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Research Article

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Evaluation of Wave Frequency Correlations in Annular Flow in Horizontal Pipe

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Abstract Annular flow in horizontal pipe was experimentally investigated with emphasis on wave frequency using 2-inch (0.0504m ID) pipe diameter with a closed-loop pipe of 28.68m long. The experiment was conducted using a two-phase (water/air) with a superficial liquid velocity of 0.0501m/s to 0.2001m/s and superficial gas velocity of 8.0774m/s to 23.7260m/s. To understand the dynamics of annular in pipe, wave frequency was analysed using power spectral density. The analysis revealed that both superficial liquid and gas velocities have great impact on wave frequency though, with more impact from gas velocity. However, the results from the experiments were extended into a correlation which was compared with other wave frequency correlations in annular flow in horizontal pipes. At higher superficial liquid velocities of 0.0903m/s to 0.1851m/s, there was a convergence between this study correlation and other correlation, showing a good performance.

Keywords Wave Frequency, Annular Flow, Horizontal pipe, velocity, Correlation

1. Introduction

Annular flow is encountered in petroleum production systems, where gas and liquid are conveyed from gas wells or oil wells (dominated by gas) to the surface via transport lines. Likewise, in nuclear power plants, chemical and refining processes (e.g. reactors, heat exchangers). The gas, together with the entrained liquid droplets, flows within the core of the pipe at high velocities, while the liquid flows as a film along the pipe walls under gravity as noted by [14] and [6]. In such flow, a non-uniform liquid film exists circumferentially across the pipes. This non-uniform liquid film (asymmetry distributions) are promoted by wave characteristics in annular flow.

Wave characteristics could be grouped into: wave velocity and wave frequency in annular flow. However, wave is an oscillation with a transfer of energy that travels through a medium, while frequency is the time-dependent for wave transfer. More so, the interfacial wave in annular flow could be grouped into: ripple and disturbance waves.

Ripples are low amplitude and high frequency waves that contribute to the interfacial shear stress in the pipes [7]. Also, they are characterized by low velocity, short-life time and non-coherent wave that creates interfacial roughness and promote pressure drop in annular flow, [15]. While disturbance waves travel with higher velocities, higher film thickness, higher amplitude, and longer-life time, which are responsible for liquid entrainment in the gas core, [15]. To investigate disturbance wave effect in annular, the understanding of wave frequency, wave velocity and spacing are necessary, [15], [13], and in this study, wave frequency is of high relevance.

Wave frequency in annular flow, is obtained from a corresponding frequency of the largest peak of the "***power spectral density***" ***(PSD)*** function as shown in appendix 1. In annular flow, several investigations exist to show the effects of superficial liquid and gas velocities on wave frequency. Among several experimental investigations on wave frequency in horizontal pipes, the following correlations were unique in their own ways based on pipe diameters used, concept applied, superficial gas and liquid velocities also used.

The correlation of [10], was also part of the experimental works carried out while developing the wave frequency correlation. However, the same flow conditions and pipe internal diameters used in wave velocity correlation exists in the wave frequency correlation which is expressed as:

$$f_W = 0.066\frac{V_{SL}}{D}\left(\frac{R_{eG}}{R_{eL}}\right)^{1.18} \quad \textbf{(1)}$$

The developed correlation for wave frequency of [13] was based on the experiments conducted with pipe internal diameters of 8.8mm and 15.1mm.

$$f_W = 0.005\left(\frac{V_{sg}}{D\sqrt{x}}\right) \quad \textbf{(2)}$$

Also, a second wave frequency correlation was developed based on the subsequent experiments, conducted with a pipe internal diameter of 26.3mm.

$$f_W = 0.035\left(\frac{V_{sg}\sqrt{Fr_{\mathrm{mod}}}}{D}\right) \quad \textbf{(3)}$$

For liquid entrainment from gas-liquid flow, [8] conducted his experiments using 2-inch horizontal pipe with an internal diameter of 0.0486mm and 6-inch pipe. Based on his investigations, liquid entrainment correlation and wave frequency correlation were proposed. On wave frequency, he used Strouhal number and Lockhart-Martinelli X parameter to develop wave frequency as:

$$St = 0.25X^{-1.2} \quad \textbf{(4)}$$

where,

$$X = \sqrt{\frac{\rho_L}{\rho_g}\frac{(Vsl)^2}{(Vsg)^2}} \quad \textbf{(5)}$$

Based on angle of inclinations, [1] carried out experiments on wave characteristics from horizontal pipe with an in internal diameter of 0.0762m and inclination angles of 10^o, 20^o, 45^o, 60^o. 75^o and 90^o. The experiments were used to investigate the effects of liquid viscosity, pipe diameter, Reynold number (Liquid) and surface tension. At the end, a dimensionless wave frequency correlation was developed based on Strouhal Number with Lockhart-Martinelli X parameter as:

$$St = 1.1X^{-0.93} \quad \textbf{(6)}$$

$$X = \sqrt{\frac{\rho_L}{\rho_g}\frac{(Vsl)^2}{(Vsg)^2}} \quad \textbf{(7)}$$

These researchers [16], studied the correlation of [13] and improved on it, using pipes with internal diameters of 16mm and 26mm. The correlation is as follows:

$$f = 0.035\left(\frac{V_{sL}^{0.02}V_{sg}^{0.9}Fr_{\mathrm{mod}}^{0.25}}{D^{0.8}x^{0.25}}\right) \quad \textbf{(8)}$$

From the experimental results, [16] reported that the superficial liquid velocity has negligible impact on wave frequency compared to superficial gas velocity on wave frequency.

Also, two-phase (gas-liquid) annular flow experiments in horizontal pipe with internal diameters of 16mm and 26mm were conducted by [15]. The aim was to investigate effect of fluid flow properties on wave characteristics (wave velocity and wave frequency). [15] in course of conducting the experiments, developed a wave frequency correlation as:

$$St = 0.258\left(\frac{\rho_l}{\rho_g}\right)^{0.574}\left(\frac{\mu_l}{\mu_g}\right)^{-1.148}\left(\frac{R_{el}}{\mathrm{Re}_{Gm}}\right)^{-1.148}\left(\frac{\sigma_L}{\sigma_W}\right)^{-0.11} \quad \textbf{(9)}$$

2. Experiments Setup

In this study, experiments were conducted using a 2-inch (0.0504m) horizontal pipe. The pipeline was a 28.68m closed-loop system with water inlet pipe connected to a water storage tank and the outlet pipe connected back to the same water storage tank. The plastic fibre water storage tank with a capacity of 4.4m^3, was designed with double chambers: suction chamber that acts as water source to the experimental test flow loop and returning chamber that retains the returning water. The flow loop had 2-pairs of pressure transducers installed at 2.13m apart, light emission diode infrared sensors (LED), two double pairs of conductivity rings sensors installed at 0.07m apart, pairs of conductance probes installed at 0.20m apart and the temperature sensors. The gas (air) was delivered using a 2-inch (0.0504m) air pipe from a compressor with a capacity of 400m^3/h and a maximum discharge pressure of 10bar. The air was metered using a gas flowmeter (vortex) with temperature and pressure sensors installed on the air flow line as presented in Figure 1.

On the sketch of the experimental 2-inch flow loop facility in Figure 1, the red flow line represents the air supply pipe, green line is for sand/water slurry pipe, the blue shows the water pipe flow and the pink represents multiphase flow to the delivery water tank.

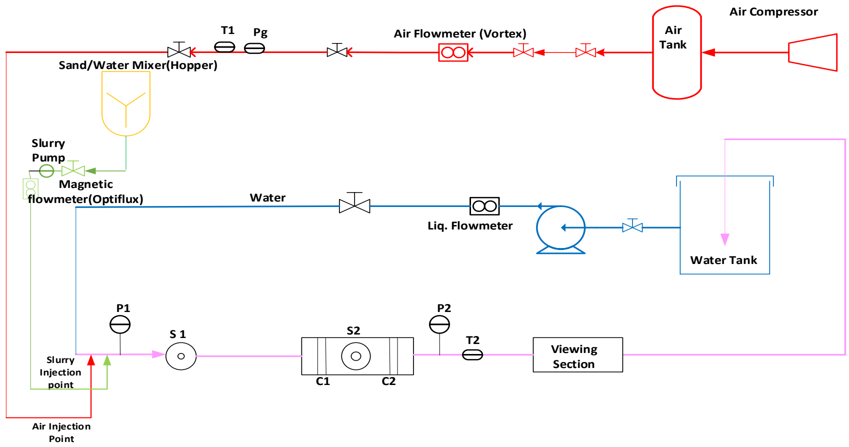

Figure 1: A Sketch of Experimental 2-inch Flow Loop Facility used

Table 2: Experimental Properties and Ranges Used

Properties	**Range**	**Units**
Temperature	16.5-19.3	°C
Pipe internal diameter (flow loop)	0.0504	m
Air flow line internal diameter	0.0504	m
Superficial liquid velocity	0.0501-0.2001	m/s
Superficial gas velocity	8.0774-23.7260	m/s

3. Study Correlation

In this study, wave frequency was developed by studying wave frequency correlations of [1] and [8]. The wave frequency correlations, preferably were closer to the wave frequency of the experimental investigations conducted. The proposed wave frequency in this study from the experimental results is:

$$St = 2.21X^{-0.3905}$$

Where X, is taken as Lockhart-Martinelli X parameter, as shown in [1] and [8] as:

$$X = \sqrt{\frac{\rho_L}{\rho_g}\frac{(Vsl)^2}{(Vsg)^2}}$$

4. Results and Discussion

Wave frequency analysis was presented using conductivity ring sensors' data from the experiments. The wave frequency results, from the experimental data were achieved using Matlab 2015 version on PSD against Frequency.

Wave frequency plot against superficial gas velocity in Figure 2, shows that wave frequency increases, with increase in superficial gas velocity as reported also by [15], [10], [12] and [13]. However, the experimental results of Figure 2, had refuted [16], whose report presented superficial liquid velocities to have insignificant effect on wave frequency.

Figure 2 illustrates the impact of superficial liquid velocity on wave frequency in line with [12] that says wave frequency decreases with increase in superficial liquid velocity. From Figure 2, the wave frequency of Vsl = 0.0505m/s was presented to be higher than of wave frequency of Vsl = 0.1851m/s. Meaning, wave frequency decreases with increase in superficial liquid velocity in annular flow in horizontal pipe.

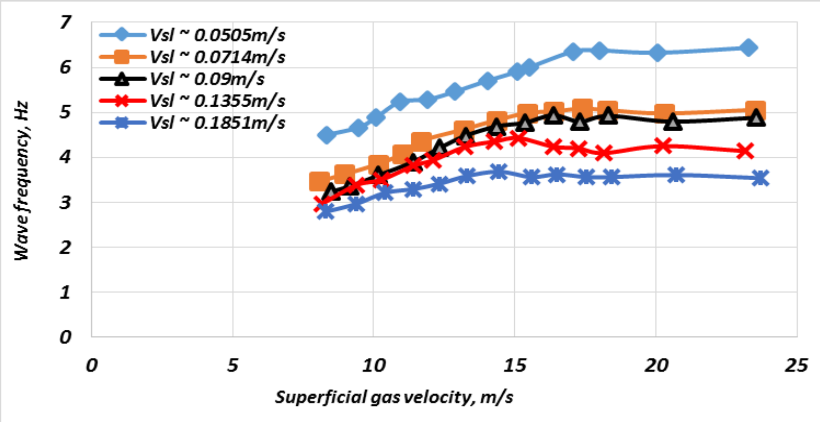

Figure 2: Wave frequency against superficial gas velocity

The graphs of Figures 3 to 7 illustrate the predicted wave frequency against the measured wave frequency results from the experiment conducted. For Vsl=0.0505m/s, [8] correlation which underestimated was close while [1] correlation over estimated. At Vsl=0.0714m/s, [1] correlation became closely even as it was over estimated. As the superficial liquid velocity increases the [1] correlation matched better with the measured or experimental results of this study for wave frequency. However, [16] was close enough at Vsl=0.1851m/s even though it was underestimated.

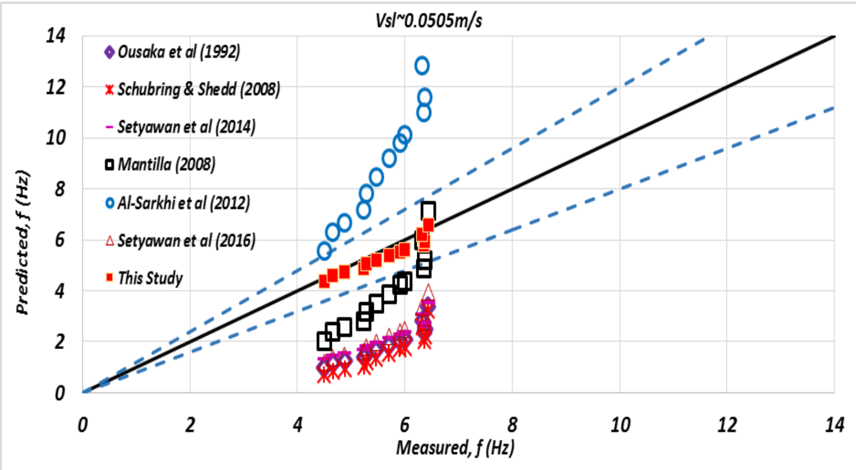

Figure 3: Predicted against measured Wave Frequency (Vsl=0.0505m/s)

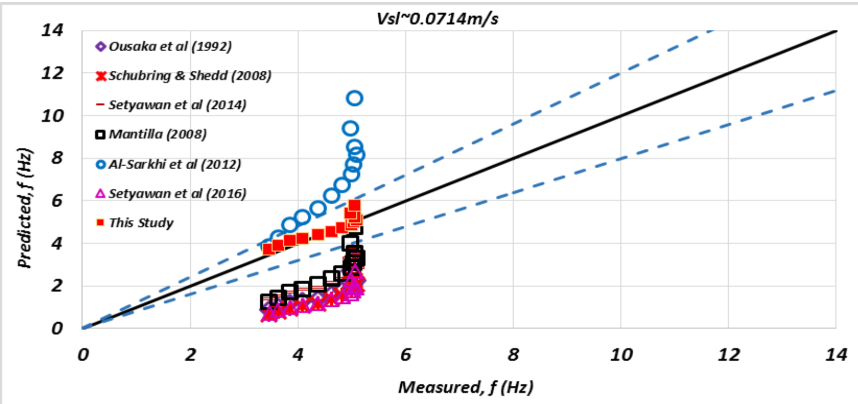

Figure 4: Predicted against measured Wave Frequency (Vsl=0.0714m/s)

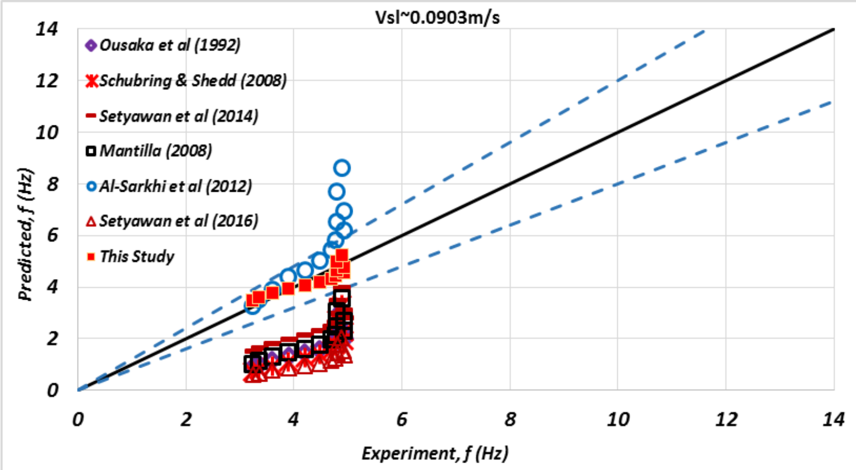

Figure 5: Predicted against measured Wave Frequency (Vsl=0.0903m/s)

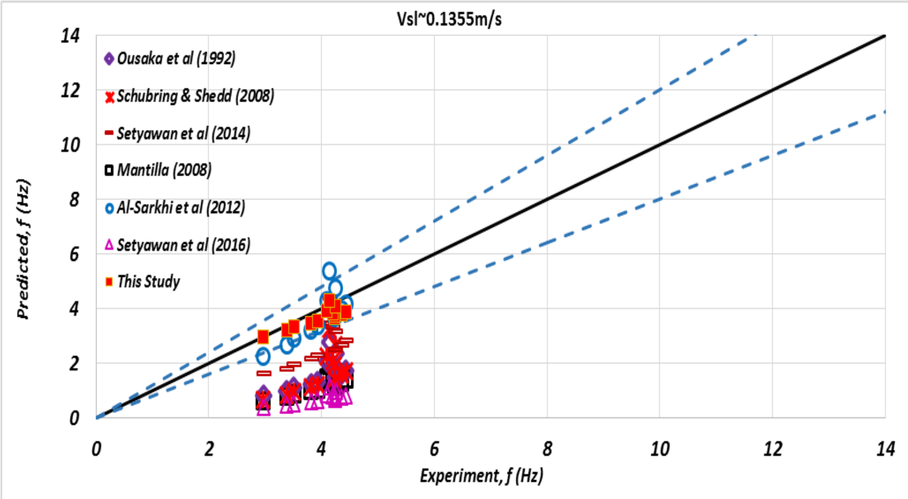

Figure 6: Predicted against measured Wave Frequency (Vsl=0.1355m/s)

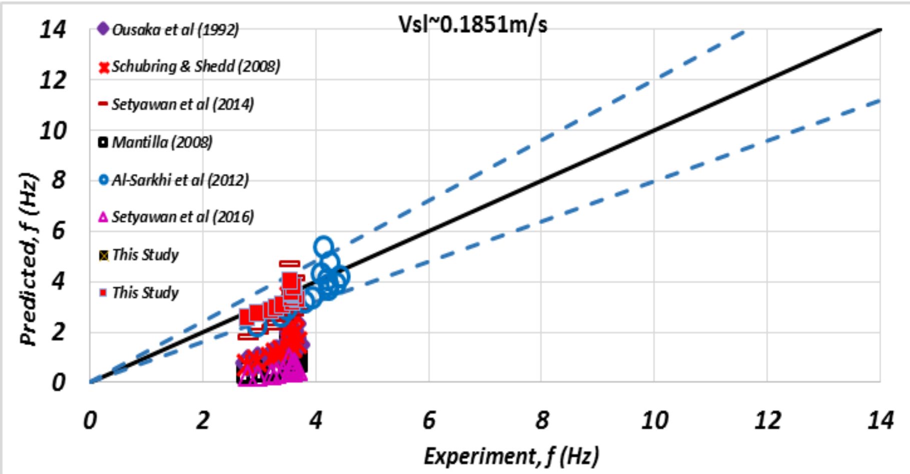

Figure 7: Predicted against measured Wave Frequency (Vsl=0.1851m/s)

5. Conclusion

In conclusions, the correlations and the experimental results of wave frequency had proven that superficial liquid velocity has impact on wave frequency. From the superficial liquid velocity of 0.0505m/s, the wave frequency from the experiment were between 4.499Hz to 6.4358Hz with Vsg of 8.3179m/s and 23.2796m/s respectively. While at an average superficial liquid velocity of 0.1851m/s, the wave frequency from the experiments were between 2.7945Hz to 3.5396Hz with Vsg of 8.3042m/s and 23.7259m/s respectively. This has shown, that the higher the superficial liquid velocity, the lower the wave frequency and the higher the amplitude, the more disturbing waves are created which forms ring structures across the pipe.

Lastly, the correlation results of [10], [13], [16] and [15] differed because the correlations were derived using small pipe diameters of 8.8mm to 26mm.

From the graphs of Figures 4-7, the [1] was the only correlation that matched closely with the measured wave frequency on average Vsl=0.0903m/s, 0.1355m/s and 0.1851m/s. At low Vsl of 0.0505m/s, it was [8] that was close.

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