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PRESSURE DROP FLUCTUATIONS AND BUBBLE-SLUG TRANSITION IN A VERTICAL TWO PHASE AIR-WATER FLOW

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Abstract—Evolution of the probability density function of pressure drop fluctuations with increasing volumetric quality in a vertical two phase air-water flow is presented. The measurements are used to develop two quantitative criteria for identification of the bubble-slug transition.

1. INTRODUCTION

Although many flow regime maps for vertical two phase gas-fluid flows have been empirically developed, it is well known (see, e.g. Dukler & Taitel 1977) that there is little agreement among these. Part of the reason for this discrepancy has been attributed to the fact that most of the flow regime maps are based on visual observations, and are therefore subjective in nature. Another important reason is that the flow may not have been fully developed at the point of observation in the experiments of these investigators. Here we are only concerned with the bubble-slug transition portion of the flow regime map, and in this connection Griffith & Wallis (1961) have observed that the entrance region for the two phase slug flow can be very large and dependent upon the method in which the gas and liquid are mixed. For slug flow they have observed entrance lengths (distance from the point at which gas and liquid are mixed to the first appearance of slug flow) as large as 200 pipe diameters under certain flow rates.

Ideally, in a general flow regime map the bubble-slug transition would be expressed as a functional relationship between the various relevant dimensionless numbers. For example:

$$f\left(\frac{J_L D}{\nu_L}, \frac{\nu_G}{\nu_L}, \mathrm{Fr}, \frac{\rho_L J_L^2 D}{\sigma}, \frac{\rho_L - \rho_G}{\rho_L}, \beta, \frac{x}{D}\right) = 0 \qquad [1]$$

where ρ is the density, ν the kinematic viscosity, J the superficial velocity, D the pipe diameter, x the longitudinal distance from the point where gas and liquid are mixed, σ the surface tension, $\beta = J_G/(J_G + J_L)$ the volumetric quality, g the acceleration due to gravity, $\mathrm{Fr} = J_L/(gD)^{0.5}$ the Froude number based on the liquid superficial velocity, and the subscripts L and G refer to liquid and gas phases respectively. It must be emphasized that the list of dimensionless numbers in [1] is not meant to be exhaustive, nor is it implied that all the included non-dimensional groups are important. In view of the large disagreement among the various published flow regime maps, it is clear that before one can attempt to determine this relationship experimentally, quantitative criteria must be agreed upon for the transition. In what follows, it is shown that the probability density function (PDF) of the instantaneous pressure drop can be used to define such criteria. This should not be surprising since the pressure drop fluctuations are intimately connected to void fraction fluctuations via the momentum and continuity equations, while the void fraction fluctuations are dependent upon the flow regime (Jones & Zuber 1975; Vince & Lahey 1982).

2. EXPERIMENTAL SET UP

The measurements were performed at atmospheric pressure in an air-water loop described elsewhere by Tutu (1982). A vertical 52.2 mm inside diameter (D) clear PVC pipe served as the test section, and pressure drop fluctuations were measured at 42 dia. downstream of the mixing chamber. Two Endevco Model 8506–5 piezoresistive pressure transducers were mounted flush with the inside pipe wall. The transducers, which have a resonance frequency of 65 kHz, are mounted along the same vertical axis and are separated by $D/2$. Both the phases (air and water) flow upwards in the test section.

The pressure drop signal, which was generated by means of an analog difference circuit, and the two pressure signals were recorded on an analog tape using a Honeywell Model 96 tape recorder. Experiments were done for three liquid flow rates (Fr = 0.27, 0.54 and 1.08), and for each case the gas flow rate was varied over the flow regimes of bubbly through churn-turbulent. NEFF System 620 and an HP21 MX series computer were used to digitize, acquire and process the data when played back from the Honeywell tape recorder. The data were sampled at 12.5 kHz and low pass filtered at 5 kHz (− 3 dB, 24 dB per octave) prior to sampling. For each run the sampling size was 0.3072×10^6.

3. RESULTS AND DISCUSSION

Let p_{21} be the instantaneous pressure drop $(p_2 - p_1)$, where p_2 and p_1 are the instantaneous pressure signals from the lower and upper pressure transducers respectively. It can be normalized with the hydrostatic pressure drop $(\Delta p)_h = \rho_L g D/2$ between the two transducers when only water is present in the test section. This dimensionless pressure drop is denoted by p_{21}^* and equals $p_{21}/(\Delta p)_h$.

Figure 1 shows the PDF of p_{21}^* with β as a parameter for the case when Fr = 0.54. The relationship between these PDFs and the various flow regimes has been discussed by Tutu (1982). For clarity, each curve in this figure has been displaced upwards by one small division with respect to the curve below. As expected, during bubbly flow (small β) the PDF shows a single peak around $p_{21}^* = 1$. When the gas flow rate is increased (at a fixed liquid flow rate) this peak widens, and the PDF develops a second peak in the neighborhood of $p_{21}^* = 0$ during the slug flow regime. With increasing gas flow rates, this

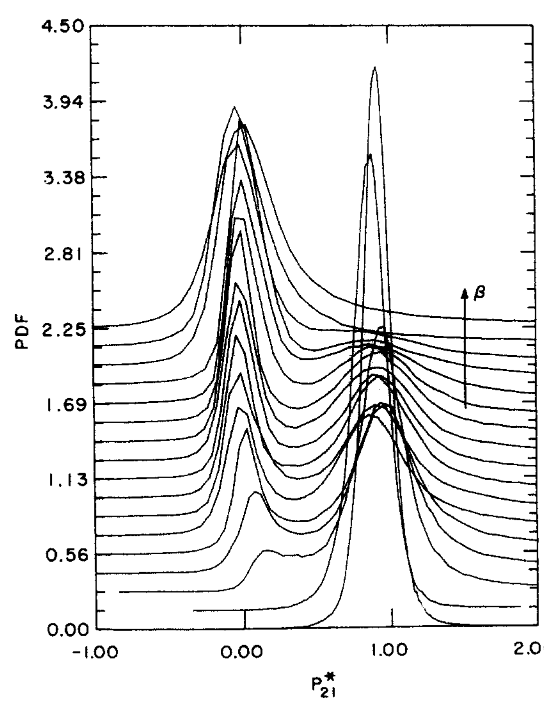

Figure 1. Evolution of the PDF of the dimensionless pressure drop with increasing gas superficial velocity. Fr = 0.54. Each succeeding curve displaced upwards by one small division. For lower curve, $\beta = 0.171$, for top curve, $\beta = 0.947$.

second peak at $p^*_{21} \simeq 0$ increases in magnitude, while the peak at $p^*_{21} \simeq 1$ decreases in amplitude until it completely disappears. As has been pointed out elsewhere (Tutu 1982), the peak around $p^*_{21} = 1$ corresponds to liquid plugs filled with bubbles, and the peak around $p^*_{21} = 0$ corresponds to gas slugs. The PDFs for the cases Fr = 0.27 and Fr = 1.08 were found to be qualitatively similar.

The root mean square (rms) value of the pressure drop fluctuation, p'_{21}, is easily calculated from the PDF of p_{21} and is plotted in figure 2 as a function of β for various Fr. For small β, p'_{21} increases with increasing β; the rate of rise apparently the largest during the bubble-slug transition. At higher values of β, as the flow becomes more chaotic (churn-turbulent), p'_{21} continues to increase; it, however, begins to drop rapidly as the flow regime approaches "annular". Due to compressor output limitations annular flow regime could not be achieved at these Fr. Although for the present experiments the average pressure drop is mostly gravitational, it should be noted that dynamic effects contribute significantly to the value p'_{21}. The hydrostatic part of p^*_{21} is bounded between 0 and 1, and could therefore contribute a maximum of only 0.5 to $p'_{21}/(\Delta p)_h$. This is also clear from the PDFs (figure 1), where p^*_{21} exists outside this domain with significant probability.

To determine the bubble-slug transition, first a successful transformation was found by trial and error to collapse the data for $p'_{21}/(\Delta p)_h$ (shown in figure 2) for the three cases of Fr along a single curve in the bubble-slug region. This is shown in figure 3. Since a comparison with the PDFs suggested that the slope reaches a maximum in the bubble-slug transition zone, bubble-slug transition could be "defined" to occur at the point of inflection on the curve shown in figure 3. For the data presented here, this results in:

$$\beta_{b-s} = 0.16\,\mathrm{Fr}^{-0.62} \qquad [2]$$

where β_{b-s} is the volumetric quality at the bubble-slug transition.

Another, more direct criterion for the bubble-slug transition can be defined. As indicated by the inset in figure 4, let a_G and a_L be the areas under the peaks of the PDF of p^*_{21} at $p^*_{21} \simeq 0$ and $p^*_{21} \simeq 1$, respectively. The boundary between a_G and a_L is assumed at the point where the PDF has a minimum. Then, for a given liquid superficial velocity, the bubble-slug transition is indicated by the minimum value of β that results in a non-zero value of a_G. From figure 4, which shows $a_G/(a_G + a_L)$ as a function of ($\beta\,\mathrm{Fr}^{-0.075} - \mathrm{Fr}^{-0.15}$) for three values of Fr, we then have for the bubble-slug transition:

$$\beta_{b-s} = \mathrm{Fr}^{-0.075} - 0.84\,\mathrm{Fr}^{0.075}. \qquad [3]$$

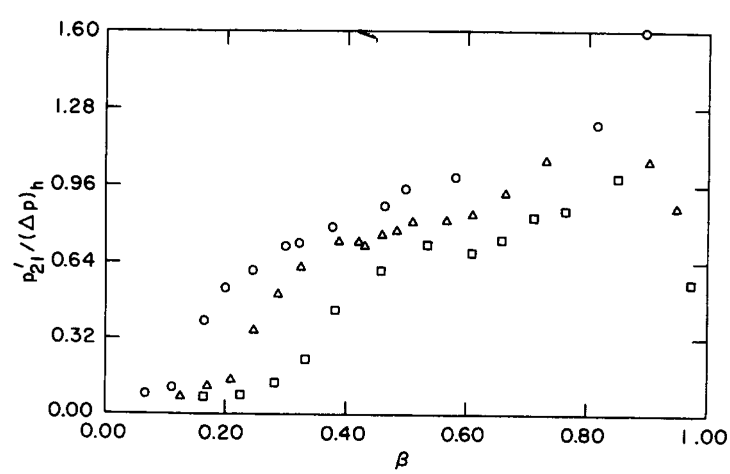

Figure 2. Pressure drop fluctuation rms. ○, Fr = 1.08; △, Fr = 0.54; □, Fr = 0.27.

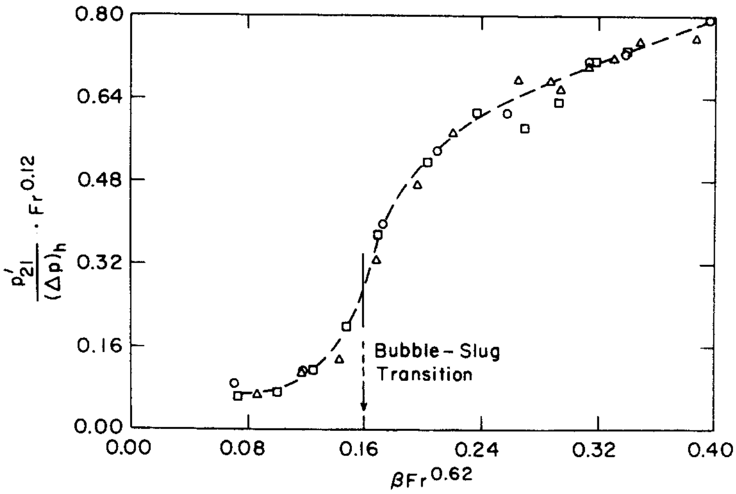

Figure 3. Bubble-slug transition from pressure drop fluctuation rms. ○, Fr = 1.08; △, Fr = 0.54; □, Fr = 0.27.

The transformation apparent in figure 4 was again found by trial and error. Of course, by ignoring this transformation and passing three individual curves through the data of figure 4 gives us three transition points corresponding to the three Froude numbers. These bubble-slug transition points are denoted by filled in circles in figure 5. Since β is bound between 0 and 1, it is obvious that [2] and [3] can only be used in a limited range. At any rate, it must be remembered that these are based on experimental data in the region $0.27 \leq Fr \leq 1.08$.

Figure 5 shows these bubble-slug transition curves along with those of other investigators. Bubble-slug transition curves proposed by Weisman & Kang (1981) and Dukler & Taitel (1977) have also been plotted in this figure. Even though the fluid pair used in all the cases is the same, the pipe diameters are not. But the various transition data do not show any particular variation with the pipe diameter (besides Fr). The overwhelming wide range over which the data of various investigators is scattered demonstrates the seriousness of the problem. Provided high speed photographs are used, the bubble and slug flow regimes outside the transition zone are rather easy to distinguish visually. Thus

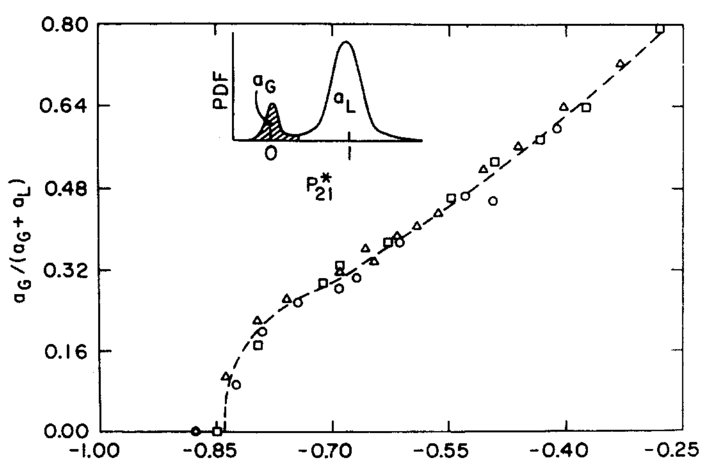

Figure 4. Prediction of bubble-slug transition from the PDF of p^*_{21}. ○, Fr = 1.08; △, Fr = 0.54; □, Fr = 0.27.

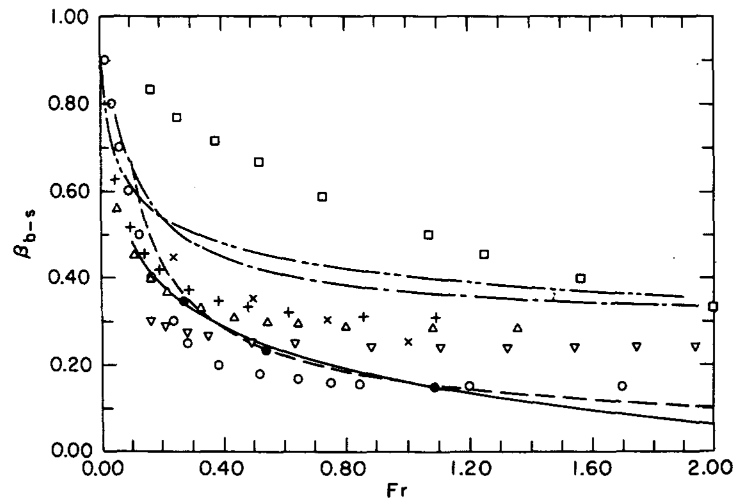

Figure 5. Bubble-slug transition map. —-— Weisman & Kang (1981); —·— Dukler & Taitel (1977); ---- [2]; —— [3]; ● present data; × Vince & Lahey (1982), Air-water, $D = 25.4$ mm; □ Spedding & Nguyen (1980), Air-water, $D = 45.5$ mm; ▽ Hsu & Dudukovic (1980), Air-water, $D = 19.1$ mm; △ Hsu & Dudukovic (1980), Air-water, $D = 31.8$ mm; + Hsu & Dudukovic (1980), Air-water, $D = 40.4$ mm; ○ Griffith & Wallis (1961).

the subjectivity of the observer in determining the transition point enters in the form of a threshold; for example, Hsu & Dudukovic (1980) assumed the bubble-slug transition to take place when large bubbles having a length equal to the pipe diameter were observed. So it is clear that before the experimental data from various sources can be effectively utilized to develop general transition maps of the form of [1], a quantitative criterion for transition must be defined and agreed upon. The inflection point on the pressure drop fluctuation rms vs β curve (figure 3), and the use of an integral of the PDF of p^*_{21} as shown in figure 4, provide two examples of such a criterion. Another important problem is the fact that the flow may not be "fully developed" in every case. The present simple method of using the pressure drop fluctuations, and the proposed bubble-slug transition criteria are very well suited for studying the evolution of bubble-slug transition with x/D.

Unlike the pressure drop fluctuations, the pressure fluctuations may be a function of the particular experimental setup. However, for the sake of completeness, the pressure fluctuation rms, p'_1 is plotted in figure 6. For the same reason the time average value of p^*_{21}, which is an approximation to the liquid holdup, is tabulated in table 1.

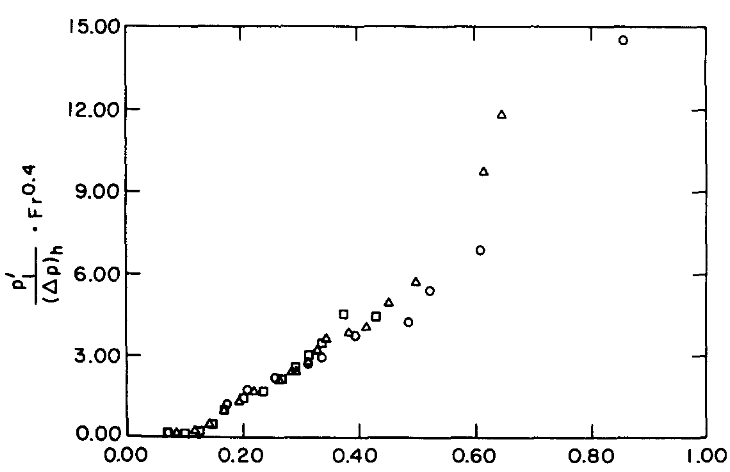

Figure 6. Pressure fluctuation rms. ○, Fr = 1.08; △, Fr = 0.54; □, Fr = 0.27.

Table 1. Average dimensionless pressure drop

Fr = 1.08		Fr = 0.54		Fr = 0.27	
β	$\overline{P^*_{21}}$	β	$\overline{P^*_{21}}$	β	$\overline{P^*_{21}}$
0.067	0.963	0.126	0.902	0.164	0.908
0.112	0.921	0.171	0.911	0.225	0.87
0.165	0.892	0.209	0.854	0.281	0.832
0.199	0.86	0.247	0.874	0.333	0.804
0.245	0.832	0.287	0.836	0.382	0.793
0.298	0.795	0.323	0.823	0.458	0.727
0.321	0.768	0.388	0.754	0.477	0.701
0.377	0.718	0.420	0.710	0.534	0.644
0.462	0.667	0.430	0.724	0.608	0.574
0.497	0.626	0.459	0.699	0.659	0.52
0.579	0.563	0.483	0.682	0.711	0.464

4. CONCLUDING REMARKS

Pressure drop fluctuations in a vertical two phase air–water flow have been measured as a function of volumetric quality β for three values of Froude number based upon the liquid superficial velocity. It is shown that the pressure drop fluctuation rms and the PDF of the instantaneous pressure drop lead to two quantitative criteria for the bubble-slug transition. The resulting transition maps are compared with those of other investigators, and it is argued that before general transition maps can be developed, transition criteria must be quantitatively defined and agreed upon.

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