Evaluation of Wave Frequency Correlations in Horizontal annular Flow

Andriyanto Setyawan[1], Indarto[2], Deendarlianto[2], Prasetyo[3], Agus Suandi[4]

Department of Refrigeration and Air Conditioning Engineering, Politeknik Negeri Bandung, Bandung 40012[1]
andriyanto@polban.ac.id
Department of Mechanical Engineering, Gadjah Mada University, Yogyakarta 55281[2]
Department of Mechanical Engineering, Politeknik Negeri Bandung, Bandung 40012[3]
Department of Mechanical Engineering, Universitas Bengkulu, Bengkulu 38371[4]

ABSTRACT

The evaluation of the existing wave frequency correlations was discussed in this paper. Four correlations were tested using the experimental data of the air-water horizontal annular flow in 16 mm and 26 mm inner diameter pipes. Different liquid viscosity and surface tension were used in the experiment. To obtain annular flow pattern, the superficial gas and liquid velocity were set at 12 to 40 m/s and 0.05 to 0.2 m/s, respectively. The wave frequency increases with the increasing of gas and liquid superficial velocity. However, the effect of superficial liquid velocity is less significant than that of superficial gas velocity. The examination of the existing correlations for the wave frequency shows that the accuracy of the correlation is generally only valid for certain cases of experiment and producing large error for the other cases

Keywords: *annular flow, wave frequency, surface tension, viscosity*

1. PENDAHULUAN

In practical applications, annular two-phase flow could be found in oil and gas industries, boiler, geothermal powerplant (Palsson, 2006; Valdimarsson, 2011), nuclear reactor, and refrigeration and air conditioning (Hulburt dan Newell, 1995, 1997; Shedd, 2001). In a gas-liquid annular flow, the gas and liquid flow in the same direction in the pipe but with different velocity. Liquid flows in the pipe wall as a film while the gas that containing droplets flows at a higher velocity in the core.

In a horizontal annular flow, the film thickness distribution is not uniform around the pipe circumference. The film is thicker at the bottom than that of the side and the top of the pipe. The asymmetry is affected by the gravity that tends to pull the liquid downward and other mechanisms for maintaining liquid film in the upper part of the pipe.

The studies on the wave behaviors in annular flow have been carried out in the recent decades. In general, two types of wave are found in annular flow. The first is the large structure wave, flowing with high velocity, called disturbance wave. It has a significant role in the transfer of momentum and energy (Sawant, 2008).

In annular flow, two kinds of wave structure are found, disturbance waves and ripple waves. Disturbance waves are responsible for transfer of mass, momentum, and energy along the tube (Sawant, 2008). With a higher amplitude and relatively long-lived structures along the pipe (Shedd, 2001), disturbance waves are also responsible for the entrainment of liquid droplets into the gas core when high velocity gas flows and shears the wave. Ripple waves, with the low amplitude surface waves, create interfacial roughness and, therefore, are responsible for the pressure drop. To investigate the effect of disturbance waves on annular flow, the knowledge of wave velocity, frequency, and spacing are required (Schubring and Shedd, 2008).

In analyzing annular flow, one of the most important parameter is disturbance wave frequency. This parameter affects the characteristics and mechanism of annular flow, especially in horizontal orientation.

The correlation of Ousaka et al. (1992) related the wave frequency as a function of superficial liquid velocity and gas and liquid Reynolds numbers. The effect of superficial velocity is, however, compensated by the liquid Reynolds number.

Correlation of wave frequency involving the modified Froude number has been proposed by Schubring and Shedd (2008). The effects of surface tension and viscosity are, however, not taken into account in this correlation.

Using the results of experiment in various pipe inclinations, Al-Sarkhi et al. (2012) proposed a correlation for wave frequency in term of modified Lockhart-Martinelli parameter. This parameter is modified as the ratio of liquid and gas Froude number.

The paper is aimed to compare the existing correlations for wave frequency in annular flows. The correlations are tested using experimental data using 16 mm and 26 mm pipes and liquids with different surface tension and viscosity.

2. Methodology

To analyze the existing correlations for wave frequency, a series of experiment were conducted in Fluids Laboratory, Department of Mechanical Engineering, Gadjah Mada University. The obtained wave frequency from the experiment was then compared with the existing correlations and analyzed.

The rig for the experimental purpose is given in Figure 1. The rig consists of piping section, water supply, air supply, test section, and visual observation section. The piping was constructed from 26 mm and 16 mm transparent acrylic pipes to facilitate visual observation. Before entering the test and visualization sections, air and water were passed through a mixer to guarantee the fully developed annular flow in both sections.

The experiment use a range of superficial liquid velocity of 0.05 m/s to 0.2 m/s and superficial gas velocity of 12 m/s to 40 m/s. In Mandhane map (1974), most of the experimental runs are located in the annular flow region (Figure 2).

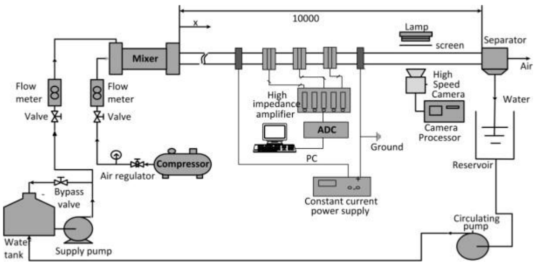

Figure 1. Experimental rig.

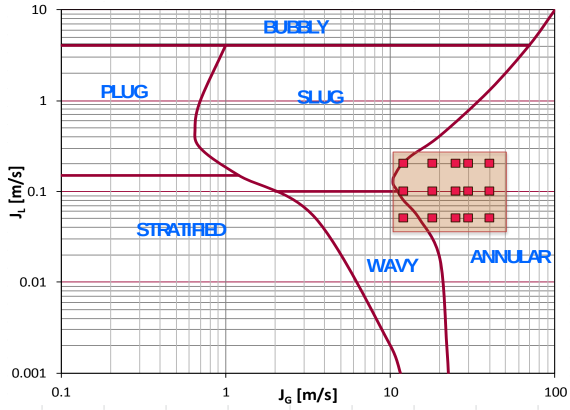

Figure 2. Experimental matrix.

In addition to air-water, liquids with different surface tension and viscosity were also employed in this experiment. To vary the surface tension, water with surface tension of 71 mN/m and 2% and 5% butanol solutions with surface tensions of 47 mN/m (denoted by S1) and 34 mN/m (S2) were used. The liquid viscosity was varied using water, 30%-glycerin solution (V1), and 50%-glycerin solution (V2). They give viscosity of 1.0 mPa.s, 2.6 mPa.s, and 5.2 mPa.s, respectively.

To obtain the wave frequency, a power spectral density function was employed. This tool calculates dominant frequency of a time series signal. The resulted wave frequency was then compared with the correlations from previous publications. The difference between the experimental result and the correlations are expressed in the mean absolute error (MAE).

In the test section, the liquid holdup data were measured using constant-electric current method (CECM) sensors developed by Fukano (1998). These sensors measure the holdup signal (that is the fraction of pipe cross sectional area occupied by liquid) based on the voltage drop caused by the change of the amount of each phase of fluid passing through the sensors. The visual observation was carried out using high speed video camera to trace the dynamics of the fluid flows along the visualization section. Detail of the experimental rig could be found in Setyawan et al. (2014).

3. Results and Discussion

In the present experimental study, the wave frequency was determined from the power spectral density function and it was validated by using the manual counting from the variation of liquid holdup signals. In general, the wave frequency increases with the increase of superficial gas velocity. It is in accordance with the experiment of Fukano et al. (1983), Jayanti et al. (1990), Paras and Karabelas (1991), Ousaka et al. (1992), and Schubring and Shedd (2008). Detailed examination of the correlations proposed by Alamu and Azzopardi (2011), Al-Sarkhi et al. (2012), and Gawas et al. (2014) also show that the wave frequency increases with the increase of superficial liquid velocity. The possible explanation is that as the liquid flow rate increases, the momentum transfer between the gas core and the liquid film also increases. It results in the creation of more waves.

The effect of viscosity on the wave frequency is shown in Figure 7. As seen in the figure, a higher liquid viscosity provides the lower wave frequency. This is due to the need of higher force to form a wave in liquid with a higher viscosity. Therefore, the lower frequency is resulted for the experiment with the higher viscosity under the same superficial gas and liquid velocity. A more significant effect of liquid viscosity is observed at the higher superficial gas velocity. The increase of wave frequency with increasing superficial gas velocity could be found in most of experimental range. Mantilla (2008) proposed different results, in which the wave frequency decreases when superficial gas velocity is high for experiment with 47%-glycerol solution. At superficial liquid velocity of 0.0034 m/s, the wave frequency decreases for superficial gas velocity higher than 30 m/s. At superficial liquid velocity of 0.018 m/s, the wave frequency decreases at higher gas velocity (> 50 m/s). Instead of disturbance waves, at high gas velocity the gas-liquid interface is covered by packs of wave, which move slower than that of disturbance wave. It results in lower passing wave per unit time, hence lower wave frequency. In the present experiment, the lowest liquid superficial velocity is 0.05 m/s. Therefore, the occurrence could not be compared.

The correlations for the wave frequency, f, have been developed for decades. Ousaka et al. (1992) proposed a correlation involving liquid superficial velocity, gas and liquid Reynolds numbers, and pipe diameter as follows

$$f = 0.066\,\frac{J_L}{D}\left(\frac{Re_G}{Re_L}\right)^{1.18}. \quad (1)$$

In Eq. (1), the effect of gas and liquid superficial velocities are expressed directly using J_L and indirectly using Re_G and Re_L. The diameter, D, is taken into account and it is shown that the wave frequency is inversely proportional to the pipe diameter. The comparison of this correlation with experimental data is presented in Figure 3 in term of dimensionless frequency or Strouhal number, ($St = fD/J_L$). In comparison to the experimental data, this correlation provides MAE of 192% for experiment with varying liquid viscosity and 28% for that of varying surface tension. The correlation presumed that the liquid viscosity has a very significant effect on the wave frequency, as could be seen from the power of the liquid Reynolds number. In addition, this correlation implied that the wave frequency increases as the liquid viscosity increases. In contrary to this correlation, the experimental data shows that the wave frequency decreases as the liquid viscosity increases. It results in the larger error when the liquid viscosity was varied.

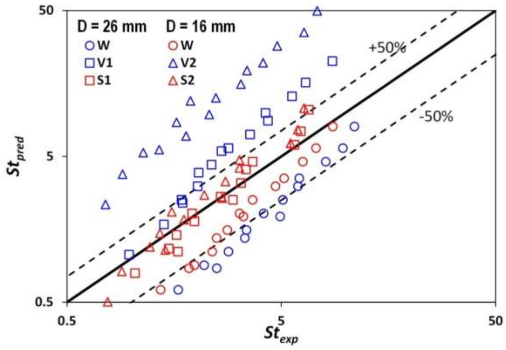

Figure 3. Wave frequency: comparison of the experimental data with the correlation of Ousaka et al. (1992).

Schubring and Shedd (2008) proposed different approximation for correlation of the wave frequency. For smaller pipe diameters (8.8 mm and 15.1 mm) the proposed correlation is

$$f = 0.005\,\frac{J_G}{D\sqrt{x}} \quad (2)$$

For 26.3 mm pipe, the correlation is expressed as

$$f = 0.035\,\frac{J_G\sqrt{Fr_{mod}}}{D} \quad (3)$$

where the modified Froude number, Fr_{mod}, is defined by

$$Fr_{mod} = \frac{J_G\rho_G}{\rho_L\sqrt{gD}}\ . \quad (4)$$

where g is the gravitational acceleration. Eq. (3) was tested by the experimental data for 16 mm inner diameter pipe and results in MAEs of 23%, 15%, and 22% for experiment with water, S1, and S2, respectively. Eq. (4) was tested by the experimental data of the 26-mm pipe and results in MAEs of 49%, 20% and 21% for experiment with water V1, and V2, respectively. As the liquid viscosity and surface tension were not involved in Eq. (2) and (3), the errors for the both correlations are still relatively large. The comparison of experimental data and this correlation is given in Figure 4.

The use of Lockhart-Martinelli parameter in correlation for wave frequency has been proposed by Mantilla (2008) based on his experiment results using different surface tension and viscosity in 2-inch and 6-inch inner diameter pipes. The liquids were water, water-5% butanol, and water-47% glycerin. The correlation of the wave frequency is non-dimensionally expressed in a relationship between Strouhal number and the Lockhart-Martinelli parameter, *X*,

$$St = 0.25\, X^{-1.2}\,, \tag{5}$$

where

$$X = \sqrt{\frac{\rho_L\, J_L^2}{\rho_G\, J_G^2}}\,. \tag{6}$$

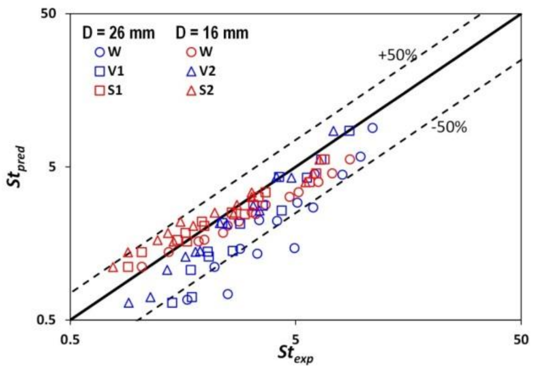

Figure 4. Wave frequency: comparison of the experimental data with the correlation of Schubring and Shedd (2008).

The correlation somewhat overpredicts to the experimental data, especially under varying surface tension. As the effect of surface tension and viscosity were not considered as important parameters in Eq. (4), the correlation gives better prediction for the case of experiment with water than that of liquids with different surface tension and viscosity. For all experimental data, the correlation gives a total MAE of 32% and its performance is given in Figure 5.

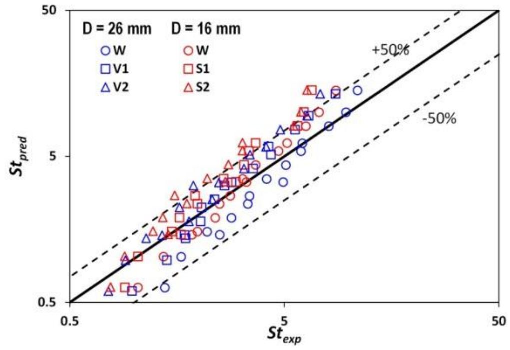

Figure 5. Comparison of wave frequency with correlation of Mantilla (2008).

Another similar correlation to predict the wave frequency was proposed by Al-Sarkhi et al. (2012). It was resulted from experiment with different pipe inclination from horizontal to vertical by using air and water as working fluids. It is written as follows

$$St = 1.1\, X^{-0.93}\,. \tag{7}$$

As shown in Figure 6, this correlation gives a considerably large error for all cases of experiments. It substantially overpredicts for all cases of the experimental data. The total MAE for this correlation is 185%, and larger errors are probably attributed to the cases of experimental with increased liquid viscosity and reduced surface tension.

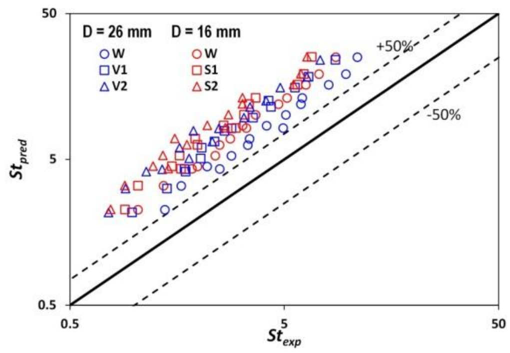

Figure 6. Comparison of wave frequency with correlation of Al-Sarkhi et al. (2012).

2. **4. Conclusion**

An examination and analysis of the existing correlations on the wave frequency have been carried out. In many correlations, the wave frequency is expressed in Strouhal number.

The performance of wave frequency correlations in some cases are in a good agreement with experimental data, especially for the experiment with water. If the liquid viscosity and surface tension were changed, the correlations are no longer in accordance with the experimental data. The large errors for both experiment with different liquid viscosity and surface tension are presumed to be the result of the neglected effect of both liquid properties in these correlations. In general, there is no standard formula in developing correlations for wave frequency. The kinds of parameters used for correlation development are also not well defined. As a result, the accuracy of the prediction of wave frequency is generally only valid for certain cases of experiment and producing large error for the other cases.

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1. Reference

Alamu, M. B., & Azzopardi, B. J. (2011). Wave and drop periodicity in transient annular flow. Nuclear Engineering and Design, 241(12), 5079–5092.

Al-Sarkhi, A., Sarica, C., Magrini, K. (2012). Inclination effects on wave characteristics in annular gas–liquid flows. AIChE J. 58, 1018–1029.

Andritsos, N. (1992). Statistical analysis of waves in horizontal stratified gas–liquid flow. Int. J. Multiphase Flow 18, 465–473.

Fukano, T., Ousaka, A., Morimoto, T., and Sekoguchi, K.. (1983). Air-water annular two-phase flow in horizontal pipe (2nd Report, Circumferential variations of film thickness parameters). Bulletin of the JSME, Vol. 26, No. 218, August 1983.

Fukano, T. (1998). Measurement of time varying thickness of liquid film flowing with high speed gas flow by CECM", *Nuclear Engineering & Design*, *184*, 363–377. http://dx.doi.org/10.1016/S0029-5493(98)00209-X.

Gawas, K., Karami, H., Pereyra, E., Al-Sarkhi, A., & Sarica, C. (2014). Wave characteristics in gas – oil two phase flow and large pipe diameter. Int. J. Multiphase Flow, 63, 93–104.

Hurlburt, E.T., and T. A. Newell, 1995. Optical Measurement of Liquid Film Thickness and Wave Velocity in Liquid Film Flows. ACRC Project 45, Two-Phase Modeling of Refrigerant Mixtures in the Annular/Stratified Flow Regimes.

Jayanti, S., Hewitt, G. F., & White, S. P. (1990). Time-dependent behaviour of the liquid film in horizontal annular flow. Int. J. Multiphase Flow, 16(6), 1097–1116.

Mandhane, J.M. , G.A. Gregory, K. Aziz (1974). A Flow Pattern Map for Gas-Liquid Flow in Horizontal Pipes, Int. J. Multiphase Flow, Vol. 1, pp. 537-553.

Mantilla, I. (2008). Mechanistic Modeling of Liquid Entrainment in Gas in Horizontal Pipes. Dissertation for Doctor of Philosophy in Petroleum Engineering, the University of Tulsa.

Ousaka, A., A. Kariyasaki, S. Hamano, T. Fukano, Relationships between Flow Configuration and Statistical Characteristics of Hold-up and Differential Pressure Fluctuations in Horizontal Annular Two-Phase Flow, Japanese J. Multiphase Flow Vol.7 No.4, 1993, pp. 344-353.

Ousaka, A., Morioka, I., & Fukano, T. (1992). Air-water annular two-phase flow in horizontal and near horizontal tubes: Disturbance wave characteristics and liquid transportation. Japanese Journal of Multiphase Flow, 6(9). http: //dx.doi.org/ 10.3811/jjmf.6.80.

Palsson, H., Berporsson, E.S., and Palsson, O.P, 2006. Estimation and Validation of Models Two-Phase Flow from Geothermal Wells, 10th International Symposium on District Heating and Cooling, September 3-5, 2006.

Paras, S. V., & Karabelas, A. J. (1991). Properties of the liquid layer in horizontal annular flow. International Journal of Multiphase Flow, 7(4), 439-454. http://dx.doi.org/10.1016/ j.nucengdes.2005.12.001.

Paras, S.V., Vlachos, N.A., Karabelas, A.J. (1994). Liquid layer characteristics in stratified—atomization flow. Int. J. Multiphase Flow 20, 939–956.

Rodriguez, J.M., Numerical simulation of two-phase annular flow. Thesis for Doctor of Philosophy, Faculty of Rensselaer Polytechnic Institute, 2009.

Sawant, P., Ishii, M., Hazuku, T., Takamasa, T., & Mori, M. (2008). Properties of disturbance waves in vertical annular two-phase flow. Nuclear Engineering and Design, 238, 3528–3541. http://dx.doi.org/ 10.1016/j.nucengdes.2008.06.013.

Schubring, D., & Shedd, T. A. (2008) Wave behavior in horizontal annular air–water flow. International Journal of Multiphase Flow, 34, 636–646. http://dx.doi.org/ 10.1016/j.ijmultiphaseflow.2008.01.004

Setyawan, A., Indarto, Deendarlianto, Experimental Investigation on Disturbance Wave Velocity and Frequency in Air-Water Horizontal Annular Flow, Modern Applied Science, 8 (2014) 84-96.

Shedd, T. A. (2001). Characteristics of the liquid film in horizontal two-phase flow. Thesis for Doctor of Phil. in Mechanical Engineering, the University of Illinois at Urbana-Champaign