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Modeling of a homogenous gas-water two phase flow through a Venturi and vertical pipe; (A prediction of pressure drop sign change in two phase flow)

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ABSTRACT

In two phase flow, differential pressures technique can be used to measure the volume fraction of the gas phase. In the case where no restriction is available in the pipeline, the differential pressure technique can be used only in vertical or inclined pipelines. Two phase air-water pressure drop across a Venturi meter may change its sign from positive to negative due to change in the compressibility of the gas phase. In other words, the inlet of the venturi (upstream section) is not always positive as in a single phase flow. A new model to predict the sign change of the two phase pressure drop across a Venturi was developed and checked against data recently obtained from an air-water flow rig at the University of Huddersfield. The predication of a two phase pressure drop through a vertical pipe was also investigated and compared with experimental data. Four sets of data were investigated. In each set the water volumetric flow rate was fixed while the gas volumetric flow rate was varied (see table-1). It was inferred from the model proposed in this paper and the experimental data that the sign of the differential pressure drop across Venturi meter and parallel pipe for homogenous air-water flow depends mainly on the parameters C_1, C_2, U_h and K. Therefore, if $C_1 > C_2$ then, the differential pressure drop across Venturi tends to be negative and if $U_h^2 > K$ then the differential pressure drop across a 1m long Perspex pipe will be negative.

Keywords pressure drop, Venturi meter, Bernoulli's equation, friction factor, homogenous flow

1. INTRODUCTION

In industrial processes the need to measure fluid flow rate arises frequently. The accuracy and repeatability of the flow rate measurements are necessary for process development and control. Two phase or even three phase flows are commonly found in industrial fields and in ordinary life. In order to measure the flow rate in multiphase flows using differential pressure devices (e.g. Venturi meter) it is necessary to ensure that the HIGH and LOW pressure tapping are connected correctly.

Considerable theoretical and experimental studies have been published to describe mathematical models of Venturis in multiphase flow applications including the use of Venturi in vertical and horizontal flow. The study of multiphase flow through contraction meters are described for example by; Shires [1], Herringe [2], Thang and Davis [3,4], Azzopardi et al. [5], Kowe et al. [6], Couet et al. [7], Wolf [8], Boyer et al. [9], Guet et al. [10] and Fang et al. [11]. Abbas [16] reviewed some of the matimatical models used for Venturi in horizontal flow.

The differential pressure technique has proven attractive for many applications because it is simple in operation, easy to handle, non intrusive and low cost. The most common differential pressure device is the Venturi meter, but orifice plates have also been used widely. The advantage of the Venturi meter over the orifice plate is that the Venturi meter is much more predictable and repeatable than the orifice plate for wide ranging flow conditions. Further, the smooth flow profile in a Venturi meter reduces frictional losses which increase the reliability of the device. This reduction of frictional losses can improve the pressure recovery in the flow stream [17].

Differential pressure devices such as Venturi meter are most widely used in flow measurements. In multiphase flow measurements, the relationship between the overall mass flow rate and the pressure drop ΔP in Venturi meter is not unique and includes also the flow quality or holdup.

The complexity of two phase flow is due to many characteristics. These include difference in velocity of the two phases, distributional effects of the phases, compressibility of the gas phase, gas liquid interfaces and the problem of turbulent motion [12]. The predication model of two phase pressure drop described in this paper is valid only for homogenous flow where the slip ratio is assumed to be unity (S=1).

2. THEORETICAL WORK

2.1 Use of Venturis in vertical and inclined homogenous two phase flows

In the case of homogenous flow where the two phases are normally well mixed, the gas and water are assumed to have the same velocity. That is, the velocity ratio is unity (S=1). Fig.1 shows air/water two phase flow in an inclined Venturi meter.

From fig.1, it is possible to write;

$$\Delta P_v = P_i - P_t - \rho_w g h_t \cos\theta \tag{1}$$

where ΔP_v is the pressure drop across the Venturi, g is the acceleration of the gravity, h_t is the pressure tapping separation in Venturi (h_t=0.06m), θ is the angle of inclination from vertical and ρ_w is the water density.
Equation (1) is only true for water filled line.
From Bernoulli's equation it is possible to write;

$$P_i - P_t = \frac{1}{2}\rho_m (U_t^{\,2} - U_i^{\,2}) + \rho_m g h_t \cos\theta + F_{mt} \tag{2}$$

where U_t & U_i are the velocities at the throat and inlet respectively, F_{mt} is the frictional pressure loss (from inlet to the throat of Venturi) and ρ_m is the mixture density and given by;

$$\rho_m = \alpha\rho_g + (1-\alpha)\rho_w \approx (1-\alpha)\rho_w \tag{3}$$

The mass conservation equation is given by;

$$U_t = U_h \frac{A_i}{A_t} \tag{4}$$

where A_t and A_i are the areas at the throat and the inlet of the Venturi respectively ($A_t = 1.6417\times10^{-3}$ and $A_i = 5.02654\times10^{-3}\ m^2$)
Substituting (2), (3) & (4) into (1) gives;

$$\Delta P_v = -\alpha\rho_w g h_t \cos\theta + F_{mt} + \frac{1}{2}\rho_w (1-\alpha) U_h^2 \left((\frac{A_i}{A_t})^2 - 1 \right) \tag{5}$$

where α is the gas volume fraction at the inlet of the Venturi and U_h is the homogenous velocity of the mixture at the inlet of the Venturi meter.
F_{mt} in equation (5) is defined by;

$$F_{mt} = \frac{2\rho_w h_t f U_h^{2^*}}{D^*} \tag{6}$$

where U_h^* is the average homogenous velocity between parallel section and the throat and D^* is the average diameter between inlet (parallel section) and the throat of Venturi.

It is well known that the mixture volume flow rate is given by;

$$Q_m = U_h A_i \tag{7}$$

Substituting U_h from equation (5) into equation (7) gives;

$$Q_m = \frac{A_i}{\sqrt{\left(\frac{A_i}{A_t}\right)^2 - 1}} \sqrt{\frac{2}{\rho_w (1-\alpha)}} . \sqrt{\Delta P_v + \alpha\rho_w g h_t \cos\theta - F_{mt}} \tag{8}$$

or; in terms of discharge coefficient C_{dm};

$$Q_m = \frac{C_{dm} A_i}{\sqrt{\left(\frac{A_i}{A_t}\right)^2 - 1}} \sqrt{\frac{2}{\rho_w (1-\alpha)}} . \sqrt{\Delta P_v + \alpha\rho_w g h_t \cos\theta} \tag{9}$$

where C_{dm} is the discharge coefficient of the mixture.

2.2 The prediction model for the pressure drop sign change in two phase flow through Venturi meter

From equation (5) it is possible to write;

$$\Delta P_v = K_1 (1-\alpha) U_h^2 - \alpha K_2 + F_{mt} \tag{10}$$

K_1 and K_2 in equation (10) are defined by;

$$K_1 = \frac{1}{2}\rho_w \left((\frac{A_i}{A_t})^2 - 1 \right) \tag{11}$$

and;

$$K_2 = \rho_w g h_t \cos\theta \tag{12}$$

where K_1 and K_2 are equal to 4187.27 and 588.6 respectively for the Venturi and fluids currently under investigation.
Substituting (11) & (12) into (10) yields;

$$\Delta P = 4187.27(1-\alpha)U_h^2 - 588.6\alpha + F_{mt} \quad (13)$$

ΔP_v across Venturi is negative if;

$$C_1 \rangle C_2 \quad (14)$$

where; $C_1 = 588.6\alpha$ and $C_2 = 4187.27(1-\alpha)U_h^2 + F_{mt}$ (15)

2.3 The prediction model for the pressure drop sign change in two phase flow through a vertical and inclined pipe

The gas volume fraction α in equation (5) can be measured by the differential pressure technique [13]. Consider fig.2 in which the tubes, connected to an upper and lower pressure tapping, are filled with water.

From fig.2, it is possible to write [13];

$$\Delta P_{pipe} + F_m = gh_s \cos\theta(\rho_w - \rho_m) \quad (16)$$

where ΔP_{pipe} is the measured differential pressure across parallel pipe, h_s is the pressure tapping separation (h_s=1 m) and F_m is the frictional pressure loss term across parallel pipe, and is given by (Darcy's law);

$$F_m = \frac{2\rho_w h_s f U_h^{\,2}}{D} \quad (17)$$

In equation (17), f is a single phase friction factor and can be expressed as;

$$f = \frac{\Delta P_w \times D}{2\rho_w h_s u^2} \quad (18)$$

where u is the single phase flow velocity and ΔP_w is the water phase pressure drop across vertical pipe.
Substituting (3) into (16) and solving for α would give;

$$\alpha = \frac{\left(\Delta P_{pipe} + F_m\right)}{gh_s \cos\theta(\rho_w - \rho_g)} \quad (19)$$

The gas volume fraction α in equation (5) can also be estimated from the Lucas and Jin method [15];

$$U_g = C_o U_h + U_t(1-\alpha) \quad (20)$$

where U_t and C_o are the terminal rise velocity and the distribution parameter respectively.
Substituting ($C_o = 1.1 \; and \; U_t = 0.25$ m/s) into equation (20) and solving for α would give;

$$\alpha = \frac{U_{gs}}{(1.1U_h + 0.25)} \quad (21)$$

From equations (17) and (19), it is possible to write;

$$\Delta P_{pipe} = \alpha g h_s \cos\theta(\rho_w - \rho_g) - \frac{2\rho_w h_s f U_h^{\,2}}{D} \quad (22)$$

It is clear from equation (22) that ΔP_{pipe} becomes negative if;

$$U_h^2 \rangle K \quad (23)$$

K in equation (23) is defined by; ($K = \dfrac{\alpha g \cos\theta(\rho_w - \rho_g)D}{2f\rho_w}$) . For vertical flow;

$$K = 0.3919\frac{\alpha}{f} \quad (24)$$

The constant (0.3919) depends on the flow and experimental conditions.

3. EXPERIMENTAL SETUP AND TEST PROGRAM

3.1 Air-water-solid multiphase rig

To carry out the measurements of two phase flows using a vertical pipe and Venturi meter, several items of equipment are needed. The experiment was carried out using resources which are already available at Huddersfield University namely; an air-water multiphase rig, Venturi meter, a range of pressure, differential pressure and temperature sensors, Lab-Jack interfacing system and a PC. Fig.3 shows the equipment. Water was pumped into 80 mm Perspex pipe. The gas was injected from the bottom of the pipe. The reference values of gas and water volume flow rates ($Q_{g,ref}$ & $Q_{w,ref}$) were measured by thermal mass flow meter and turbine flow meter respectively. Two DP cells were used to measure the differential pressure drop across vertical pipe and Venturi meter. A Yokogawa DP cell was used to measure ΔP_{pipe} across the vertical pipe while a Honeywell DP cell was connected across upstream and the throat of Venturi meter via a change-over valves configuration. The throat diameter was 0.04572 m and the distance between inlet and throat was 0.06m.

3.2 Interfacing the Pressure & Temperature sensors, 2 DP cells, Thermal mass flow meter and Turbine flow meter with a PC via Labjack-U12 and MATLAB test program.

Six signals were interfaced with a PC via Labjack-U12 (fig.4b); Two DP signals. (two I/V converters were needed to convert 4-20mA to 1-5V), gauge pressure signal, temperature signal, reference gas volume flow rate in SLPM and reference water volume flow rate via CNT channel. (A sine to square wave converter was designed to convert the turbine flow meter sine wave output into a square wave).

Once all required signals have been interfaced with LabJack-U12, the MATLAB test program was run and the required parameters was recorded (see fig.4b).

4. EXPERIMENTAL RESULTS AND MODEL EVALUATION

4.1 Flow loop friction factor calculation

In order to calculate the single phase friction factor, f, Q_w and therefore the water velocity in the working section, u, was measured, using the turbine meter, over a wide range of flow conditions. By combining the pressure drop across the working section (parallel pipe), ΔP_w, with equation (18) it was possible to determine the value of f for various flow conditions. The resulting calibration curve is shown in fig.5.

The value of friction factor, f depends primarily on the relative roughness of the pipe surface [14]. The experimental data in fig.5 shows a classic increase in f as the flow velocity decreases. Equation (25) shows a good fit to the experimental data over the full range of flow velocities.

$$f = 0.0085u^6 - 0.0831u^5 + 0.3233u^4 - 0.6436u^3 + 0.6945u^2 - 0.3895u + 0.0976 \qquad (25)$$

4.2 A prediction of two phase pressure drop sign change through a vertical pipe and Venturi

Experiments were carried out in vertical upward gas-water flows. Four sets of data with different flow conditions were tested for $Q_{w,ref}$ in the range of $3.077\times10^{-4} m^3/s$ to $5.034\times10^{-3} m^3/s$ (1.107 m^3/hr to18.12 m^3/hr), and for values $Q_{g,ref}$ in the range of $2.99\times10^{-6} m^3/s$ to $1.2\times10^{-3} m^3/s$ (0.01 m^3/hr to 4.32 m^3/hr). At each set of data $Q_{w,ref}$ was fixed while $Q_{g,ref}$ was varied. The homogenous velocity U_h was in the range of 0.075 to 1.17 m/s . The gas volume fraction was in the range of 0.025 to 0.26. The flow conditions of all four sets are summarized in table-1;

conditions	Set #1	Set #2	Set #3	Set #4
$Q_{w,ref}$ (m^3/s)	3.07716×10^{-4}	1.224×10^{-3}	3.27×10^{-3}	5.034×10^{-3}
$Q_{g,ref}$ (m^3/s)	6.44×10^{-5} to 4.707×10^{-4}	4.89×10^{-5} to 1.20×10^{-3}	2.92×10^{-6} to 1.08×10^{-3}	2.99×10^{-6} to 8.68×10^{-4}
α	0.046 to 0.184	0.025 to 0.26	0.05 to 0.165	0.05 to 0.11
U_h (m/s)	0.075 to 0.156	0.254 to 0.485	0.651 to 0.866	1.002 to 1.174

Table-1: Flow conditions for 4 data sets

Fig.6 shows the variation between ΔP_v and Q_g at fixed Q_w. It is clear that at set-1, (in which Q_w was small and C_1>C_2), ΔP_v was negative for different values of Q_g. When Q_w increased ΔP_v was always positive. From fig.7, it is obvious that ΔP_{pipe} was negative when $U_h^2 \rangle K$ and positive when $U_h^2 \langle K$. This is what equation (23) tries to prove. Fig.8 shows the variation of ΔP_{pipe} with different values of Q_g at fixed Q_w for all four sets of data. It is clear that, in sets 3 and 4 (where Q_w was high and Q_g was low) the pressure drop across vertical pipe was negative. After Q_g increased, ΔP_{pipe} values became positive.

5. CONCLUSIONS

Void fraction and two phase pressure drop where measured across 1m long Perspex pipe and Venturi meter. A new model to predict the sign change for two phase pressure drop across vertical pipe and Venturi meter were investigated and compared against four different experimental sets of data.

It should be noted that the Honeywell DP cell can not read negative differential pressure drop. Therefore, the change-over valves were used. Since the objective of the proposed model described in this paper was only to predict the pressure drop sign change, the correct pressure drop values after using change-over valves were not discussed.

Equation (5) is an average estimation of frictional pressure drop between inlet to the throat of Venturi meter. Much further work would be required to investigate the actual two phase frictional pressure drop across Venturi meter.

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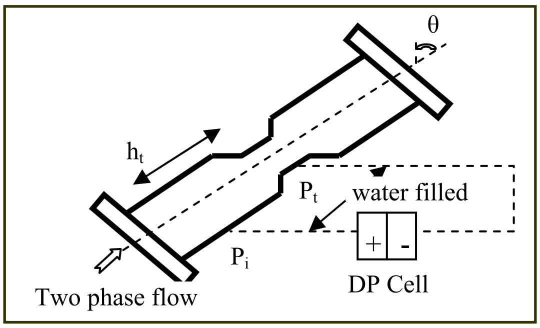


Fig.1: Air/water two phase flow in an inclined Venturi meter

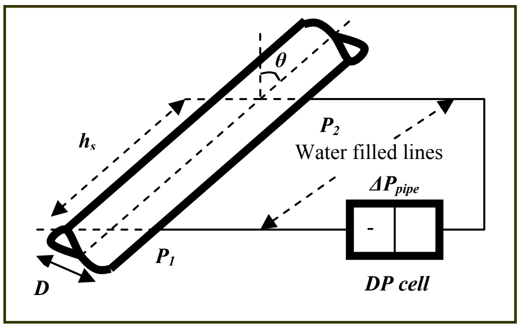


Fig.2: Measurement of void fraction using the differential pressure technique

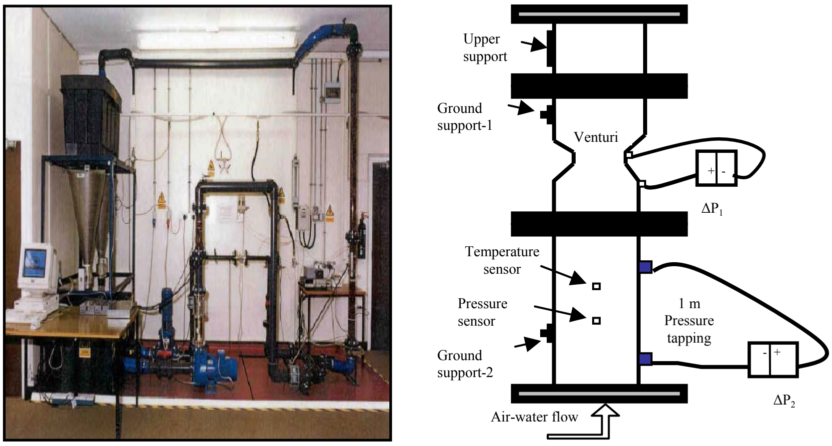
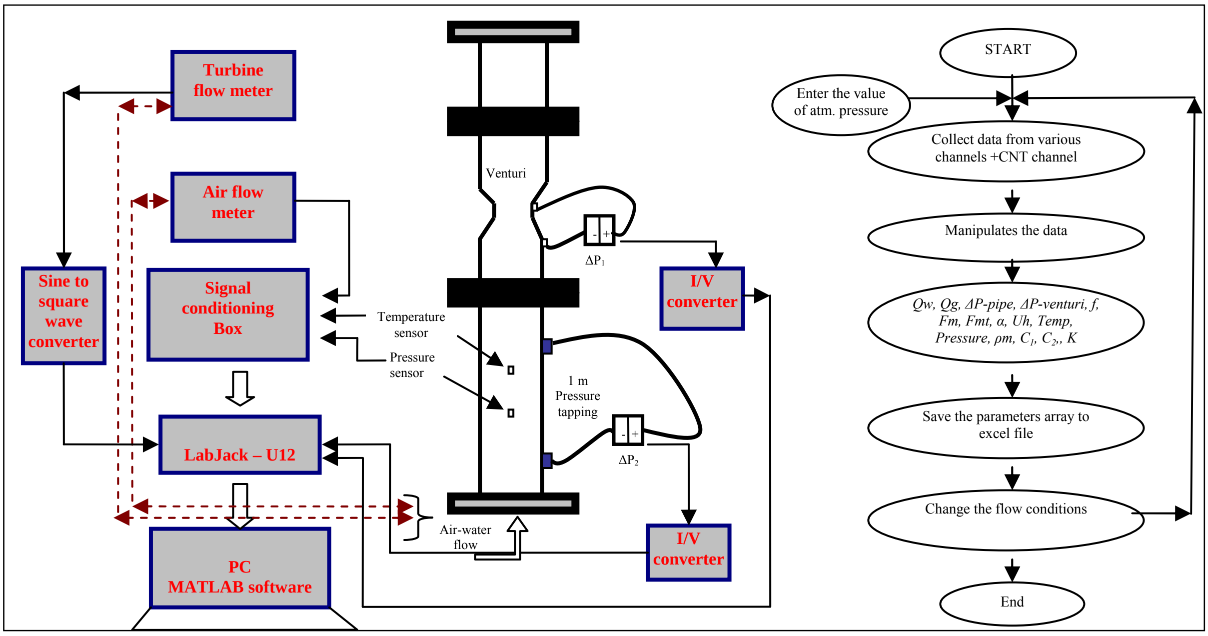
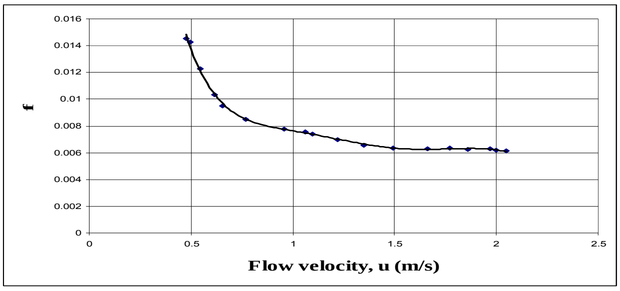


Fig.3: Air-water-solid multiphase rig (left), Design of a Venturi meter section (right); A_t=1.6417*10-3 m^2 and A_i=5.02654*10-3 m^2



(a) **(b)**

Fig.4: Interfacing the measurement signals with a PC via a Labjacl-U12 (left) and the test program flow chart (right)



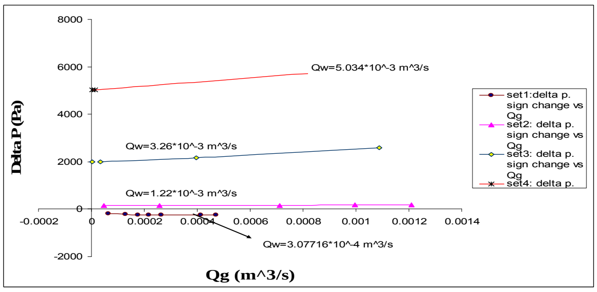
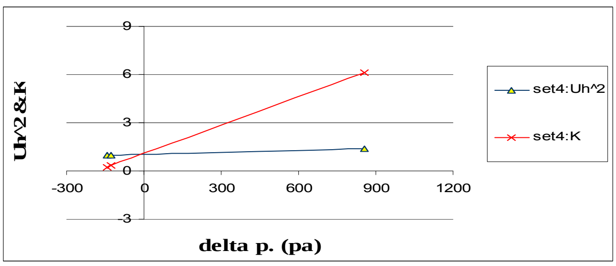


Fig.5: Friction factor variation with flow velocity

Fig.6: Pressure drop sign change in two phase flow through Venturi vs Q_g at fixed Q_w



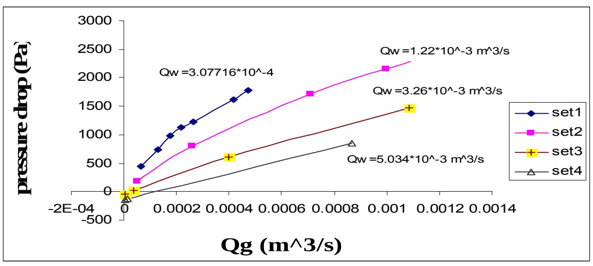


Fig.7: Variations of ΔP_{pipe} with U_h^2 and K through a vertical pipe

Fig.8: Variations of ΔP_{pipe} with Q_g through the vertical pipe at fixed Q_w