SCALING BUFFETING FORCES OF AIR-WATER FLOW IN A ROD BUNDLE

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ABSTRACT

Random turbulence excitation forces can be a matter of concern in the U-bend region of steam generators. Presented in this paper are recent measurements of such forces in the lift direction, taken in a regular square array of rigid cylinders. These cylinders are subjected to air-water cross flow in a wide range of void fractions ($10\% \leq \alpha \leq 90\%$*). Two different measurement techniques are used simultaneously. A bi-optical probe provides local void fractions, bubble velocities and diameters, as well as the bubble frequency of impact on the probe tip. Right in the middle of the bundle, one tube is instrumented with a strain gauge which informs about the structure response by measuring the buffeting lift forces. These new data are compared with previous data gained upstream of a single rigid tube and are used in scaling relationships for the construction of non-dimensional spectra. Among the parameters effective in collapsing the data are the flow regime along with the interstitial void fraction and its fluctuations. An attempt is made to relate these dynamic characteristics and the random forces exerted inside the bundle.*

1. INTRODUCTION

At present, knowledge of the mechanisms that induce the two-phase random buffeting forces is very limited although since 1994, several researchs have been undertaken in air-water cross flow to explain the main causes of excitation in tube arrays. Of particular interest for our purpose are the experimental programs in which the local void fraction and its fluctuations have been measured.

In their work on tube bundle flow regimes, Ulbrich and Mewes (1994) use the measurements of the two-phase mixture pressure drop as a parameter characterizing the fluctuations of void fraction. It results that the void fluctuations are generally small in bubbly and intermittent flow regimes, but much more significant in annular-dispersed flow regime. However, the qualitative features of the flow are insufficient to be linked to an eventual cause of the external forces.

Joo and Dhir (1995) determined the drag coefficient for a single tube and for a tube placed in an array. They found that it increases with void fraction up to $\alpha = 30\%$. They shown that void profiles for both types of tube are asymmetrical with respect to the equator and, for all Reynolds numbers, they observed a deficiency of voids in the region near the downstream stagnation point. Studying vibrations of a flexible tube in a rigid square array, Lian et al (1997) revealed that the rms amplitude of void fraction fluctuations play an important role in two-phase mechanism of damping and their variation with local void fraction present the same parabolic profile as the damping ratio. Subsequent measurements by Noghrehkar et al (1999) have shown that the rms amplitude of local void fraction fluctuations increases with increasing void fraction up to $\alpha = 30\%$ in bubbly flow regime, reaches a peak at about $\alpha = 40\%$ and then remains almost constant at higher void fractions in the intermittent flow regime.

However, none of these authors has attempted to measure the forces on the tube. Present studies by Pettigrew et al (2005) are ongoing for the detailed measurements of two-phase flow in a rotated triangular tube array with the aim to understand the origin of pseudo-periodic forces measured both in drag and lift directions on the tubes. In a recent analysis of the damping and fluidelastic instability in a tube bundle, Moran and Weaver (2007) introduced various functions of the void fraction, depending on the flow regime, to better explain the relation between the damping mechanisms and the onset of fluidelastic instability.

Following a comparable approach, the present authors have applied successfully a scaling procedure for studying the effect of local void fraction and flow regimes on the lift buffeting forces exerted on a single rigid cylinder (Pascal-Ribot and Blanchet (2007)). An extension of this procedure is proposed here to a rigid bundle configuration crossed by an air-water flow. By way of nondimensional power spectral density (NPSD) of the forces, the present work is directed at understanding how two-phase flow patterns across the bundle may influence turbulence-induced forces.

2. EXPERIMENTAL WORK

2.1. Description of the setup

The test channel is a 650 mm long transparent acrylic rectangular duct with a 70 mm x 100 mm cross section, containing an in-line tube bundle composed of five rows of three full tubes and two half tubes. The tubes are 100 mm long with 12.15 mm outer diameter D and arranged with a pitch-to-diameter ratio 1.44. In the third row of the tube bundle, a strain gauge installed at the extremity of the mid-cylinder measures the buffeting lift forces. In the same time, local measurements of air-water flow characteristics around this instrumented cylinder (void fraction, bubble velocity and diameter, bubble count rate) are performed with a bi-optical probe (BOP). The probe is placed in the middle tube gap which forms a straight, upward flow passage.

2.2. Instrumentation and test matrix

The water and air flow rates are measured by flowmeters located at the mixer inlet. The gas velocity V_g is directly obtained from the BOP while the liquid velocity V_l is estimated as

$$V_l = \frac{Q_l}{(1-\alpha)\ A} = \frac{J_l}{1-\alpha} \tag{1}$$

which combines a local variable α with an average variable Q_l; A is the cross section of the test channel, J_l the superficial liquid velocity and Q_l the volume flow rate of liquid. Water and air flow rates were varied in the 5.10^{-6} - 2.10^{-3} m^3/s and 2.10^{-6} - $2.2\ 10^{-2}$ m^3/s ranges, respectively. Based on the flow regime map of Ulbrich and Mewes (1994), completed by observations made in Taylor and Pettigrew (2001), the experimental data set appears to cross over from the pure bubbly and churn-bubbly to the intermittent flow regimes. This is of particular interest, as the subsequent analysis suggests that different behaviours exist between these three flow regimes.

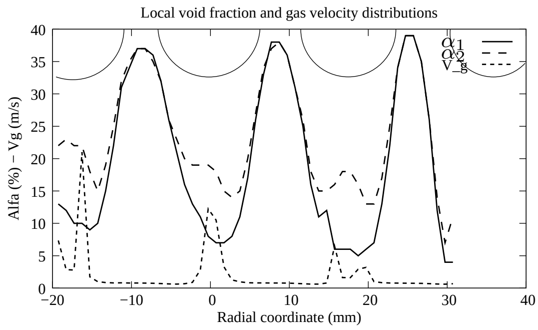

Figure 1: *Void Fraction and Gas Velocity Distributions in Bubbly Flow Regime.*

3. EXPERIMENTAL RESULTS

3.1. Characteristics of flow in the bundle

Effects of the tube bundle. A comparison with previous data gained with a single cylinder is possible since both series of tests have been performed in the same conditions of air and water flow rates. To summarize, a tube bundle is a non-homogeneous obstacle that enhances the dissipation of turbulence and the amplitude of two-phase lift forces, that exhibits a characteristic frequency extreme in their PSD profile, and in which the transition from one flow regime to another occurs at lower void fractions than with a single cylinder.

Void fraction distributions. The distributions of local void fraction obtained from a horizontal traverse of the BOP between the second and third rows show a strong increase of void fraction between tube columns due to pressure drop (figure 1). The variables are plotted against the transverse distance across the bundle and α_1 and α_2 are respectively the void fractions provided by the upstream and downstream sensors. This increase of void fraction through the bundle was already found by Lian et al (1997) and is reasonably justified by gas plumes emanating from the bottom and sides of tubes as well as gas accumulation from the lower parts of the bundle. As the mass flow rises, this increase between two adjacent tubes becomes relatively less important. Conversely, in tests performed with two-phase Freon HCFC-123, the void fractions behind the tubes are generally higher than in the gaps (Ueno et al (1997)). The measurements by the upstream and downstream sensors - separated by 1.35 mm - reveal a strong instability of void fraction upstream of the cylinders where α may vary

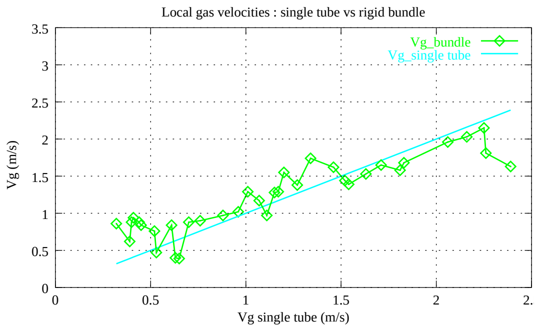

Figure 2: *Gas Velocity vs Void Fraction for Single Tube and Tube Bundle.*

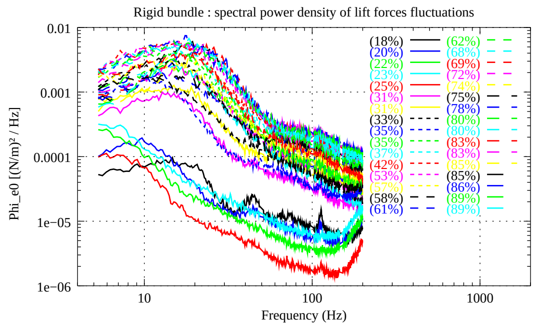

Figure 3: *Spectral Power Density of Buffeting Lift Forces.*

between 5% and 19% in the example of figure 1. On the contrary, between two adjacent cylinders, both probes indicate exactly the same α.

Gas velocity distributions. It can be noticed in figure 1 that gas velocity peaks and void fraction peaks present unlike phases. Figure 2 shows that gas velocity between two adjacent tubes is higher than gas velocity upstream of a single tube below 1.5 m/s and lower beyond this limit which corresponds to the inception of intermittent flow regime.

3.2. Spectral contents of fluctuating lift forces

For the same inlet flow conditions, the tube bundle configuration results in higher lift forces than the single cylinder configuration. However, this difference tends to reduce with the highest void fractions.

Figure 3 is an illustration of the 32 power spectral densities (PSD) of the dynamic lift forces measured in the tests. At a glance these raw spectra can be divided into two broad categories:

- a lower group ($10\% \leq \alpha \leq 35\%$) where the profiles of PSD look like those obtained with a single rigid cylinder and their amplitudes exhibit an increase with void fraction,

- an upper group ($\alpha > 35\%$) where the maxima of PSD gradually increase with void fraction up to $\alpha = 60\%$ then slowly decrease.

It seems that, beyond a limit of the mixture velocity, the characteristic scale of turbulent structures is not modified and the lift forces stop growing. In this group the profiles typically resemble frequency spectra of surface pressure fluctuations in turbulent boundary layers. These are rather different profiles from those measured upstream of a single cylinder by the authors, as well as from the narrow peaks obtained by Inada et al (2007) in a tube bundle crossed by a single-phase water flow. Moreover, in this second group, the distinction between spectra is less sensitive to the measured void fraction than in the first group.

4. SPECTRAL SCALING OF LIFT FORCES FLUCTUATIONS

4.1. Proposed model and discussion

The data reduction process has been approached in two steps. First, an appropriate time scale was defined to align the two-phase frequency extremes of the spectra, second a pressure scale was determined. In the first step, a peak frequency associated with each lift PSD is plotted versus void fraction. Then are selected the variables whose variation versus void fraction present an analogy with this plot. This results in the selection of

$$Q_l,\ J_g,\ J_g + J_l,\ V_g,\ V_g + V_l,\ V_g - V_l$$

Depending on flow regime as discussed in §2.2, the three couples of scaling parameters P_0, f_0 for pressure and time have the form of equations (2) - (7). The selection of a scale of velocities in P_0 may also be supported by the fact that the extremes of raw spectra are localized in the domain of low frequencies. This suggests the presence of large scale vortices resulting from the inlet conditions and confinement of the flow. And for a fixed in-line square tube bundle and a fixed pitch, the most relevant parameters of the physics are the velocities of the phases.

- In pure bubbly flow ($V_g \leq 0.5$ m/s), below 20% void fraction,

$$P_0 = k\ \rho_l\ g\ \sqrt{\frac{\sigma}{\Delta\rho\ g}}\ [\alpha\,(1\ -\ \alpha)]^2\ (\frac{V_r}{V})^2 \quad (2)$$

$$f_0 = \frac{3}{2}\ \frac{V_g}{D} \quad (3)$$

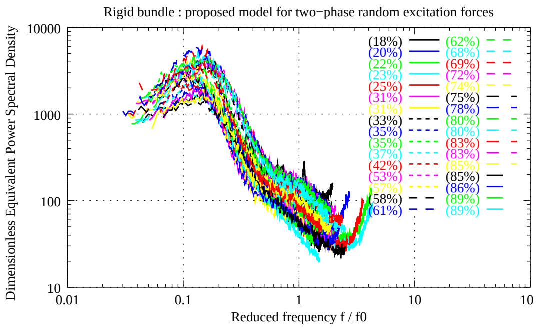

Figure 4: *Power spectra of lift forces fluctuations normalized using eq.(2), (4), (6) as the pressure scale and eq.(3), (5), (7) as the time scale.*

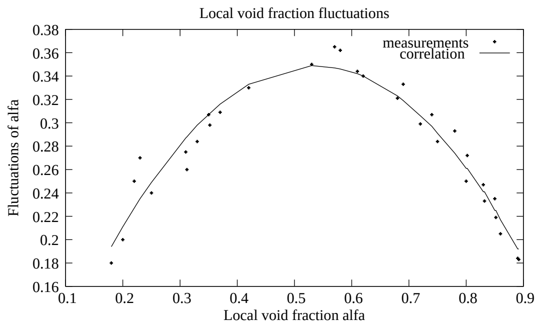

Figure 5: *Local Void Fraction Fluctuations.*

where k is a constant, σ the surface tension, $\Delta\rho = \rho_l$ - ρ_g, g the gravitational acceleration, $V_r = V_g$ - V_l and $V = V_g + V_l$, with subscripts g and l for gas and liquid.

- In churn-bubbly flow (0.5 m/s $\leq V_g \leq$ 0.9 m/s) :

$$P_0 = k\ \rho_l\ g \sqrt{\frac{\sigma}{\Delta\rho\ g}}\ 0.35\ \alpha^2\ (\frac{V_r}{V})^{-1} \quad (4)$$

$$f_0 = \frac{3}{2}\ \frac{V_g}{D} \quad (5)$$

- In intermittent flow ($V_g \geq$ 0.9 m/s), above $\alpha_i = 35\%$ void fraction :

$$P_0 = k\ \rho_l\ g \sqrt{\frac{\sigma}{\Delta\rho\ g}}\ \alpha_i^2\ (1\ -\ \alpha_i)\ (\frac{V_r}{V})^{-1/2} \quad (6)$$

$$f_0 = \frac{V_g}{D} \quad (7)$$

Examination of figure 4 reveals that the proposed scaling combinations successfully collapse the lift forces spectra within measurement uncertainties. Percentages in the caption indicate the measured void fractions of each test.

Discussion of P_0. The factor $[\alpha\,(1\ -\ \alpha)]^2$ in eq.(2) was already introduced in the scaling model of the authors for a single rigid tube. It is representative of the void fraction fluctuations which show a typical parabolic-like drop with α in figure 5 where the data are compared to the curve fitting equation
$\sigma_\alpha = 1.238\ (1.065 - \alpha)(\alpha - 0.003)$.
A low value of σ_α represents a flow regime where the gas structures (bubbles or slugs) have the same size. Conversely, large values of σ_α reveal the existence of both small and large gas structures.

Investigating turbulent mixing rate between two identical rectangular subchannels, Kawahara et al (1997) have found the same parabolic variation with α when plotting rms values of both the pressure difference fluctuations and of the turbulent mixing rate of the liquid phase. Their configuration can be compared to the control volume of our local flow characteristics, namely the vertical subchannel between two columns of the in-line bundle. These authors concluded that the turbulent mixing of the liquid phase in two-phase flows is dominated by the instantaneous pressure difference between the subchannels. From this it can be inferred that, together with the void fraction fluctuations, these two correlated factors are key characteristics of the fluctuating lift forces inside the array and that they form a triangular linkage.
Compared with the single rigid cylinder, the present pressure scaling parameters reveal an additional ratio $S^* = V_r/V$ in all flow regimes. This ratio may be interpreted as a modified slip ratio of relative gas velocity to the liquid core velocity. An empirical correlation was already proposed by Taylor et al (1996) to define a characteristic void length $d_B = 0.00163\ \sqrt{V_p/(1-\alpha)}$ where V_p is the two-phase pitch velocity. In contrast, the success of the proposed model based on local flow parameters depends on the relative velocity and interfacial mechanisms between phases rather than on the average velocity of the mixture.
Table 1 gives variation ranges for velocity ratios defined in eqs.(2), (4), (6).

	vel. ratio	variation
eq.(2)	$(V_r/V)^2$	0.46 - 0.91
eq.(4)	$(V_r/V)^{-1}$	1.81 - 2.47
eq.(6)	$(V_r/V)^{-1/2}$	1.02 - 1.54

Table 1: *Ranges of variation.*

Discussion of f_0. The pitch-to-diameter ratio $P/D = 1.44$ which expresses the confinement due to surrounding tubes would have the same effect as the coefficient 3/2 in eqs.(3) and (5). However, according to Pettigrew et al (2005), this ratio seems to have no influence on the turbulent forces and was not considered here. Moreover, this expression of f_0 can be paralleled with the expression of the bubble count rate given in Pascal-Ribot and Blanchet (2007) :

$$f_b = \frac{3}{2} \frac{\alpha V_g}{d_b} = \alpha \frac{D}{d_b} f_0 \tag{8}$$

where d_b is the bubble diameter. In other words, below 35% void fraction, the time scaling factor of lift forces spectra in the bundle differs from the single cylinder spectra by a factor α / $\frac{d_b}{D}$. This suggests that both parameters α and d_b/D should be significant in the excitation mechanisms inside the bundle. We will return to this point in the next section.

4.2. Alternative model and discussion

A second model has been investigated, in which the time scaling parameters are unchanged but the local phase velocities in the pressure scaling parameters are replaced by the flow rates of gas and liquid at the channel inlet. In this case, the effects of void fraction are sensibly different:

- In pure bubbly flow ($V_g \leq 0.5$ m/s), below 20% void fraction,

$$P_0 = k \, \rho_l \, g \sqrt{\frac{\sigma}{\Delta\rho \, g}} \, \alpha^2 (1 - \alpha)^3 \, (\frac{Q_g}{Q_l})^{0.3} \tag{9}$$

- In churn-bubbly flow (0.5 m/s $\leq V_g \leq$ 0.9 m/s) :

$$P_0 = k \, \rho_l \, g \sqrt{\frac{\sigma}{\Delta\rho \, g}} \, \alpha^2 (1 - \alpha) \, (\frac{Q_g}{Q_l})^{0.3} \tag{10}$$

- In intermittent flow ($V_g \geq 0.9$ m/s), above 35% void fraction :

$$P_0 = k \, \rho_l \, g \sqrt{\frac{\sigma}{\Delta\rho \, g}} \, \alpha_i (1 - \alpha_i)^2 \, (\frac{Q_g}{Q_l})^{-0.1} \tag{11}$$

  with $\alpha_i = 0.35$

The results of normalization with these equations are illustrated in figure 6 which still shows a reasonable collapse of the data.

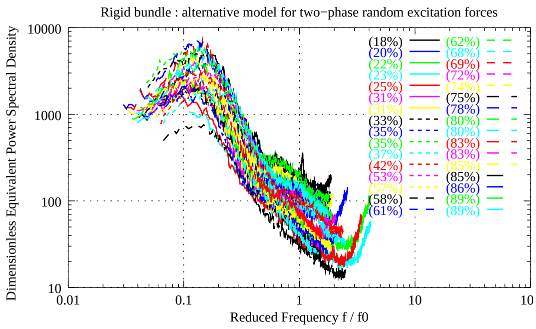

Figure 6: *Power spectra of lift forces fluctuations normalized using eq.(9), (10), (11) as the pressure scale and eq.(3), (5), (7) as the time scale.*

Discussion of P_0. Relative to the flow, a tube bundle is a 3D porous medium which hinders the motion of gas and liquid phases. The pressure loss for the resulting two-phase flow through the bundle is determined by the friction forces at the tubes as well as by the interfacial drag between the phases.

Recently, Schmidt (2007) has proposed enhancements for the formulation of the interfacial drag by fitting experimental data of isothermal air/water experiments with a modified Tung-Dhir model. The original model expresses the friction coefficients as:

$$C_1 = 18 \, \alpha \text{ and } C_2 = 0.34 \, \alpha (1 - \alpha)^3$$

for bubbly flows ($\alpha \leq 30\%$),

$$C_1 = 5.21 \, \alpha \text{ and } C_2 = 0.92 \, \alpha (1 - \alpha)^3$$

for slug flows ($52\% \leq \alpha \leq 60\%$).

This is an illustration of some of the formal similarities between our proposed pressure scaling factors and various closure laws for the interfacial gas-liquid momentum transfer due to friction and for the tube bundle flow resistance (see also the work of Pezo et al (2006) in which the bundle is modeled with the porous media approach).

Likewise, analyzing intermittent flows, Feenstra et al (2002) mention that the ratio d_b/D already discussed in §4.1 is a possible factor relevant in flow-induced vibration which could affect the pressure drop of the flow through the array. This supports the abovementioned triangular linkage when investigating the two-phase random excitation mechanisms in a square in-line array.

Furthermore, this alternative model is a first step in direction of the ultimate stage which should rely essentially on average - instead of locally measured - parameters. Another interest of this model is to release from evaluating V_l which was not measured in the present study. However it remains dependent on the local void fraction which is a paramount variable of these two models. More work will be necessary to enhance this approach, especially by measuring the liquid velocities and deepening possible relationships with pressure drop of flows through tube arrays.

5. CONCLUSION

Buffeting lift forces in an in-line square rigid tube bundle were shown to be maximal for an interstitial void fraction of about 60%. A normalization of the raw spectra by proper time and pressure scaling parameters has been proposed with the help of two-phase flow characteristics measured within the stream between two adjacent tubes. Directly or not, this procedure has revealed a number of important factors which could contribute to the random excitation mechanisms, associated with the flow regimes. These are:

- the local void fraction and its fluctuations,
- the interfacial structures, via a modified slip ratio,
- the turbulence dissipation, via the turbulent mixing rate of the liquid phase, and
- the pressure loss between the successive subchannels of the array.

Among these factors, only the first was operative in our previous scaling models developed for a single rigid cylinder.

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