Springer

KSME

Journal of Mechanical Science and Technology 24 (10) (2010) 1981~1988
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-010-0706-8

# An experimental study on characteristics of two-phase flows in vertical pipe

Woo Gun Sim[1,*], B. M. Bae[1] and N. W. Mureithi[2]

[1]*Department of Mechanical Engineering, Hannam University, Taejeon, 306-791, Korea*
[2]*Department of Mechanical Engineering, Ecole Polytechnique, Montreal, H3T 1J4, Canada*

(Manuscript Received May 21, 2009; Revised April 5, 2010; Accepted May 4, 2010)

**Abstract**

The characteristics of two-phase flow in a vertical pipe are investigated to provide information for understanding the excitation mechanisms of flow-induced vibration. An analytical model for two-phase flow in a pipe was developed by Sim et al. (2005), based on a power law for the distributions of flow parameters across the pipe diameter, such as gas velocity, liquid velocity and void fraction. An experimental study was undertaken to verify the model. The unsteady momentum flux impinging on a 'turning tee' (or a 'circular plate') has been measured at the exit of the pipe, using a force sensor. From the measured data, especially for slug flow, the predominant frequency and the RMS value of the unsteady momentum flux have been evaluated. It is found that the analytical method, given by Sim et al. for slug flow, can be used to predict the momentum flux.

*Keywords*: Bubbly flow; Drift flux model; Dynamic reaction force; Homogeneous model; Momentum flux of two-phase flow; Power law distribution; Slug flow; Strouhal number; Void fraction

## 1. Introduction

Many nuclear power plant components, such as steam generator tubes, are exposed to flowing two-phase coolants. Under certain operating conditions, the components can be subjected to excessive flow-induced vibrations which can lead to fretting-wear damage. To understand the fluid dynamic forces acting on the structure subjected to two-phase flow, it is essential to get detailed information about the characteristics of two-phase flow. Hydrodynamic forces in two-phase flows have been investigated by Carlucci [1], Carlucci and Brown [2] and Pettigrew et al [3-6]. However, little is known about the physical behavior of two-phase flow especially with respect to flow-induced vibration. At certain conditions, severe vibrations were observed in flow-turning elements subjected to internal two-phase flow by significant unsteady forces. The fluctuation of momentum flux in two-phase flow is a possible source of structural vibrations of heat exchanger U-tubes and reactor fuel elements. Very few studies have been performed for unsteady momentum fluxes associated with two-phase flow. Knowledge of the momentum flux is important to develop a technology and its application to engineering problems related to flow-induced vibrations. Momentum flux through a section of pipe with steam-water and air-water flows was measured by Andeen & Griffith [7]. Various two-phase flow models were evaluated by using the results.

Most widely used approaches are homogeneous and separated flow models. Using quick-closing plate valves, Schrage et al. [8] measured void fraction in an in-line bundle with air-water cross-flow. It is found that the void fraction varies with mass flux and is greatly over-predicted by the homogeneous equilibrium model (HEM) which neglects the effect of the velocity difference between the phases. In vertical upward two-phase flow, the gas velocity is affected by the tendency of the bubbles to rise through the center of the pipe. Relative motion between the bubble and the liquid is governed by a balance between buoyancy and drag forces: it is a function of void fraction but not of flow rate. A drift-flux model was developed by Zuber & Findlay [9]. It is essentially a separated-flow model where attention is focused on the relative motion between phases rather than on the motion of the individual phase. This model was later extended for the various flow patterns (Ishii et al [10], Zuber et al. [11], Wallis [12]). The drift-flux theory has widespread application to bubbly, slug, and droplet flow regimes of gas-liquid flow as well as to fluid-particle system such as fluidized beds.

In two-phase flow, three dominant flow patterns are bubbly, slug and annular flow (Cheng et al. [13, 14], Jones & Zuber [15]). The probability density function of void fraction fluctuations could be used as an objective and quantitative discriminator of the flow patterns. Heywood & Richardson [16] formulated a correlation for the dominant frequency in slug

[†] This paper was recommended for publication in revised form by Associate Editor Gihun Son
[*]Corresponding author. Tel.: +82 42 629 8089, Fax: +82 42 629 8293
E-mail address: wgsim@hnu.kr

flow. It was reported that the dominant frequency depends linearly on the superficial water flow velocity only, independent of gas velocity for superficial gas velocities (Leguis et al. [17], Azzopardi & Baker [18]). To understand the nature of the excitation mechanism of in-plane vibration of U-tubes under two-phase flow, a series of experiments were conducted by Riverin & Pettigrew [19].

Recently, a parametric study of two-phase flow has been developed by Sim et al. [20]. The integral analysis based on distributions of flow parameters across a pipe (such as gas velocity, liquid velocity and void fraction) has been used for the study. The momentum flux and the average quantities of two-phase flow were derived by integral analysis. To obtain the average void fraction, the existing empirical formulations for the average void fraction, proposed by Wallis, Zuber et al. and Ishii et al., were used. In particular, a model for the unsteady momentum flux of slug flow has been developed using the frequency correlation suggested by Heywood & Richardson. An experimental study was undertaken to verify the model. The unsteady momentum flux impinging on a 'turning tee' (or a 'circular plate') has been measured at the exit of the pipe, using a force sensor. From the measured data especially for slug flow, the predominant frequency and the RMS value of unsteady momentum flux have been evaluated.

## 2. Power law for flow parameters

### 2.1 Distribution of flow parameters

To understand the nature of fluid dynamic forces acting on a structure subjected to two-phase flow, it is required to obtain detailed information about the characteristics of two-phase flow [21]. However, it is difficult to determine the average density, void fraction and effective flow velocity accurately because these depend on the velocity ratio, $S$, which is defined as the ratio of gas to liquid phase velocity. These parameters are needed to formulate flow-induced vibration and predict fluid forces in pipes subjected to two-phase flow for instance. In the previous study [20], the average values of the parameters were calculated by the integral approach. Exploiting these power law profiles, the Reynolds transport theorem was used to formulate the momentum flux acting on the pipe. In particular, to formulate the unsteady momentum of slug flow, the results of the integral analysis and the frequency correlation (Heywood and Richardson) were utilized.

As mentioned before, distribution of void fraction is a strong function of the flow pattern. The distribution changes from a saddle-shaped profile to a parabolic-shaped profile, as gas velocity or quality increases (Cheng et al. [13], and Serizawa et al. [22]). A saddle-shaped distribution corresponds to bubbly flow, and a parabolic shape to slug flow. For homogeneous flow, the distributions are assumed to be uniform across the pipe. It was found that the average void fraction given by the homogeneous model is greatly over-estimated for slug flow and that the slip ratio for bubbly and slug flows increases with mass quality while the ratio is constant ($S$=1) for homogeneous flow.

In the previous study [20], the distributions of flow parameters across a pipe, such as gas velocity, $u_{gL}$, liquid velocity, $u_{fL}$, and void fraction, $\alpha_L$, are assumed to follow a power law. The subscripts, $g$, $f$ and $L$, stand for gas, liquid and local, respectively. The power law distributions take the form

$$\frac{\alpha_L}{\alpha_{\max}} = \left(1-\frac{r}{r_o}\right)^{1/p}, \quad \frac{u_{gL}}{u_{g\max}} = \left(1-\frac{r}{r_o}\right)^{1/m}, \quad \frac{u_{fL}}{u_{f\max}} = \left(1-\frac{r}{r_o}\right)^{1/n}, \tag{1}$$

where the subscript "$max$" denotes the maximum values at the center of the pipe, $r=0$. The integers ($m$, $n$ and $p$) are a priori unknown.

### 2.2 Average values with integral analysis

Average values of the parameters are calculated by integrating the local parameters, shown in Eq. (1), across the pipe, based on the power law. Details are shown in reference [20]. As a result, the average velocities are expressed in terms of the coefficients and the maximum values of the velocities, as examples;

$$u_f = \frac{1}{\pi r_o^2(1-\alpha)}\int_0^{r_o}(1-\alpha_L)2\pi r u_{fL}dr = C_{f1}\frac{C_{f2}-\alpha}{1-\alpha}u_{f\max},$$
$$u_g = \frac{1}{\pi r_o^2\alpha}\int_0^{r_o}2\pi r\alpha_L u_{gL}dr = C_g u_{g\max} \tag{2}$$

Similarly, the mass quality and void fraction can be expressed as

$$x = \frac{1}{1+\dfrac{\rho_f}{\rho_g}\dfrac{u_{f\max}}{u_{g\max}}\dfrac{C_{f1}}{C_g}\dfrac{C_{f2}-\alpha}{\alpha}}, \tag{3}$$

$$\alpha = \frac{\beta}{\dfrac{u_{g\max}}{u_{f\max}}\dfrac{C_g}{C_{f1}C_{f2}} + \dfrac{\beta}{C_{f2}}\left(1-\dfrac{u_{g\max}}{u_{f\max}}\dfrac{C_g}{C_{f1}}\right)}, \tag{4}$$

where the coefficients are given in Table 1. These relations are useful to calculate average values in the laboratory from measurements of the maximum values at the center providing the distribution profile is known. However, in the above formulations, one needs to know the average void fraction for the calculation.

The drift flux model was developed by Zuber & Findlay [9], starting from an analytical approach. They suggested the following simple formulation for the void fraction:

$$\alpha = \frac{\beta}{C_o + \overline{u_{gj}}/j}. \tag{5}$$

In the above equation, $\overline{u_{gj}}$ is the bubble rise velocity in a pipe containing stagnant liquid for the case where inertia forces dominate. $\beta\,(=Q_g/Q_f)$ and $j\,(=\alpha u_g+(1-\alpha)u_f)$ are volumetric quality and superficial velocity, respectively. For slug flow, Wallis [12] suggested the following expressions for $\overline{u_{gj}}$ and $C_o$ in Eq. (5):

$$\overline{u_{gj}}=0.345\left[\frac{gD(\rho_f-\rho_g)}{\rho_f}\right]^{1/2},\ C_o=1.2\,. \tag{6}$$

The proposed integral analysis has several advantages over existing empirical models. The integral forms can be easily incorporated into models for the determination of momentum flux and eventually flow-induced forces in flow-structure interactions.

### 2.3 Reynolds' transport theorem and steady momentum flux

When a vertically rising two-phase flow impacts a plate or a T-junction in a pipe thus changing flow direction, integral analysis has been proposed to estimate the momentum flux. Considering the fluid mass within the control volume shown in Fig. 1, the reaction force, $F_R$, acting on the control volume can be estimated by the Reynolds' transport theorem as follows:

$$\begin{aligned}F_p+F_g+F_R&=\frac{d}{dt}\int_{V_f}(\rho_f U_{fL})dV_f+\frac{d}{dt}\int_{V_g}(\rho_g U_{gL})dV_g\\&+\int_{A_f}\rho_f U_{fL}{}^2 dA_f+\int_{A_g}\rho_g U_{gL}{}^2 dA_g\end{aligned}\ , \tag{7}$$

where $F_p(=\Delta PA)$ is the pressure force. The control volume is located between the plate and the exit of pipe and the volume is surrounded by atmosphere. Thus, the pressure force can be negligible. The gravity terms are expressed as

$$F_g=\int_{V_g}\rho_g g dV_g+\int_{V_f}\rho_f g dV_f\,.$$

The gravity force is not considered in the present analysis, since the force is minor as compared to effect of momentum change. The right-hand side of Eq. (7) represents the time rate of momentum change and steady momentum flux across the control surface.

Steady reaction force associated with the momentum fluxes, given by liquid and gas, was derived by Sim [20], considering the power law for the distribution of flow parameters. The force can be expressed as

$$\begin{aligned}F_{Rs}&=\int_{A_f}\rho_f u_{fL}{}^2 dA_f+\int_{A_g}\rho_g u_{gL}{}^2 dA_g\\&=C_{mf1}(C_{mf2}-\alpha)\rho_f A u_{f\max}{}^2+C_{mg}\alpha\rho_g A u_{g\max}{}^2\end{aligned} \tag{8}$$

where the coefficients for the momentum are expressed as

Table 1. Coefficients defined for Average Velocity and Steady Momentum Flux.

| P | n | m | $C_{f1}$ | $C_{f2}$ | $C_g$ | $C_{mf1}$ | $C_{mf2}$ | $C_{mg}$ |
|---|---|---|---|---|---|---|---|---|
| ∞ | 7 | 7 | 0.8167 | 1 | 0.8167 | 0.6806 | 1 | 0.6806 |
| | ∞ | ∞ | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 7 | 7 | 0.8334 | 0.98 | 0.8334 | 0.7059 | 0.9641 | 0.7059 |
| 2 | 2 | ∞ | 0.625 | 0.8533 | 1 | 0.4286 | 0.7778 | 1 |
| | 7 | ∞ | 0.8637 | 0.9456 | 1 | 0.7538 | 0.9028 | 1 |
| | 7 | 7 | 0.8637 | 0.9456 | 0.8637 | 0.7538 | 0.9028 | 0.7538 |
| | 2 | 2 | 0.625 | 0.8533 | 0.625 | 0.4286 | 0.7778 | 0.4286 |

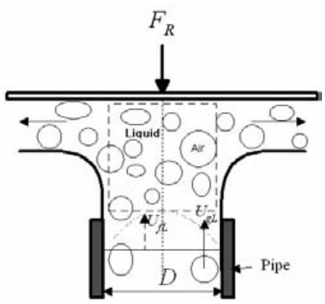



Fig. 1. Schematic diagram for momentum flux and reaction force acting on a control volume.

$$C_{mf2}=\frac{2(p+n/2+pn/2)(p+n/2+pn)}{(1+p)(1+2p)(1+n/2)(1+n)}\,,$$

$$C_{mf1}=\frac{n^2(1+p)(1+2p)}{4(p+n/2+pn/2)(p+n/2+pn)}\,,$$

$$C_{mg}=\frac{m^2(1+p)(1+2p)}{4(p+m/2+pm/2)(p+m/2+pm)}\,.$$

And the values for various flows are tabulated in Table 1. In Eq. (8), the first and second terms of the right hand side are the momentum fluxes, given by liquid and gas flow, respectively.

### 2.4 Unsteady momentum flux for slug flow

Using detailed information for the unsteady terms of two-phase flow parameters, it is feasible to evaluate unsteady reaction force. In spite of this, little work relating the unsteady nature of two-phase flow to flow-induced vibration has been done. However, a correlation for slug frequency in horizontal flow was proposed by Heywood & Richardson [16]. They determined the slug frequency from probability density functions of the liquid content in a pipe and related this to the mixture velocity, $j$, and the pipe diameter, $D$. The formulation they proposed is

$$f_{slug}=\frac{u_g}{l_t}=C\left[\frac{Q_f}{Q_f+Q_g}\left(\frac{2.02}{D}+\frac{j^2}{gD}\right)\right]^a \tag{9}$$

where $l_t$ denotes the total length of the unit slug. Fig. 2 shows

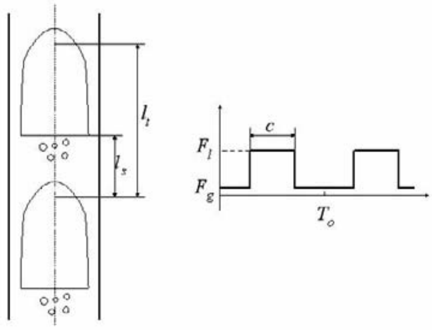



Fig. 2. Schematic diagram of slug flow and sequence of momentum flux by liquid and gas.

an idealized slug flow with several important parameters which characterize the slug flow defined. On the basis of experimental data, Legius et al. [23], $C$=0.0543 is suggested for vertical flow while $C$=0.0434 for horizontal flow, with $a$=1.02. Generally, a gas slug has a spherical nose and a flat tail (Fig. 2). Thus, the average void fraction can be approximated by

$$\alpha \approx \frac{l_t - l_s}{l_t} = 1 - \frac{l_s}{l_t} = 1 - \frac{c}{T_o} \tag{10}$$

where $T_o = 1/f_{slug}$ denotes the period of the unit slug motion. A reduced frequency based on superficial liquid velocity may be defined as

$$S_N = \frac{f_{slug}D}{j_f} = C\frac{1}{jD^{0.2}}\left(2.02 + \frac{j^2}{g}\right)^a . \tag{11}$$

As shown in Fig. 2, the liquid momentum flux is followed by gas momentum flux. The flux, denoted by a unit step function, is a periodic function of time. Considering liquid momentum flux defined in Eq. (8) with $p$=2 for slug flow, the flux given by liquid slugs can be formulated by the following Fourier series:

$$\begin{aligned} F_l(0<t<T_o) &= \left( u(t-\frac{T_o}{2}+\frac{c}{2}) - u(t-\frac{T_o}{2}-\frac{c}{2}) \right) \bullet \int_A \rho_f u_{fL}{}^2 dA \\ &= K_{sfm} A\rho_f u_{f\max}{}^2 \left( (1-\alpha) + \frac{2}{\pi}\sum_{k=1}^{\infty}\frac{(-1)^k}{k}\sin(k\pi(1-\alpha))\cos(2k\pi f_{slug}t) \right) \\ &= A_{fo} + \sum_{k=1}^{\infty} A_{fk}\cos(\omega_k t) \end{aligned} \tag{12}$$

where the coefficient for the unsteady momentum flux is defined as $K_{sfm} = n^2/[2(1+0.5n)(1+n)]$.

Similarly, one can express the gas flux by the Fourier series

$$\begin{aligned} F_g(0<t<T_o) &= K_{sgm} A\rho_g u_{g\max}{}^2 \bullet \\ &\quad \left( \alpha + \frac{2}{\pi}\sum_{k=1}^{\infty}\frac{(-1)^k}{k}\sin(k\pi\alpha)\cos(2k\pi f_{slug}t+\pi) \right) \\ &= A_{go} + \sum_{k=1}^{\infty} A_{gk}\cos(\omega_k t + \pi) \end{aligned} \tag{13}$$

where $K_{sgm} = m^2/[2(1+0.5m)(1+m)]$. The phase difference between the gas flux and liquid flux is π and the zero order term of the each momentum flux acts as a steady component. The coefficients defined for the unsteady momentum flux of slug flow with $p$=2, $n$=7 and $m$=∞ are $K_{sfm} = 0.6806$ and $K_{sgm} = 1$, respectively.

The root mean square of the unsteady momentum flux of slug flow is given by

$$F'_{RMS} = \sqrt{\frac{c}{T_o}(F_{l_{\max}} - A_{fo})^2 + \left(1-\frac{c}{T_o}\right)(F_{g_{\max}} - A_{fo})^2} . \tag{14}$$

Generally, the effect of gas flux on the value is minor. Considering Eqs. (10) and (12), the RMS value can be simplified as

$$F'_{RMS} \approx K_{sfm} A\rho_f u_{f\max}{}^2 \sqrt{\alpha(1-\alpha)} . \tag{15}$$

Details are shown in reference [20].

As a result, the reaction force of slug flow depends on the void fraction. The effect of slug frequency on the RMS force is included in the effect of void fraction.

## 3. Experimental considerations

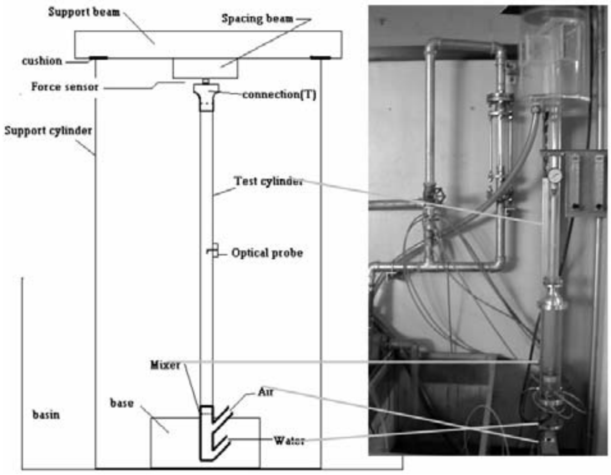
The final purpose of the present experimental study is to verify the analytical method given by Sim et al. and to obtain information on the periodic reaction force due to the momentum flux, especially for slug flow. Two air-water loops were constructed to the other (HNU) at Hannam University, Korea. Air from the local compressed air service is mixed with simulate two-phase flow as shown in Fig. 3. One (EPM) was designed at Ecole Polytechnique, Montreal, while water to produce two-phase flow. The mixers at the inlet of test section are used to homogenize the two-phase mixture. The water is re circulated from the tank. Major specifications of each loop are presented in Table 2.

The classification of the flow pattern was mainly based on visual observation and verified by the power spectral density function of the reaction force. From bubbly flow, as the mean void fraction increases further, the flow becomes slug flow and the slugs are always first observed at the top of the column. The time record of the bubbly flow shows an apparently random fluctuation, while the record of slug flow a periodic excitation is observed. The flow conditions were selected to cover the main flow patterns encountered in two-phase flow, namely: slug, bubbly and churn according to the map of Taitel et al. [24], shown in Fig. 4.

A piezoelectric force sensor was used to measure the net dynamic reaction exerted by the unsteady momentum flux at the exit of the pipe, as shown in Fig. 3. The flux is impinging on a 'turning tee' (EPM) or a 'circular plate' (HNU). The force transducer was attached on the support beam to measure the net vertical component of the fluctuating force.

Table 2. Major specifications of each Loop.

| | | EPM | HNU |
|---|---|---|---|
| Test Cylinder | Length (m) | 1.52 | 1.01 |
| | Inner Dia-meter (mm) | 20.8 | 30 |
| Mixture | | Fine screen | Multiple inlet holes (equally distributed) High contraction ratio |
| Control volume for the reaction force | | Turing Tee | Circular Plate (Diameter=280 mm) |




(a) EPM (b) HNU

Fig. 3. Air-water loops.

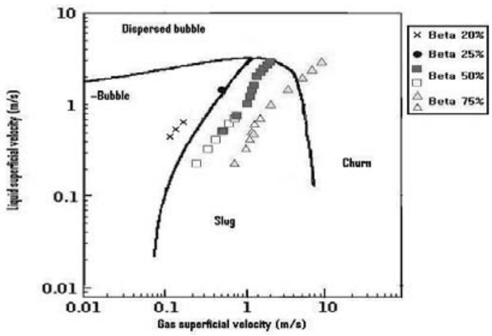



Fig. 4. Flow patterns selected for bubbly and slug flow.

## 4. Experimental results and discussions

Typical time traces from the force transducer are shown in Fig. 5. At low homogeneous void fraction ( $\beta = 20$ %), the form of the traces corresponds to a narrow-band random excitation. As the void fraction is increased, periodic force components become dominant and the shape of the force signal is close to a series of square pulses. The effect of flow pattern on the excitation forces could be observed for some conditions: when the two-phase flow is closer to bubble flow, the excitation is more random. When the flow pattern approaches slug flow, a more periodic excitation is observed. Spectral analysis

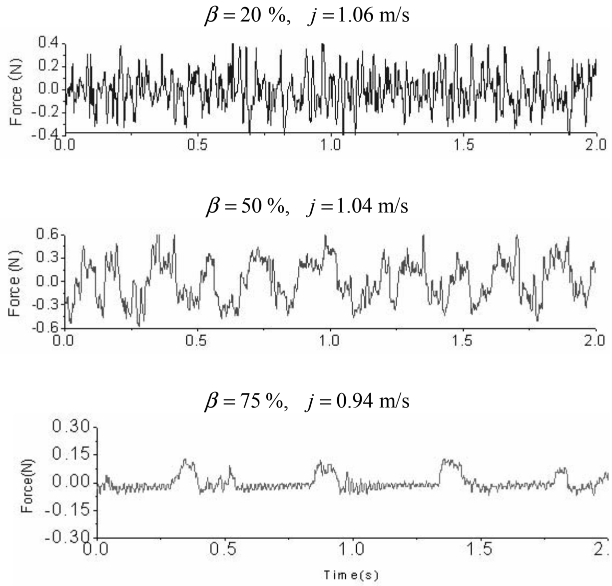
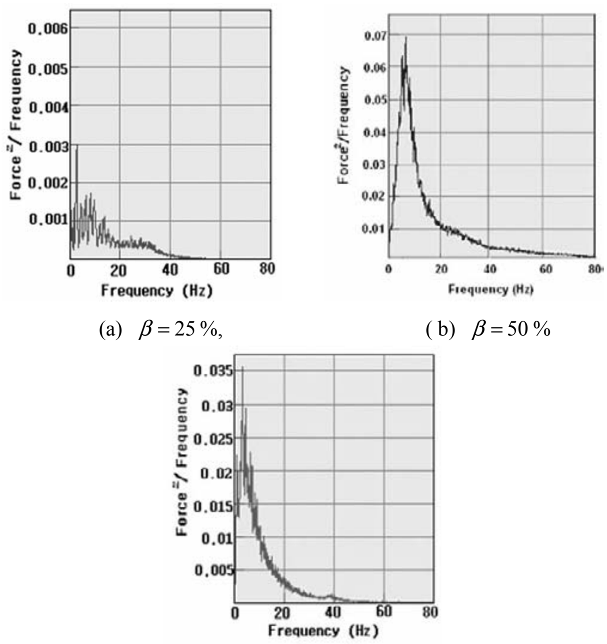



Fig. 5. Typical time traces of the dynamic reaction force given by HNU.



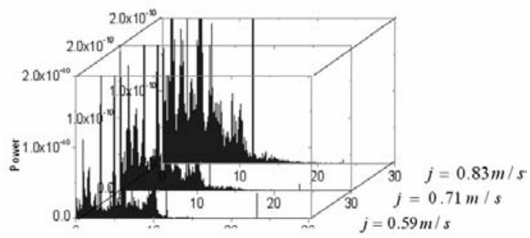

(a) $\beta = 25$ %, ( b) $\beta = 50$ %

(c) $\beta = 75$ %.

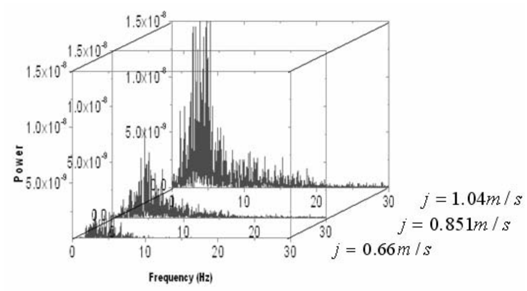
Fig. 6. Typical force spectra given by EPM for $j = 2$ *m/s*.

of the measured forces also shows that the excitation is a combination of narrow-band random and periodic components. Typical force spectra are shown in Fig. 6 (EPM) and Fig. 7 (HNU).

With the selected values of $n$=7, $m$=$\infty$ and $p$=2 for slug flow, the momentum fluxes, given by gas and liquid of slug flow, can be calculated by considering Eq. (8) for given mass fluxes of gas and liquid. And the frequency of slug flow, $f_{slug}$, was calculated by Eq. (11). In Fig. 8, typical time traces of the

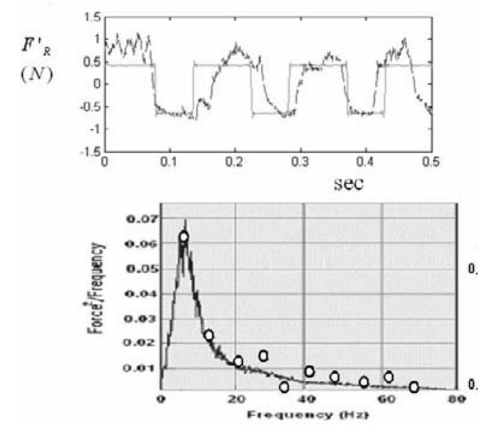



(a)

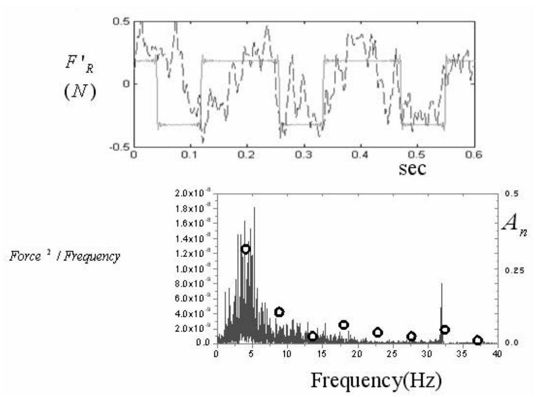



(b)

Fig. 7. Typical force spectra given by HNU : (a) $\beta = 20$ %, (b) $\beta = 50$ %.

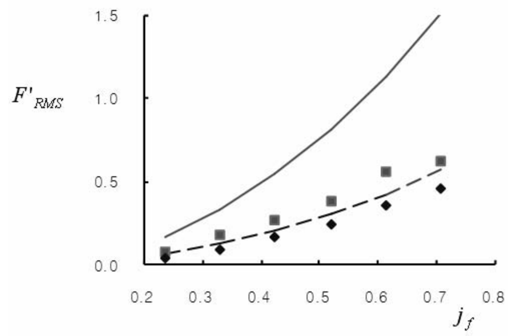



(a)

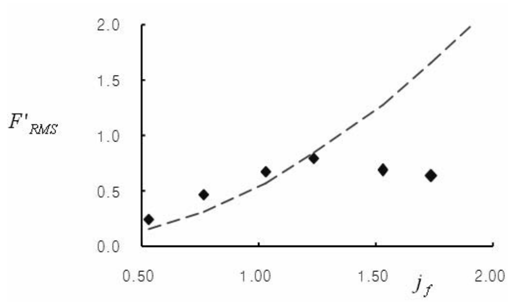



(b)

Fig. 8. Comparison of test results, given by (a) EPM $- j = 2.06 m/s$ and (b) HNU- $j = 1.04 m/s$, to analytical results for $\beta = 50$ %: o - $A_n$ defined in Eq. (12).




(a)




(b)

Fig. 9. Root mean square of the dynamic reaction force versus superficial liquid velocity, given by (a) HNU and (b) EPM : ---(Ana) ◆(Ex) for $\beta = 50$ % ——, (Ana) ■ (Ex) for $\beta = 75$ %.

periodic reaction forces and the major frequencies as defined by Fourier series, for momentum flux of slug flow, are illustrated. To verify the previous analytical method given by Sim [20], the test results are compared to analytical results. In the analytical results, the average void fraction is obtained by Eqs. (4) and (5) and the coefficients, $C$, defined in Eq. (9) for slug frequency are 0.107 for EPM and 0.122 for HNU, respectively. As expected for slug flow, the reaction force due to the momentum flux is in a sequence. The liquid flux is followed by gas momentum flux. The period reaction force can be expressed in Fourier series. The effect of gas on momentum flux can be negligible. The root mean square of the unsteady force by momentum flux of slug flow is illustrated in Fig. 9. The experimental results (Ex) are compared to the analytical results (Ana). In general, a saddle-shaped distribution of void fraction corresponds to bubbly flow, while a parabolic-shape to slug flow, in air-water flow. The analytical results are given for slug flow with $p$=2, $n$=7 m=∞. Good agreement is shown between the results, except for the cases of high superficial liquid velocity shown in Fig. 9(b). The difference could be due to the flow pattern. When the liquid velocity is increased, the flow pattern becomes closer to churn flow. The analytical results are overestimated as compared to the experimental results given by HNU. The slug flow in HNU contains more bubble compared to the flow in EMP because of the difference of the mixer between the two loops. In general, the effect of initial bubble size on the flow pattern is strong.

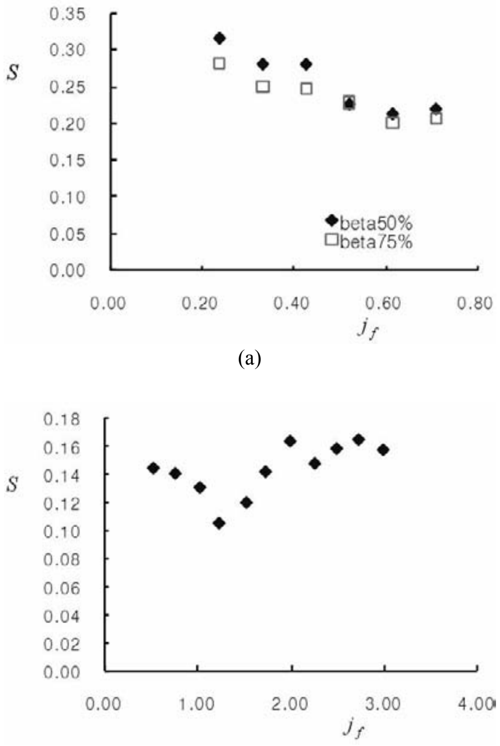



Fig. 10. Variation of the reduced frequency, $k$=1, versus superficial liquid velocity, given by (a) HNU and (b) EPM.

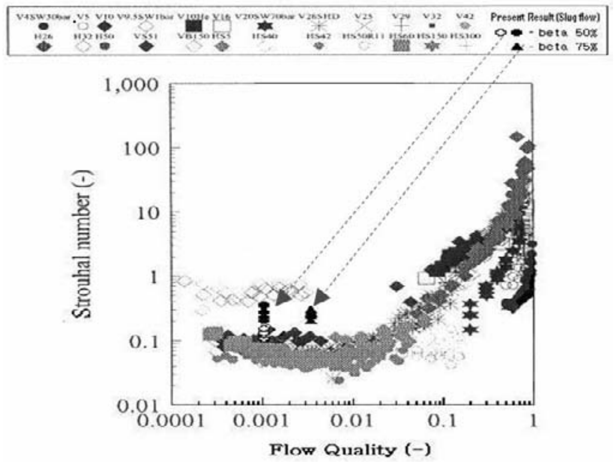



Fig. 11. Relationship between the reduced frequencies versus flow quality (Azzopardi and Baker, 2003).

Fig. 10 shows a typical variation of the reduced frequency, $S$, versus superficial liquid velocity, for $k$=1. The fundamental frequency for pure slug flow, as shown in Fig. 10(a), varies approximately linearly with superficial liquid velocity, as reported by Cheng et al. (1998), Azzopardi and Baker (2003) and Legius et al. (1997). In Fig. 10(b), the frequency is not linear with the velocity, since the flow is close to churn flow for relatively high superficial liquid velocity. Fig. 11 shows the majority of the data, including the present results, plotted as the reduced frequency (Strouhal number) versus quality.

## 5. Conclusions

To obtain information of the reaction force acting on a 'turning tee' (EPM) or a 'circular plate' (HNU), two air-water loops were constructed. For this purpose, a piezoelectric force sensor was used to measure the net dynamic reaction exerted by the unsteady momentum flux at the exit of the pipe. At low homogeneous void fraction, the form of the time traces of the reaction force corresponds to a narrow-band random excitation. As the void fraction is increased, periodic force components become dominant and the shape of the force signal is close to a series of square pulses.

In a previous study, an analytical model for two-phase flow in a pipe was developed, based on a power law for the distributions of flow parameters across the pipe diameter, such as gas velocity, liquid velocity and void fraction. Based on the power law, the average values of the parameters are calculated by integrating the local parameters across the pipe area. The integral forms can be easily incorporated into models for the determination of momentum flux and eventually flow-induced forces in flow-structure interactions. Good agreement is shown between the results, except the cases of high superficial liquid velocity. The difference could be due to the flow pattern. The analytical model, especially for the reaction force of slug flow, is verified as compared to the experimental results. The analytical model could be useful to estimate the reaction force for slug flow. It is found that the analytical results are overestimated compared to the experimental results given by HNU. The RMS value of the unsteady reaction force is not influenced by the slug frequency. The value depends on void fraction. In a future study related to flow-induced vibration, it would be desirable to investigate the reaction force including the steady term (zero order in Fourier series).

## Acknowledgment

This paper has been supported by the 2010 Hannam University Research Fund.

## References

[1] L. N. Carlucci, Damping and hydrodynamic mass of a cylinder in simulated two-phase flow, *Journal of Mechanical Design*, 102 (1980) 597- 602.

[2] L. N. Carlucci and J. D. Brown, Experimental studies of damping and hydrodynamic mass of a cylinder in confined two-phase flow", *Journal of Vibration, Acoustics, Stress, and Reliability in Design*, 105 (1983) 83-89.

[3] M. J. Pettigrew, C. E. Taylor and B. S. Kim, Vibration of tube bundles in two-phase cross flow; Part 1 – hydrodynamic mass and damping, *ASME Journal of Pressure Vessel Technology*, 111 (1989) 466-477.

[4] M. J. Pettigrew, J. H. Tromp, C. E. Taylor and B. S. Kim, Vibration of tube bundles in two phase cross flow; Part 2 – fluid-elastic instability, *ASME Journal of Pressure Vessel Technology,* 111 (1989) 478-487.

[5] M. J. Pettigrew and C. E. Taylor, Vibration analysis of shell-

and-tube heat exchangers; an overview- Part 1: flow, damping, fluidelastic instability, *Journal of Fluids and Structure*, 18 (2003) 469-483.

[6] M. J. Pettigrew and C. E. Taylor, Vibration analysis of shell-and-tube heat exchangers; an overview- Part 2: vibration response, fretting-wear, guidelines, *Journal of Fluids and Structure*, 18 (2003) 485-500.

[7] G. B. Andeen and P. Griffith, Momentum flux in two-phase flow, *Journal of Heat Transfer*, 90 (2) (1968) 211-222.

[8] D. S. Schrage, J. T. Hsu and M. K. Jensen, M. K., Two-phase pressure drop in vertical cross flow across a horizontal tube bundle, *AIChE J*, 34 (1988) 107-115.

[9] N. Zuber and J. Findlay, Average volumetric concentration in two-phase flow system, *Trans. ASME Journal of Heat Transfer*, 11 (1965) 453-468.

[10] M. Ishii, T. C. Chawla and N. Zuber, Constitutive equation for vapor drift velocity in two-phase annular flow", *AIChE,* 22 (2) (1976) 283-289.

[11] N. Zuber, F. W. Staub, G. Bijwaard and P. G. Kroeger, P. G., Steady state and transient void Fraction in two-phase flow system, GEAP 5471 (1967).

[12] G. B. Wallis, One-dimensional two-phase Flow, McGraw-Hill, (1969).

[13] H. Cheng, J. H Hills and B. J. Azzorpardi, A study of the bubble-to-slug transition in vertical gas-liquid flow in columns of different diameter, *International Journal of Multiphase Flow*, 24 (1998) 431-452.

[14] H. Cheng, J. H Hills and B. J. Azzorpardi, Effects of initial bubble size on flow pattern transition in a 28.9 mm diameter column, *International Journal of Multiphase Flow*, 28 (2002) 1047-1062.

[15] O. C. Jones Jr. and N. Zuber, The interrelation between void fraction fluctuations and flow patterns in two-phase flow, *International Journal of Multiphase Flow*, 2 (1975) 273-306.

[16] N. I. Heywood and J. F. Richardson, Slug flow of air-water mixtures in a horizontal pipe: Determination of liquid holdup by $\gamma$ -ray absorption, *Chemical Engineering Science*, 34 (1979) 17-30

[17] H. J. W. M. Legius, H. E. A. van den Akker and T. Narumo, Measurements on wave propagation and bubble and slug velocities in co-current upward two-phase Flow, *Experimental Thermal and Fluid Science*, 15 (1997) 267-278.

[18] B. J. Azzopardi and G. Baker, Characterics of periodic structures in gas/liquid two-phase flow, *UK/Japan Two-Phase Flow Meeting*, Guildford, (2003).

[19] J. L. Riverin and M. J. Pettigrew, Fluctuation forces in U-tubes subjected to internal two-phase flow, *Proceedings of ASME P.V & P. Division Conference,* Denver, Colorado, (2005) PVP2005-71424.

[20] W. G. Sim, N. W. Mureithi and M. J. Pettigrew, Parametric study of two-phase flow by integral analysis based on power law distribution, *Journal of Mechanical Science and Technology*, 24 (7) (2010) 1379-1387.

[21] W. G. Sim, Stratified steady and unsteady two-phase flows between two parallel plates, *Journal of Mechanical Science and Technology*, 20 (1) (2006) 125-132.

[22] A. Serizawa, I. Kataoka and I. Michiyosh, Turbulence of air-water bubbly flow - II. Local properties, *International Journal of Multiphase Flow*, 2 (1975) 235-246.

[23] H. J. W. M. Legius H. E. A. van den Akker and T. Narumo, Measurements on wave propagation and bubble and slug velocities in cocurrent upward two-phase flow, *Experimental Thermal and Fluid Science*, 15 (1997) 267-278.

[24] Y. Taitel, D. Barnea and , A. E. Dukler, Modeling flow pattern transitions for steady upward gas-liquid flow in vertical tubes, *AIChE*, 26 (1980) 345-356.

[25] W. G. Sim, N. W. Mureithi and M. J. Pettigrew, 2005, Two-phase flow modeling in a pipe related to flow-induced vibration, *Proceedings of ASME P.V & P. Division Conference,* Denver, Colorado, PVP2005-71171.

**Woo-Gun Sim** received his B.S. in Mechanical Engineering from Inha University, Korea, in 1982. He then received his M.S. and Ph.D. degrees from McGiLL University, Canada, in 1987 and 1992, respectively. Dr. Sim is currently a Professor at the School of Mechanical Engineering at Hannam University in Taejeon, Korea. Dr. Sim's research interests include flow-induced vibration, two-phase flow and fluid dynamics.