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# BRIEF COMMUNICATION

# RESPONSE OF SMALL PITOT TUBES IN GAS–LIQUID FLOWS

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## 1. INTRODUCTION

The response of a pitot tube in a gas–liquid mixture flow is complicated by a relative motion between gas and liquid in the region of the probe tip. Similar effects have been observed in solid/gas mixture flow by Zipse (1966), Dalmon & Lowe (1957) and Van Breugel *et al.* (1969). Pitot probes were found to respond partially to the incident flow momentum flux and a pressure rise of $\epsilon\frac{1}{2}\rho_m u_0^2$ was observed, where values of $\epsilon$ between 1.0 and 1.85 were reported, $\rho_m$ being the average mixture density and $u_0$ its speed. It is expected that similar effects are encountered in gas–liquid mixture flows as considered here.

Measurements of pitot pressure rise are to be compared with the pressure rise expected on the basis of a homogeneous flow. The gas–liquid flows considered are subject to compressibility effects as discussed by Campbell & Pitcher (1958), Targren *et al.* (1947) and Davis (1974) for nozzle and pipe flows. The density of the mixture can be related to an undistrubed flow reference condition (denoted by suffix zero) by:

$$\rho_m = \rho_{m0}(1 - \alpha_0 + \alpha_0(p/p_0)^{-1})^{-1}, \qquad [1]$$

where $\rho_m = \rho_G\alpha + (1-\alpha)\rho_L$, $\rho_L$ and $\rho_G$ being the liquid and gas phase densities and $\alpha$ the void fraction. The local mixture pressure is denoted by $p$. Isothermal compression of the gas phase has been assumed (Davies 1967).

For a one dimensional flow with velocity $u$ integration of the momentum equation leads directly to:

$$\frac{D_0}{2} = (\bar{p}_s - 1)(1-\alpha_0) + \alpha_0 \log_e [1 + (p_s - 1)], \qquad [2]$$

where $D_0 = (\rho_{m0}u_0^2)/p_0$ and $\bar{p}_s = p_s/p_0$, suffix $s$ denoting stagnation conditions. Equation [2] relates the stagnation pressure rise $\Delta\bar{p}_s = (\bar{p}_s - 1)$ to the mixture void fraction ($\alpha_0$) and the ratio $D_0$ for the undisturbed flow. The relationship is illustrated in figure 1. If the mixture Mach number $M_0$ is introduced, where the velocity of propagation of pressure disturbances is $a_0$, then from [1],

$$M_0 = \frac{u_0}{a_0} = \sqrt{(\alpha_0 D_0)}. \qquad [3]$$

On figure 1 it is seen that the departure from an effectively incompressible pressure rise corresponds to cases where the flow approaches the line for $M_0 = 1$.

Where the two phase Mach number exceeds unity (see for example the experiments of Eddington 1967, Campbell & Pitcher 1958 or Van Vijngaarden 1970) the possibility then arises that a normal shock wave would form in front of a pitot tube immersed in the flow. The

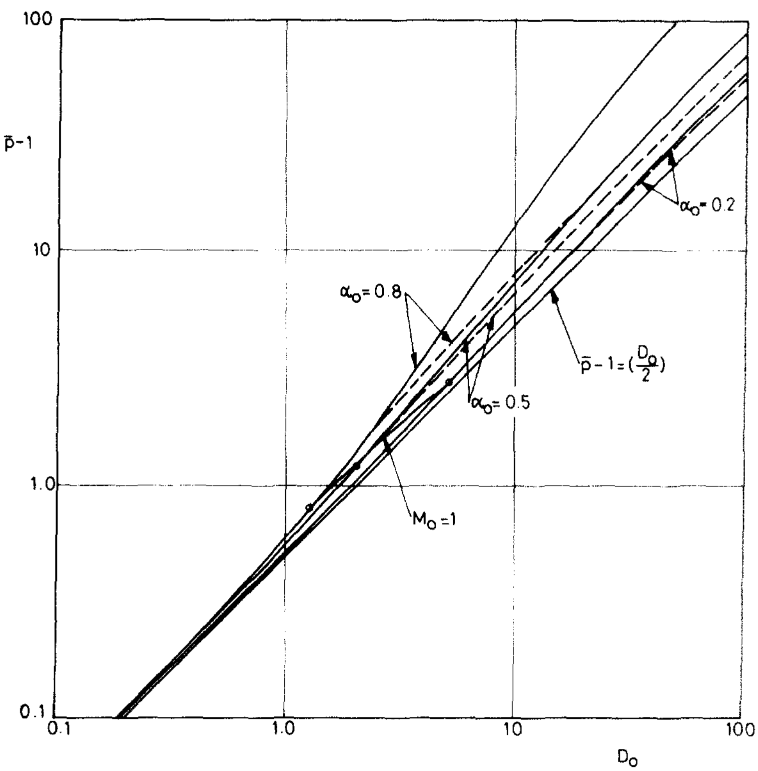


Figure 1. Stagnation pressure rise for homogeneous two phase, two component flow. ——[2]; - - -[4] for $M_0 > 1$.

equations of continuity and momentum across the shock (condition 2 applies immediately behind the shock) lead to a quadratic equation for $(p_2/p_0)$, with roots $p_2/p_0 = 1$ or $\alpha_0 D_0$. The pressure ratio across the normal shock is therefore equal to the square of the upstream Mach number. Applying [2] for the stagnation pressure rise $(p_p - p_2)$ of the flow on the pitot behind the normal shock we obtain, after expressing $\alpha_2$ and $D_2$ behind the shock in terms of conditions ahead of shock from the mixture equations of state, an equation relating $((p_p/p_0) - 1)$ to the undisturbed flow conditions:

$$\frac{((1-\alpha_0)D_0+1)}{2\alpha_0 D_0} = \left[(\bar{p}_p - 1)\frac{1}{\alpha_0 D_0} - \left(1 - \frac{1}{\alpha_0 D_0}\right)\right] \times \left[\frac{(1-\alpha_0)\alpha_0 D_0}{\alpha_0 + (1-\alpha_0)\alpha_0 D_0}\right]$$
$$+ \left[\frac{\alpha_0}{\alpha_0 + (1-\alpha_0)\alpha_0 D_0}\right] \log_e \left[(\bar{p}_p - 1)\frac{1}{\alpha_0 D_0} + \frac{1}{\alpha_0 D_0}\right]. \qquad [4]$$

This relation is also shown in figure 1, where the dotted lines mark the pressure rise corresponding to [4]. It is seen that the effect of a normal shock is to reduce the pressure rise.

## 2. MEASUREMENTS OF STAGNATION PRESSURE RISE

An extensive set of measurements has been recorded using a mixture of air and water flowing along a circular pipe in a vertical upwards direction, the apparatus being identical to that described by Davis (1974). Pitot tubes were mounted at four positions at 0.965 m intervals along a circular pipe of internal diameter 0.0382 m. The pitot tubes used were of external diameter 0.0015 m. The radial location of the pitot tubes in the pipe cross section was chosen to be at 50 per cent of the tube radius from the centre line, as it was found by traversing the pitot across the entire section that this location gave a close indication of the average pitot stagnation pressure rise for the section. Detailed studies of the flow structure using needle resistance probes as described by Herringe & Davis (1974, 1976) showed that for the majority of flow conditions the mean bubble size was approx. 0.0025 m, although this had a tendency to reduce at higher flow velocities and to increase at lower flow velocities (a typical average for these experiments was around 10 m/s). It was usually apparent that the flow was well mixed and bubbly with no severe slug formation for the conditions tested. The measurements of Herringe & Davis (1978) indicated relatively small slip effects for these vertical bubbly flow conditions, and also show that the void and velocity profiles across the pipe were relatively uniform in the central region of the flow where the pitot was located.

The results of appox. 1500 point readings of stagnation pressure rise are summarised in figure 2. Care was taken when recording the pitot pressure to ensure that all connecting leads were completely free of liquid by purging with a small flow of compressed air before taking a reading. It was not possible to observe visually the flow near the pitot which was obscured by the surrounding froth flow. It may be seen that in general the experimental pressure rise was found to significantly exceed the predicted pressure rise, although the measured rise increases with the parameter $D_0$ as expected. Approximately 160 data points lay within each of the sets of results shown in figure 2. As the void fraction of the flow increases the measured pressure rises exceed the predicted values by a progressively greater amount up to a mean void fraction of 0.65. For higher void fractions than this the measured pressure rise reduces progressively towards the predicted values. This is shown more clearly in figure 3, where the average ratio of measured pressure rise to predicted pressure (as given in figure 1) rise is shown. It is clear that there is a regular and well defined dependance of the departure from predicted value upon the mean flow void fraction. The results shown in figures 2 and 3 suggest that in the intermediate range of void fractions around 0.6 the pitot tube is responding more nearly to the incident stream momentum flux $\rho_{m0}u_0^2$. The value of $\Delta p_{\text{meas}}/\Delta p_{th}$ approaches 1.73 at maximum, and it

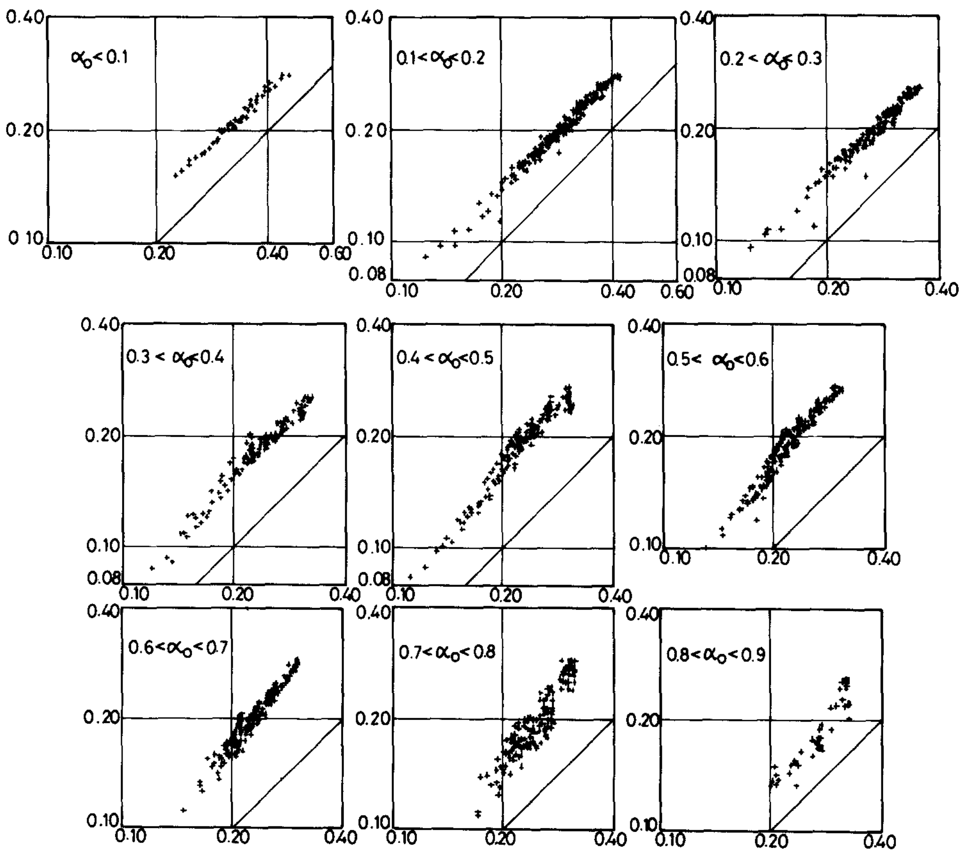


Figure 2. Measurements of stagnation pressure rise. Horizontal scales: $D_0$; Vertical scales: $\bar{p}_p - 1$; Solid line: $\bar{p}_p - 1 = D_0/2$.

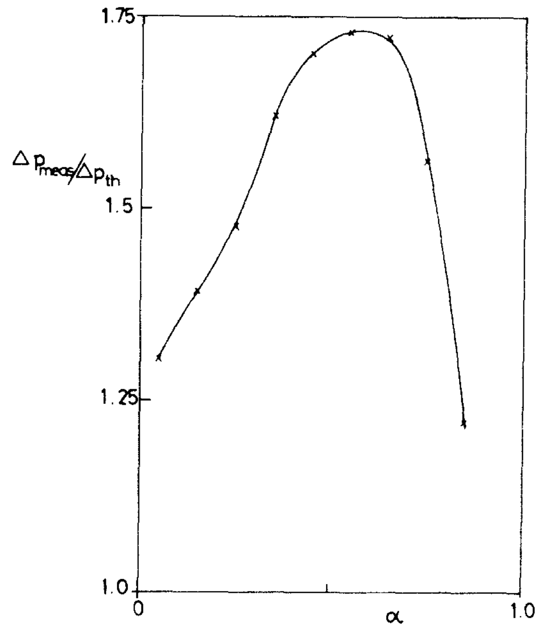


Figure 3. Variation of measured pitot pressure rise with void fraction (each point corresponds to data over a voidage increment of 0.1).

thus appears that the pitot response is intermediate between the stagnation pressure and incident stream momentum flux values.

## 4. CONCLUSIONS

The pressure rise experienced by a pitot tube immersed in a bubbly gas–liquid mixture flow exceeds that predicted by homogeneous flow analysis under conditions where the pitot is smaller than the mean bubble size. A systematic dependance of the deviation from homogeneous flow analysis exists, depending upon the mixture void fraction. A maximum effect is observed at a void fraction of 0.60, where the pressure rise was found to be 1.73 times the predicted stagnation pressure rise or 0.87 of the mixture momentum flux density. The magnitude of these effects is comparable with similar effects reported elsewhere for gas/solid mixture flow due to relative motion between phases in the vicinity of the sensing probe tip.

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