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MEASUREMENT OF TWO-PHASE FLOW RATES

M.R. DAVIS[1] and Demao WANG[2]

[1]Dept of Civil & Mechanical Engineering, University of Tasmania, Hobart, TAS 7001, AUSTRALIA

[2]Wuhan University of Hydraulic & Electric Engineering, Wuhan 430072, P R CHINA

ABSTRACT

Measurement of the two mass flow rates in a two phase, gas/liquid pipeline is considered on the basis of dual pressure differential measurements for a combined contraction/frictional pipe type of flow meter. Compressible flow effects are established as a basis in such metering for creating conditions where the two detected pressure differentials are not universally proportional.

1. INTRODUCTION

The analysis applies to gas liquid mixture flows which are well mixed and bubbly. Relative motion between the phases is generally small and the slip ratio is not greatly different from unity (Herringe and Davis, 1978). Flows in contracting nozzles have been observed (Thang and Davis 1979, 1981), the contracting nozzle section somewhat increasing bubble size. The pressure distributions along the nozzle axis are characterised by the void fraction at the nozzle throat, where the flow can be choked.

Frictional flow in a pipe also shows the characteristics of compressible flow with acceleration towards a choking point at the pipe end (Huey and Bryant, 1967; Davis, 1974). The normalised pressure distribution along the pipe is determined by the critical point void fraction.

Figure 1 illustrates the general layout of the proposed flow meter in which pressures at inlet, throat and exit from the pipe, form the basis of flow metering .

2. FLOW THROUGH A CONTRACTING NOZZLE

Gas-liquid mixtures experience close thermal contact and expansion of the gas phase takes place isothermally. Since the liquid density is constant, the mixture average density ρ_m is given by

$$\rho_m = (1 - \alpha)\rho_\ell + \alpha\rho_g = \rho_{mo}/(1 - \alpha_o + \alpha_o p_o/p) \qquad (1)$$

where suffix ℓ and g denote liquid and gas, α is the average void fraction and p the pressure. Suffix zero denotes a reference condition. The void fraction is given by

$$\alpha = \alpha_o p_o/(p(1 - \alpha_o + \alpha_o p_o/p)) \qquad (2)$$

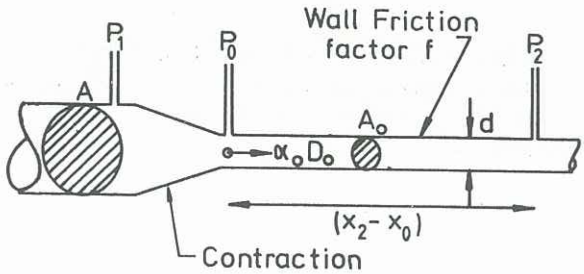

Figure 1 General configuration of contraction/pipe two phase flow meter.

For nozzles which are horizontal continuity and momentum equations are

$$\rho_m u A = \rho_{mo} u_o A_o \qquad (3)$$

and $$\rho_m u_m(du_m/dx) = -(dp/dx) \qquad (4)$$

where u_m is the average mixture velocity, x is the distance along the flow direction and A is the flow cross-sectional area. Equation (4) can be integrated to the general form

$$(D_o/2)((1 - \alpha_o + \alpha_o p_o/p_1)^2 (A_o A)^2 - 1 = (1 - \alpha_o)(1 - p_1/p_o) - a_o \log_e(p_1/p_o) \qquad (5)$$

where the dynamic pressure term is $D_o = \rho_{mo} u_{mo}^2/p_o$.

Choking (Thang and Davis, 1981) occurs when $\alpha_o D_o = 1$, as shown in figure 2 ($\overline{p}_1 = p_1/p_o$). Due to the friction in the nozzle, equation (4) can be modified as

$$\rho_m u_m \frac{du_m}{dx} = -\left[\frac{dp}{dx} + \frac{4\tau_n}{d_n}\right] \qquad (6)$$

where τ_n is defined as the sum of the shear stress between fluid and boundary ($\tau_n = k_n \rho_m u_m^2/2$). The dynamic head D_o' in real nozzle flow can be represented by: $D_o' = \phi_n^2 D_o$

where ϕ_n is the velocity coefficient of the nozzle. From figure 3 it is found that when void fraction approaches to unity or zero, the value of ϕ_n is nearly the same as for single phase flow.

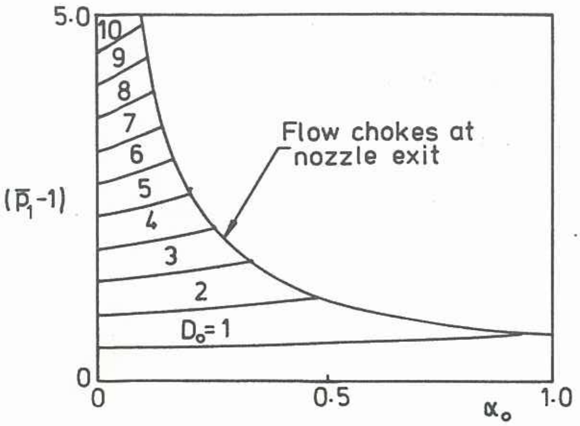

Figure 2 Normalised pressure differential across a contraction of area ratio 2.25 (equation 5).

3. PRESSURE DROP IN THE PIPE SECTION

The streamwise momentum balance equation for flow resisted by wall friction in the circular pipe section neglecting slip is

$$\tau_w + (d/4)(dp/dx) + (\rho_m u_m d/4)(du_m/dx) + \rho_m g\, d/4 = 0 \qquad (7)$$

where x denotes distance along the tube of diameter d, u_m is the mixture velocity, d is the pipe diameter, g is the component of gravitational acceleration along the pipe and the wall shear stress is τ_w. The shear stress is related to the mixture conditions by a friction factor f in the usual manner, $\tau_w = f\rho_m u_m^2/2$.

Equation 7 can be integrated along the pipe length to obtain the streamwise distribution of pressure. Extending this integration over the pipe length between positions denoted by suffixes 0 and 2, we then have

$$f(x_o - x_2)/d = a\{(\bar{p}_2 - 1) + (A/2)\log_e[(\bar{p}_2^{-2} + b\bar{p}_2 + c)/(1 + b + c)] + (B - bA/2)I + C\log_e \bar{p}_2\} \qquad (8)$$

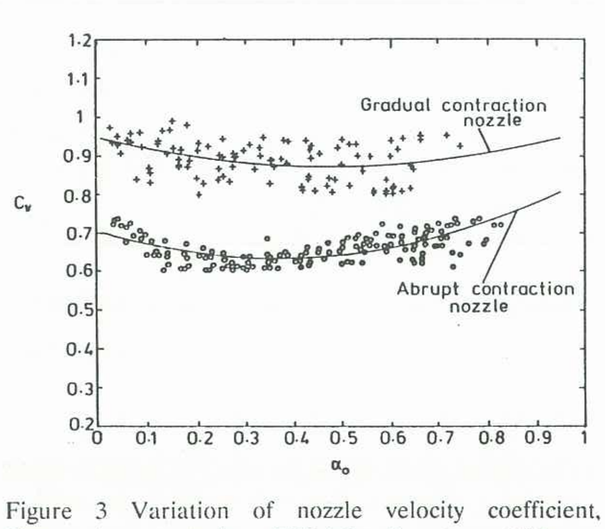

Figure 3 Variation of nozzle velocity coefficient, Contraction area ratio = 2.25, inlet diameter = 38.1 mm, axial length = 31mm.

The six constants involved in this equation are expressed only in terms of conditions at the start of the pipe section (suffix zero)

$a = (1 - \alpha_o)/\{2D_o(1 - a_o)^2 + D_o/F_of\}$, $b = 4\alpha_oD_oa$

$c = 2\alpha_o^2D_oa/(1 - \alpha_o)$, $A = \alpha_o/(1 - \alpha_o) - b - C$

$B = -\alpha_oD_o - c - bC$, $C = -\alpha_o^2D_o/[(1-\alpha_o)c]$

and I represents the integration as follows, if $c > b^2/4$

$I = [1/(c - b^2/4)^{1/2}][\tan^{-1}\{(\bar{p}_2 + b/2)/(c - b^2/4)^{1/2}\} - \tan^{-1}\{(1 + b/2)/(c - b^2/4)^{1/2}\}]$ or if $b^2/4 > c$ then

$I = \{1/2\,(b^2/4 - c)^{1/2}\}\ln[((b^2/4 - c)^{1/2} - \bar{p}_2 - b/2)((b^2/4 - c)^{1/2} + 1 + b/2)/\{((b^2/4 - c)^{1/2} + \bar{p}_2 + b/2)((b^2/4 - c)^{1/2} - 1 - b/2)\}]$

In these expressions $\bar{p}_2 = p_2/p_o$, the pressure ratio across the test length, whilst flow momentum flux and gravitational effects along the pipe are represented in the constants $D_o = \rho_{mo} u_{mo}^2/p_o$ and $F_o = u_{mo}^2/gd$. The dependence of the overall pressure ratio upon the inlet conditions of voidage and momentum flux for a given constant wall friction factor is shown in figure 4.

It is possible to determine when choking of the pipe occurs (i.e. when $\alpha_2D_2 = 1$) and to construct the limiting envelope for outlet choking of the pipe as shown in figure 4. It can thus be seen that it is necessary for the outlet flow conditions at section 2 to approach choking if a strong variation of the overall pressure ratio with void fraction (α_o) is to be introduced.

Average friction factors were calculated from the pressure ratio observed over a length of 110 tube diameters with the downstream pressure tapping at a distance of 46 tube diameters ahead of a discharge elbow. Average wall friction factors were also calculated from observed pressure differentials observed over a length of 98.75 tube diameters (with downstream pressure tapping at a distance of 9.25 tube diameters from the outlet of tube) by Davis (1991). Both sets of data are shown in figure 5 as a function of the flow Reynolds number. The

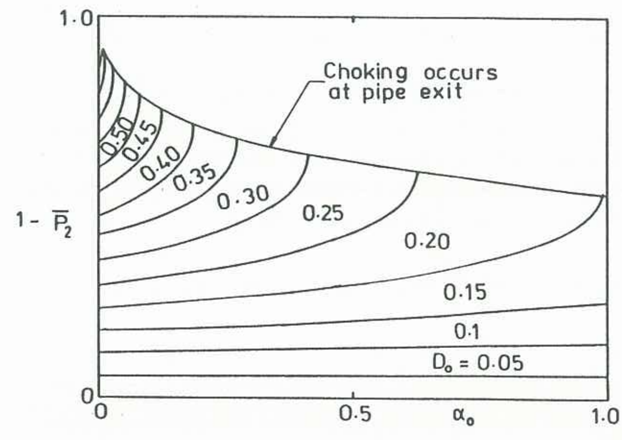

Figure 4 Normalised pressure differential over a pipe (equation 11) (fl/d = 0.6; $1/F_oF = 0$).

Reynolds number is calculated in terms of the mixture mass flow rate and liquid viscosity (μ_l) since the shear stress at the wall is transmitted through a liquid layer close to the wall, $R_e = \rho_m U_m d/\mu_l$. The difference between present correlations and the correlation proposed by Davis (1974) would be due to the variation of flow pattern through the pipe due to the influence of the pipe contraction. This is immediately upstream of the pipe length in the present work, whereas the earlier experiments (Davis, 1974) allowed a settling pipe length ahead of the test pipe length. However in the present flow meter application, it is necessary for the nozzle to lead directly to the pipe length so that only three pressure measurement points are required.

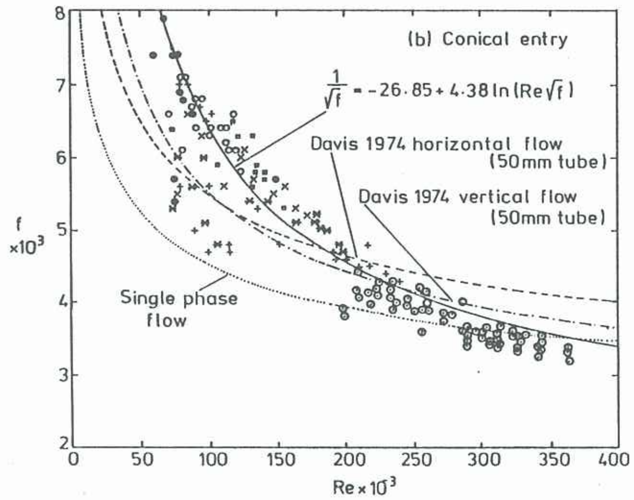

Figure 5 Variation of pipe friction factor
+, $\alpha_o < 0.25$; *, $0.25 \le \alpha_o < 0.35$; x, $0.35 \le \alpha_o < 0.45$; ⊙, $0.45 \le \alpha_o < 0.75$; •, $0.75 \le \alpha_o < 0.85$; O, Davis (1991) (25mm tube)

Having demonstrated experimentally that bubbly flows conform to the general predictions of the one dimensional flow equations for nozzles and pipes, the combined system for flow metering will be considered. Assuming a unit nozzle velocity coefficient the variation of normalised pressure differentials over the nozzle and pipe sections is shown in figure 6 as a function of the momentum flux parameter (D_o) and void fraction (α_o) at the exit from the contraction and entry to the pipe. These results demonstrate that for compressible flow conditions (i.e. larger momentum flux parameter values) the influence of void fraction on the pipe section pressure differential clearly causes a spread of the constant void fraction curves over the pressure differential diagram. Thus a measurement of dual pressure differences in the range of D_o above 0.3 make possible determination of both D_o and α_o.

4. EXPERIMENTAL OBSERVATIONS WITH A COMBINED CONTRACTION/PIPE FLOW METER

The experimental observations were carried out using air/water mixture in a horizontal flow system. The air/water mixture was formed by a conical multi-jet mixer

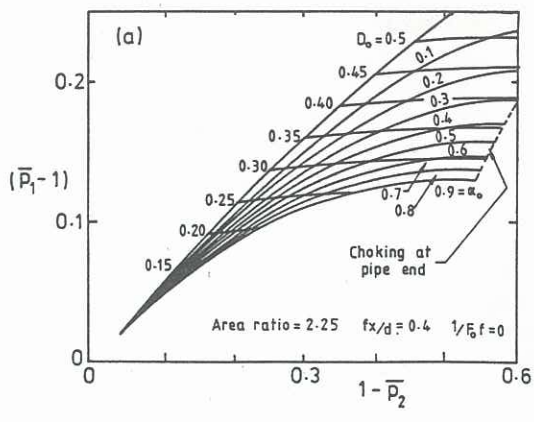

Figure 6 Variation of normalised pressure differentials across series contraction and pipe for ideal homogeneous flow model (Horizontal flow)

of the type similar to that described by Herringe and Davis (1976). The mixing chamber was of overall length 0.42m, and was in the form of a smooth conical contraction from the base plate of diameter 0.104m to the outlet of diameter 0.0381m, which was connected by a pipe of constant diameter 0.381m and of length 2.1m to the entry of the contraction. Air from compressor was injected through a central hole of diameter 0.0125m in the base plate, and water through eight 0.011m holes in the base plate on a 0.08m diameter circle. The mixture flows from the outlet of mixing chamber were of a turbulent, bubbly type, and remained relatively steady without any tendencies to form slugs or intermittent flow or to break down into annular patterns as determined from visual observation in the range of average void fractions extending from 0.2 to 0.75. The inlet of the contractions was 0.0381m diameter, and the outlet of contraction and entry of the pipe was 0.0254m diameter. The conical contraction had a length of 31mm. The mixture flow from the mixing chamber passed through the combined contraction/pipe flow meter, the pipe length being 2.75m and then travelled an additional distance of 1.4m and through an elbow before discharging.

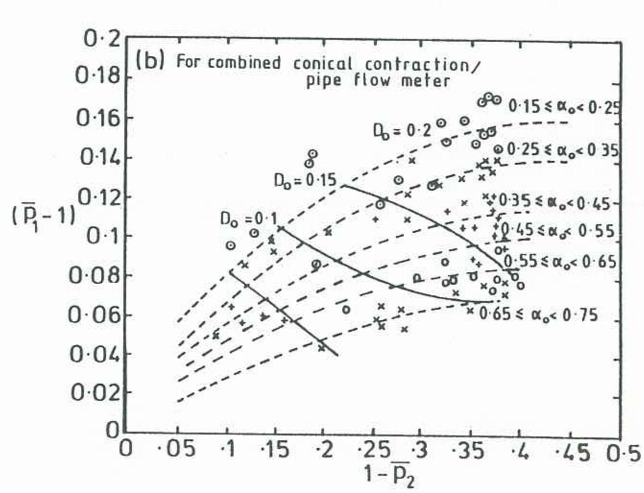

Figure 7 Observed variation of normalised pressure differentials across series contraction and pipe

The observed variation of normalised pressure differentials over the contraction and test pipe sections are shown in figure 7. The sets of solid curves with constant void fraction and constant momentum flux parameter were calculated for certain ranges of void fraction and momentum flux parameter by a least-square polynomial fit, and the points indicate observed results. The experimental data (figure 7) show a rather better spread of the measurement space than predicted. This is most likely due to slip and flow distribution effects which are not incorporated in the homogeneous flow representation (figure 6).

The void fraction and momentum flux parameter as predicted from the flow meter pressure differentials are compared with values derived from externally measured water and air flow rates in figure 8. The maximum errors between meter predictions and observations for liquid flow rate and momentum flux parameter is about 10% using the contraction/pipe flow meter. For void fraction and air flow rate, the points are more scattered and the maximum error between observed and predicted results for air flow rate is about 30% and about 20% for void fraction.

Detailed analysis shows these errors are primarily due to the accuracy of pressure measurements and the relatively limited measurement space resulting from compressible flow properties (figures 6 and 7). Improved accuracy of two phase flow measurement requires more accurate measurement of pressure data, and also accurate development of the friction factor correlations which form part of the basis of the measurement of flow rates based on observed pressure differentials.

5. CONCLUSIONS

It has been shown that the combined use of a contraction in series with a frictional pipe flow section can form the basis for the measurement of both flow rates in a gas-liquid mixture flow from the observed pressure differentials over the two sections. An essential criterion for the operation of such a metering device is that conditions of compressible flow should be established in the frictional pipe flow section so that sensitivity of the pressure drop in that section to void fraction and momentum flux is introduced. More accurate prediction of air flow rate and void fraction using the dual pressure differential flow meter could be obtained by improving the correlation of wall friction factor with Reynolds number. In particular, the influence of void fraction on wall friction factor should be considered in detail. Also any measures which promote good inlet mixing and a flow pattern much closer to the homogeneous flow will improve accuracy of metering. However, it must be borne in mind that compressible flow effects generate a limited measurement space, and thus there is an inherent requirement for accurate pressure data.

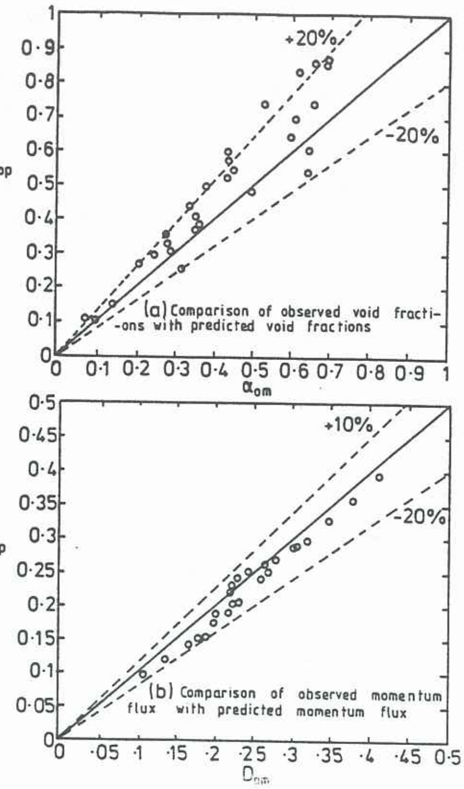

Figure 8 Comparison of observed results with the results predicted by flow model for combined conical contraction/pipe meter
(a) Comparison of void fractions;
(b) Comparison of momentum fluxes;

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