behaviour of gas-liquid flows in an inclined pipe. The sensor was placed at about 5.15 m away from the mixing section. The experiments were performed at room temperatures (15-20 degree Celsius)

III. RESULTS AND DISCUSSION

In order to determine the frequency of periodic structures (slugs) the methodology of Power Spectral Density (PSD) was applied. In addition the number of slugs visible on the liquid holdup time traces was counted. The latter was carried out using different discrimination levels.

Regarding the counting method, following the criterion used by most researchers (e.g. [17]) we used a critical value of 0.7 for the liquid holdup in the slug in order to be considered slug flow pattern. From Fig. 2, it can be seen that using different values for the threshold will result in a different number of slugs, which in turn gives a different frequency.

A very important feature of the liquid holdup signal is its average power. The holdup signal's instantaneous power is defined as the square of the signal. The average power is the average of instantaneous powers over their time interval. For a periodic signal, the natural time interval is clearly its period and the average power is the mean square value of the signal.

The Power Spectral Density, PSD, is a measure of how the power in a signal changes over frequency and therefore, it describes how the power (or variance) of a time series is distributed with frequency. Mathematically, it is defined as the Fourier Transform of the autocorrelation sequence of the time series. The Discrete Fourier Transform (DFT), sometimes called the Finite Fourier Transform, is a Fourier transform widely employed in signal processing and related fields to analyze the frequencies contained in a sampled signal, solve partial differential equations, and to perform other operations such as convolutions. The DFT can be computed efficiently in practice using a Fast Fourier Transform (FFT) algorithm.

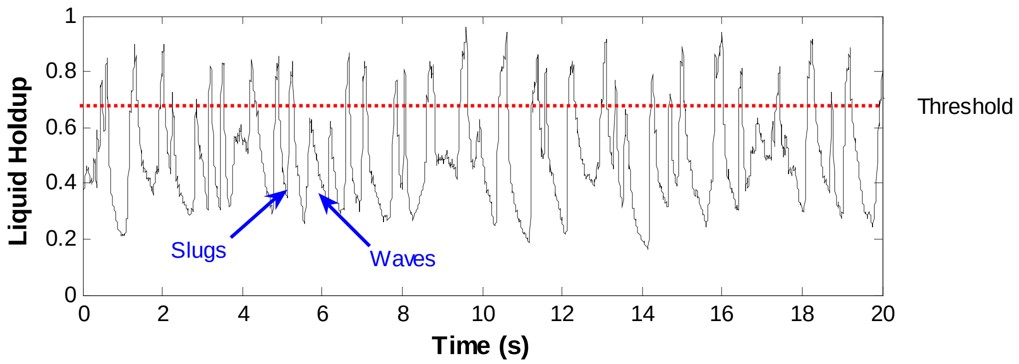

Fig. 2 Threshold for the liquid holdup level used to determine the number of slugs in the time series

In terms of signal processing, the transform takes a time series representation of a signal function and maps it into a frequency spectrum. That is, it takes a function in the time domain into the frequency domain; with decomposition of a function into harmonics of different frequencies.

A representation of a signal in the frequency domain is the frequency spectrum. This is the projection of the function onto a range of sinusoidal basis functions. A frequency spectrum contains both amplitude and phase information and describes how much of the "energy" of the function or signal lies in any given frequency band, without regard for the phase.

In order to use the PSD technique to determine the frequency we will follow the suggestions of [11]. Fig. 3 illustrates an example of the time series and corresponding PSD plot that will be used from now on.

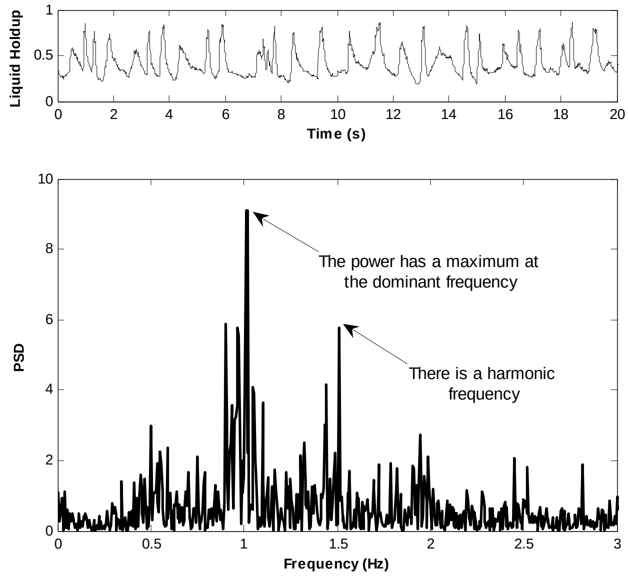

Fig. 3 Example of PSD (at the bottom) obtained from the corresponding time series (at the top) for 40° inclination, U_{SG}=0.9 m/s and U_{SL}=0.7m/s

The spectral plot is formed by:

- Vertical axis: Smoothed variance (power)
- Horizontal axis: Frequency (cycles per second)

From the analysis of the whole set of experiments, the main frequency tendencies were obtained. A parametric analysis makes it easier to understand the complex behaviour of the frequency, due to the number of variables involved.

Knowledge of slugging frequency is required as an input variable in many mechanistic models such as those of [4] and [3] and is relied upon for the design of separator vessels, [20]. In this work, the frequency was determined as described above and the results are plotted in Figures 4 to 7. It is in general affected by several parameters as described below.

For U_{SL}=0.2 m/s and the gas flow rates considered in this work, the frequency remains fairly constant for the horizontal case, the data for both pipes are overlapped. For the other inclinations, the tendency is not very clear at low values of U_{SG} but after U_{SG}=1 m/s seems to follow the slug frequency tendency found by other researchers such as [11] and [7], and the frequency does not change with the pipe diameter clearly. The biggest variation is found at the vertical position where it is clear that the frequency for 67mm pipe is bigger. This could be due to a combined effect of holdup and flow pattern.

In addition, it has been noted that at low gas superficial velocities, particularly for the 0.7 m/s liquid superficial velocity, there is some uncertainty about the values of the frequency. Indeed, the Power Spectral Density for those conditions is very small and there are several peaks on the PSD plot, see Fig. 4 where the for the condition of U_{SL}= 0.73 m/s and U_{SG}=0.15 m/s the PSD is at least one order of magnitude lower with respect to the other conditions. For these cases it is not easy to determine the frequency and the final values chosen are based on the assumption that if we reduce the gas superficial velocity to zero, then the frequency would decrease to zero.

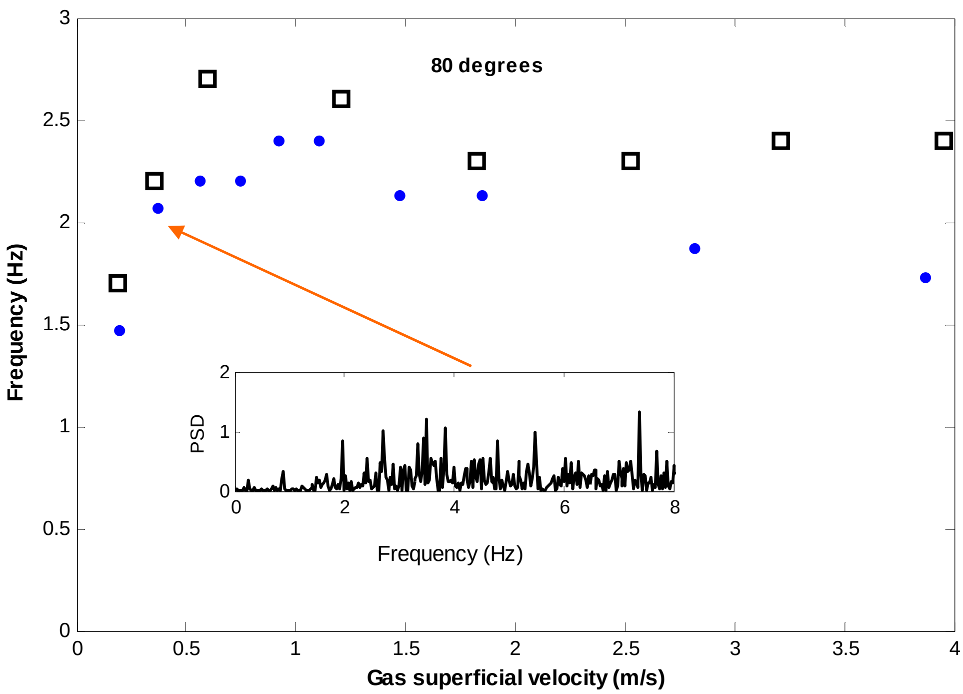

Fig. 4 Frequency for liquid superficial velocity 0.7 m/s and 80 degrees inclination in the 67 mm pipe

Also, as the gas superficial velocity approaches zero, bubbly flow exists and therefore the fluctuations are weaker over a wider range of frequencies.

For U_{SL}= 0.73 m/s, the frequency starts from a value of about 1 Hz for the lowest gas flow rate and then it grows very quickly, to a maximum as for this conditions bubble slug transition is passed and then it decreases gradually. For the horizontal case the behaviour is a bit different; for the 38mm pipe slug flow is obtained for all conditions, having a frequency around 1 Hz whereas in 67 mm the flow starts with stratified flow, where the frequency is 0 Hz and then changes to slug with an increase in the frequency.

The literature reveals that slug frequency data have been reported by several authors as well as correlations, and a comprehensive comparison of correlations for slug frequency has been made in [9], and a wide disagreement with the present data was found. Particularly for inclined flow, which is expected from the fact that none of the correlations for slug frequency found in the literature (except [21] for small inclination angles from the horizontal) take into consideration the effect of inclination angle. However, all of them agree that as the pipe diameter increases, the frequency decreases. Comparatively little has been reported on slug frequency data in inclined pipes, [19] reported data on slug frequency for inclined flow but no model or correlation was proposed, their data exhibit a tendency similar to the one found in [9], though their superficial velocities are lower. Examination of the frequency shows that it is strongly affected by the inclination angle. Therefore in this section, a correlation has been suggested to take into account the effect of inclination on the slug frequency from horizontal to vertical. Following a similar approach as that of [2] and [14] for drift velocity in inclined pipes, we correlate the slug frequency for inclined pipes from horizontal to vertical by using a linear combination of both horizontal and vertical frequencies.

Since the frequency and the velocity magnitude are directly proportional parameters, they are affected by the inclination angle in the same way. Similar to the velocity, for a particular inclination angle, the frequency can be multiplied by unity and apply the trigonometric relation $\cos^2\theta + \sin^2\theta = 1$ in order to be expressed as in equation (10).

$$f = (f\cos\theta)\cos\theta + (f\sin\theta)\sin\theta \qquad (10)$$

In addition it must satisfy the conditions that

$$f(\theta = 0^\circ) = f_h \qquad (11)$$

And

$$f(\theta = 90^\circ) = f_v \qquad (12)$$

Where f_h and f_v are the frequencies for horizontal and vertical inclinations respectively, therefore

$$f = f_h\cos\theta + f_v\sin\theta \qquad (13)$$

At this point we realise that there is no slug frequency correlation developed exclusively for the vertical case in the literature. By taking a look at Figure 6, it can be easily recognised that under the same flow conditions, frequencies in vertical flow are quite different from those in horizontal and as can be seen, literature correlations fail to predict the slug frequency for inclinations other than horizontal. Therefore the first step is to develop a correlation for vertical flow. Similarly to [15], [21] and [20], we developed the correlation based on a modification to the [7] to adapt it to the vertical frequency data, which are plotted in Fig. 5 as a function of the Froude number. Wren *et al.* [20] also compared data for 5, 19 and 35 mm pipe diameter in horizontal and showed a nonlinear decrease of frequency with increase in pipe diameter.

Gregory and Scott [7] correlation for frequency is given by equation (1)

Examination of the present data in Fig. 5 (from both 38 and 67 mm pipes) showed that for the vertical case, the more suitable values of the power and pre-constant were 0.2528 and 0.8428 respectively. This yields a new correlation for slug frequency in vertical pipes, which predicts considerably better than the correlations of the literature:

$$f_v = 0.8428\left[\frac{U_{SL}}{gd}\left(\frac{19.75}{U_m} + U_m\right)\right]^{0.25} \qquad (14)$$

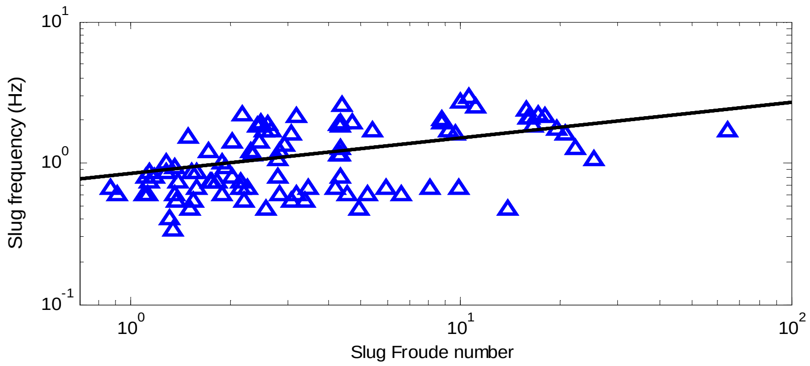

Fig. 5 Slug frequency vs. slug Froude number for vertical flow including data from both 38 and 67 mm pipes

The comparison between the values predicted by the correlations suggested by equations (13) and (14) and the experimental data gives a good agreement as can be seen in Figures 6 and 7. It seems that the effect of the pipe diameter on the frequency is that when increasing the pipe diameter, the frequency reaches its maximum at a steeper inclination angle; in Figures 6 and 7 it can be observed that the frequency has its maximum value at 60 degrees for 38mm and 80 degrees for 67 mm.

Further examination of Figures 6 and 7 shows that increasing the liquid superficial velocity, from 0.2 to 0.7 m/s, has a big effect on the frequency in horizontal, but not in vertical. In vertical even if the liquid superficial velocity is zero, we could have an intermittent flow with an associated frequency. This suggests that the frequency depends on the liquid holdup rather than U_{SL}.

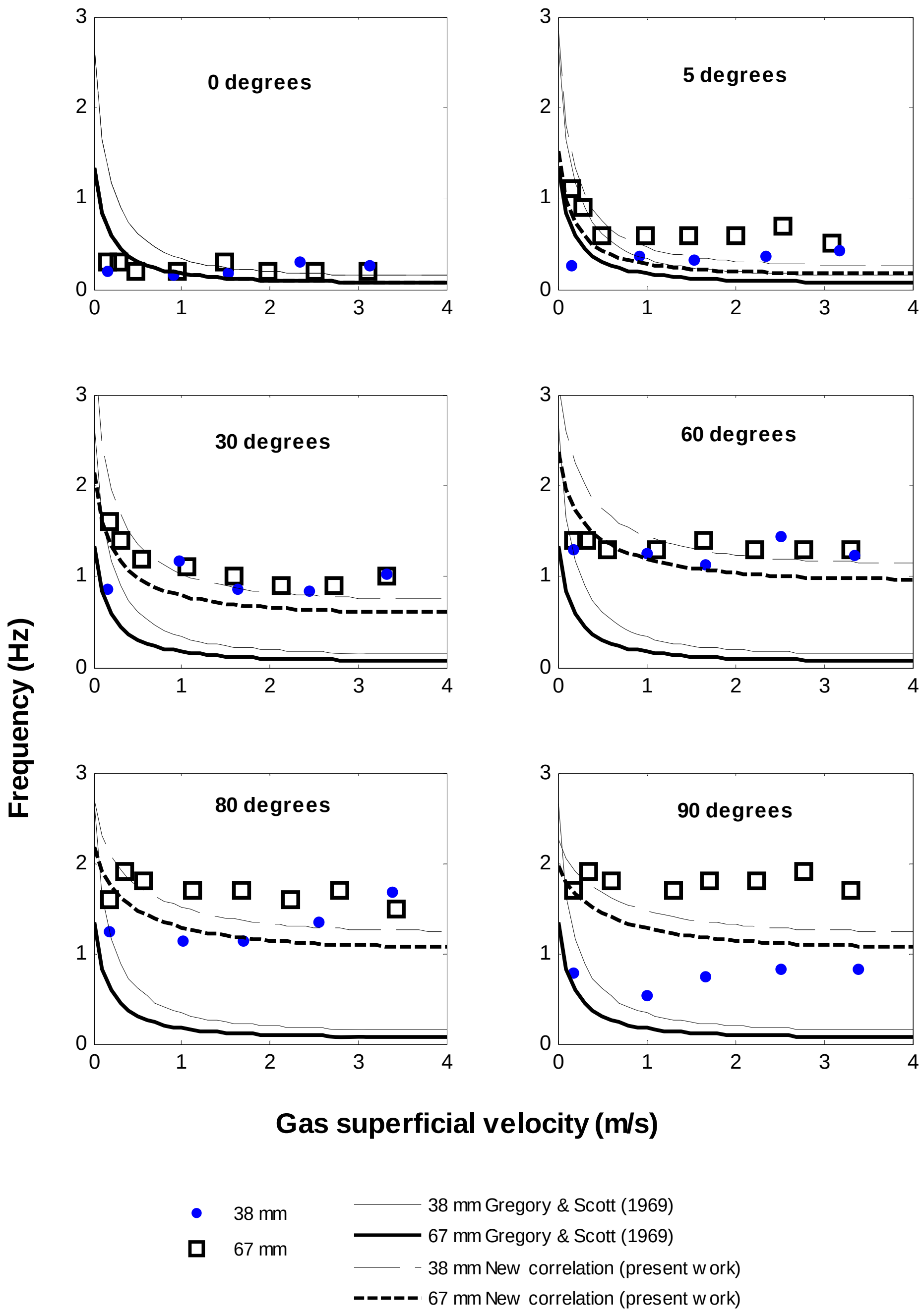

Fig. 6 Frequency results, U_{SL}=0.2 m/s and several inclination angles

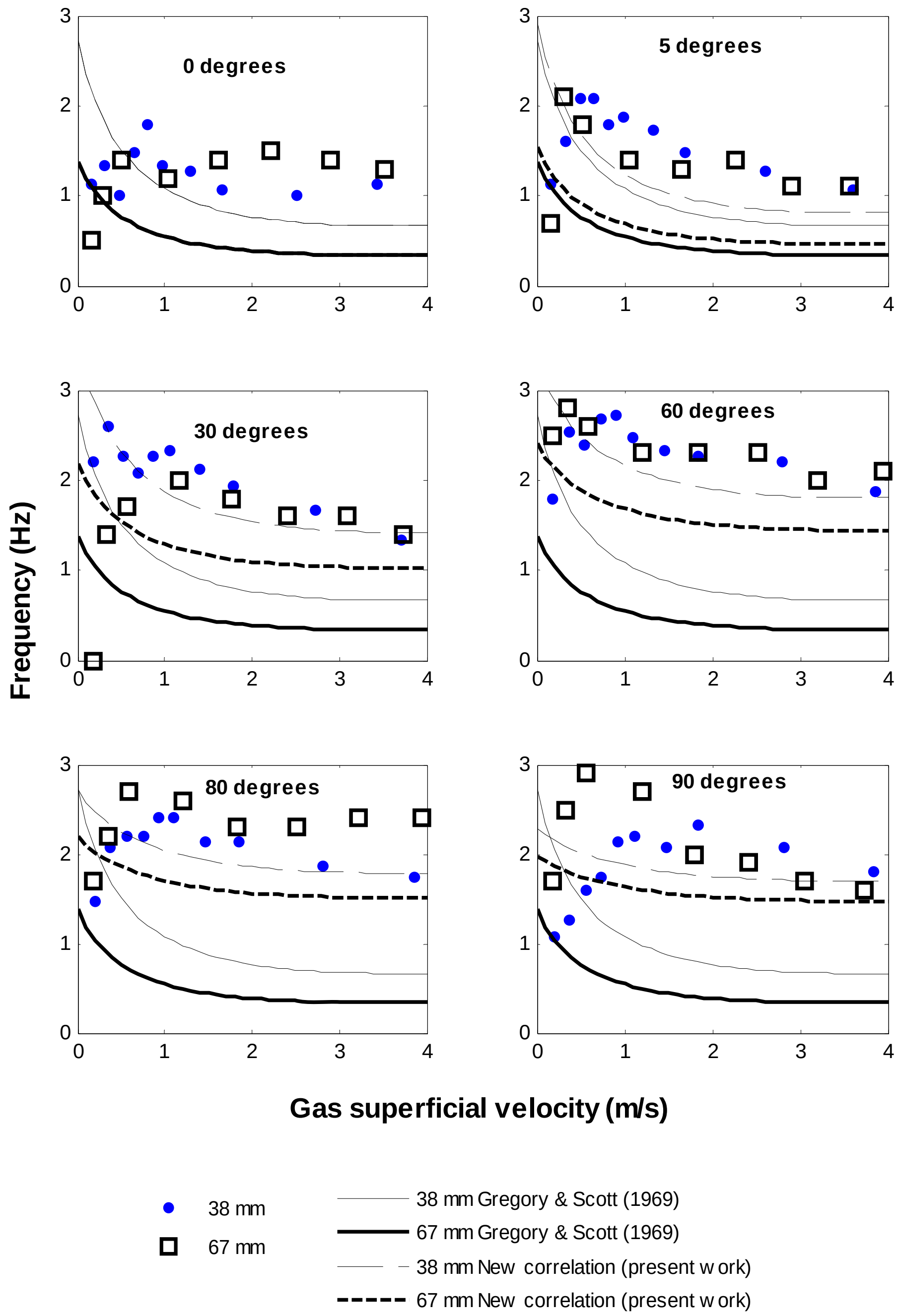

Fig. 7 Frequency, U_{SL}=0.7 m/s and several inclination angles

IV. CONCLUSION

New experimental data for slugging frequency in inclined gas-liquid flow are reported and the following conclusions can be drawn:

When analysing the frequency, it was found that it is a very complex parameter and therefore care must be taken when performing the calculations. Also interpretation of the result is important to verify the values, since the frequency is a very fundamental parameter of intermittent flow and it is used together with the translational velocity for the calculation of slug length.

A comparison of the present data with correlations available in the literature reveals a lack of agreement. A new correlation for slug frequency has been proposed for the inclined flow, which represents the main contribution of this work.

NOMENCLATURE

Symbol	Description, Units
d	Diameter of the tube, mm
Cw	Unstable waves
f	Frequency, Hz
g	Gravity constant, 9.81 m/s^2
U_m	Mixture homogeneous velocity, m/s
U_S	Slug velocity, m/s
U_{SG}	Gas superficial velocity, m/s
U_{SL}	Liquid superficial velocity, m/s
	Greek Symbols
θ	Inclination angle with respect to horizontal, °
λ	U_{SL}/U_m
	Subscripts
h	Horizontal
L	Liquid
m	Mixture
min	Minimum
s	Slug
	Dimensionless numbers
Fr	Froud Number, $Fr_m = U_m^2/gd$

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