7th Australasian Hydraulics and
Fluid Mechanics Conference,
Brisbane, 18-22 August, 1980

Effect of Suspended Particulates on the Measurement of Gas Velocity Using a Pitot-Static Tube

S.T. HUYHN
Engineer, State Electricity Commission of Victoria
and
M.J. McINTOSH
Research Engineer, State Electricity Commission of Victoria

1 INTRODUCTION

The measurement of velocity in a gas-solids suspension with a Pitot-static tube presents a problem in interpreting the total pressure reading. The reading is likely to be influenced by momentum interchanges between the gas and the particles.

From an extensive theoretical study of the dynamic interaction between the particles and the gas, Dussourd and Shapiro (1958) and Banister (1959) have developed special probes which are capable of measuring with known accuracy the gas stagnation pressure in a dust-laden gas stream. These special probes are not widely used, however, possibly because they would tend to block in situations where large particles are present. Although the common Pitot tube is still frequently used for measuring the flow of gas suspensions, there is no procedure available at present to account for the effect of the particulates on its readings. Some rather limited experimental evidence has been reported for pulverized-coal suspensions (Dalmon and Lowe, 1957; Chedaille and Braud, 1972) which indicates that the suspension can be considered as a homogeneous gas having the suspension density. On the basis of theoretical considerations found in the literature, however, this is unlikely to be a general result.

The State Electricity Commission of Victoria has recently been involved in measuring gas flows through coal-milling equipment. This involved measuring the gas velocity in ducts carrying fine pulverized brown coal using Pitot-static tubes. As the effect of the particulates on the gas flow measurements was not resolved, and a correction of about 10 per cent would be necessary if the suspension behaved as a homogeneous gas, an experimental investigation was conducted in a test rig. This paper summarizes the experimental investigation and compares the results with theoretical predictions.

2 THEORY

The behaviour of a Pitot tube in a suspension flow is summarized by Boothroyd (1971) based on an extensive analysis by Dussourd and Shapiro. The total pressure measured by a Pitot tube P_T is given by the sum of the static pressure p and dynamic pressure $\rho_g v_g^2/2$ of the gas, the pressure resulting from particles decelerating in the gas external to the probe ΔP_E, and the pressure resulting from those particles captured by the probe which decelerate in the stagnant gas inside the probe ΔP_I. (The momentum lost by the particles striking the probe walls does not contribute to the pressure.)

$$\therefore \quad P_T - p = \frac{\rho_g v_g^2}{2} + \Delta P_E + \Delta P_I \qquad (1)$$

The effect of the suspension has been represented by a factor (1 + h) defined in (2):

$$P_T - p = (1 + h)\frac{\rho_g v_g^2}{2} \qquad (2)$$

As h is expected to be strongly dependent on the mass concentration of the particulates μ, a further parameter k is defined in (3):

$$h = k\mu \qquad (3)$$

Note that for the assumption of a homogeneous gas, k = 1.

The value of ΔP_E can be estimated from the analysis of Dussourd and Shapiro. These authors obtained a velocity field by assuming a potential flow in the region near the entrance of an open-ended thin-walled cylindrical tube, the axis of which was aligned with the flow. (The analysis also allowed for a small bleed flow through the probe having a velocity of 5 per cent of the upstream velocity.) The particle velocities and trajectories were then calculated assuming that the particle and gas velocities upstream were equal. From the trajectories, the fraction of the particles approaching the probe which escape capture was obtained and these are reproduced in Figure 1. The capture efficiency e is a function of Reynolds number Re (based on upstream gas velocity $v_{g\infty}$ and particle diameter d_p) and what was called an obedience number which is a measure of how closely the particle trajectories follow the gas motion.

It is assumed in the present paper that the external velocity field is little different for a Pitot tube. As the disturbance to the velocity field due to the presence of the probe is significant only within about two probe diameters upstream of the probe, there is nearly complete capture of the particles of interest, e.g. approximately 95 per cent of 20 μm diameter brown-coal particles will be collected in a 1.2 mm bore probe. ΔP_E is found to be small and in any case may be combined in the calculation of ΔP_I when there is complete collection.

The value of ΔP_I has been estimated by the present authors by assuming that on entering the probe, the particles are decelerated in the stagnant gas. The particle motion inside the probe has been considered as one-dimensional and is described by

$$C_D \frac{\rho_g v_p^2}{2} \cdot \frac{\pi d_p^2}{2} = -\frac{\pi d_p^3}{6} \rho_p \cdot v_p \frac{dv_p}{dx} \qquad (4)$$

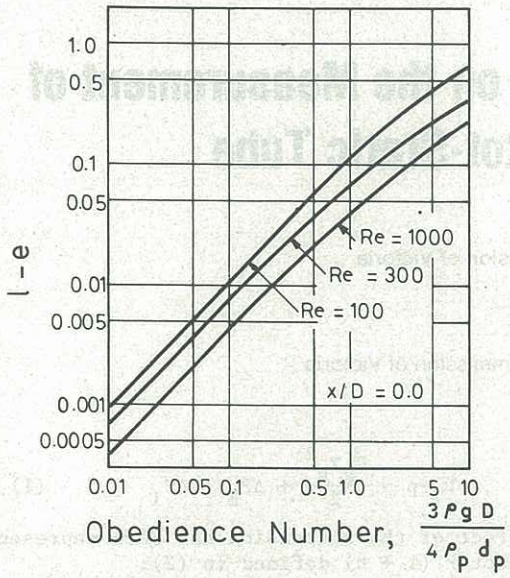

Figure 1 : Uncaptured fraction of particles for thin-walled probe of diameter D (from Dussourd and Shapiro).

where C_D is the drag coefficient, v_p is the particle velocity, and x is the distance measured downstream from the probe inlet.

Equation 4 has been solved numerically for an initial particle velocity equal to the upstream gas velocity, to give particle velocity as a function of distance inside the probe.

The pressure rise in the probe due to particle deceleration is computed from a momentum balance over a cylindrical volume of length x and cross-sectional area A:

$$-\Delta P_I . A = cAv_{g\infty}(v_p - v_{g\infty}) \qquad (5)$$

For the particulates of interest, $\mu\rho_g << \rho_p$, therefore the volume concentration c is given approximately by:

$$c = \mu\rho_g \qquad (6)$$

From (1), (2), (3), (5) and (6), the estimated value of k is:

$$k' = 2\,(1 - v_p/v_{g\infty}) \qquad (7)$$

The pressure in the probe therefore increases with distance along the probe as v_p decreases. At the mouth of the probe, $v_p \simeq v_{g\infty}$, therefore $\Delta P_I = 0$ and $k' = 0$. If all of the particles decelerate in the gas to zero velocity then $k' = 2$ and $\Delta P_I = \mu\rho_g v_{g\infty}^2$.

For a dust consisting of particles of different sizes, the change in momentum can be summed over the size range. Equation 7 then becomes:

$$k' = 2 \sum_i \alpha_i\,(1 - v_{pi}/v_{g\infty}) \qquad (8)$$

where α_i is the fraction of the dust wit' particle size d_i.

If the maximum particle velocity is significantly different from the gas velocity, the initial particle velocity should be used instead of $v_{g\infty}$.

A deceleration distance (i.e. the maximum distance available for the particles to decelerate) is therefore required in predicting k. This has been assumed to be the length of the head of the Pitot tube before the bend. This distance, although arbitrary, was chosen on the basis that particles which still had a substantial velocity at this position would collide with the tube wall and bounce or slide, so exchanging their momentum with the tube instead of the gas. Large particles may of course bounce along even the first section of the probe, and the larger the particle the higher the probability that they will strike the probe while entering the total pressure passage.

From the preceding analysis, the effect of particle size would be as follows:

. Large particles, k = 0. These have a collection efficiency of 100 per cent but are not significantly decelerated by the gas.

. Extremely fine particles, k = 1. These have a zero collection efficiency as they follow the gas motion. They contribute an increase in dynamic pressure in the same way as the gas.

. Particles of intermediate size, $2 > k \gtrsim 0$.

3 EQUIPMENT

The general arrangement of the apparatus is shown in Figure 2. The test section was a straight vertical perspex pipe through which air is drawn upward by a fan. Apart from the first few tests, the pipe used was 3 m long and 74 mm in bore, giving a maximum gas velocity of 38 m s^{-1}.

A vibrating feeder was used to introduce particles into the air stream and Pitot-static measurements were taken at a position 2 m downstream. (It was found subsequently that this length, although adequate for the two finer dusts tested, did not allow sufficient acceleration length for the coarser dust to reach its maximum velocity.)

Air leaving the pipe passed into a cyclone where most of the dust was collected. The air from the cyclone was then drawn through a large cloth filter bag to remove the fine particles before passing through an orifice plate.

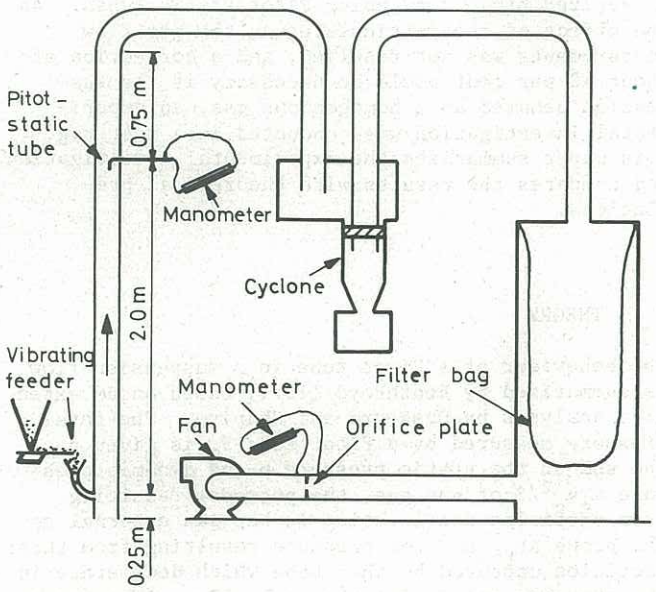

Figure 2 : Experimental arrangement

The Pitot-static tube used had an ellipsoidal nose and the following dimensions: length of head 60 mm, length of stem 290 mm, o.d. 4.1 mm, and i.d. 1.2 mm. Pressures were measured with manometers and the probe was purged between measurements.

The dusts used in the experiments were: graded sand, mean particle diameter $\bar{d}_p$ 320 μm, and density ρ_p 2610 kg m^{-3}; graded limestone, $\bar{d}_p$ 130 μm, ρ_p 2380 kg m^{-3}; and pulverized brown coal taken from a power station milling circuit, $\bar{d}_p$ 41 μm, ρ_p 990 kg m^{-3}. The size distributions are shown in Figure 3.

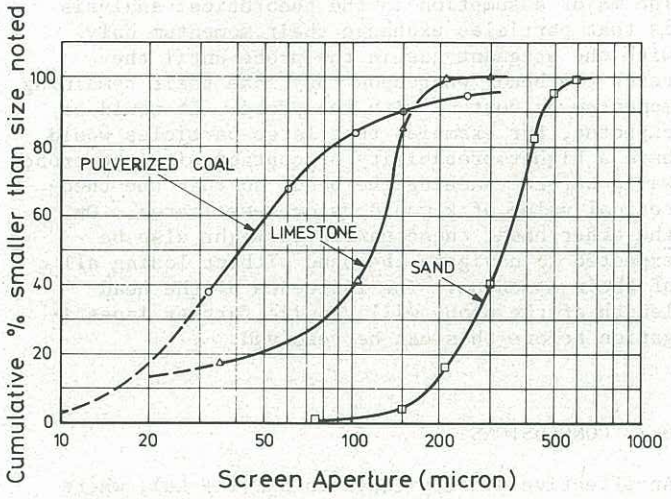

Figure 3 : Size distribution of dusts

4 PROCEDURE

The value of k can be calculated from the ratio of the Pitot-static differential pressures of dust-laden gas and clean gas at the same velocity. Unfortunately, as there is a velocity profile associated with pipe flow, which is changed by the introduction of particles, it was therefore necessary to integrate the velocity profiles to obtain the gas flows. The overall value of k was calculated from:

$$1 + h = 1 + k\mu = \left(\frac{\Sigma(\sqrt{2\ \Delta P_s/\rho_g}\ .\ \Delta A)}{\Sigma(\sqrt{2\ \Delta P_g/\rho_g}\ .\ \Delta A)} \right)^2 \qquad (9)$$

where ΔP_s and ΔP_g are average dynamic heads of suspension and gas for an elemental cross-sectional area ΔA of the pipe.

It is assumed in (9) that the dust concentration is uniform in the duct and that k is not dependent on gas velocity.

Pitot-static readings were generally obtained from traverses along four equally spaced diameters of the pipe. Each traverse consisted of seven points evenly spaced, including one point at the centre of the pipe. At high feed rates, the length of the test was limited by the capacity of the feeder hopper. In these tests, traverses were conducted along two diameters at right angles.

In each test, the desired air flow rate was set and once the orifice-plate reading became stable, the dynamic pressures were measured for air alone. After this survey had been completed, dust particles were introduced into the air stream via the vibrating feeder which had been set to give approximately the desired feed rate.

The Pitot-tube survey was then repeated with purging between readings. The data were adjusted for the small change in gas flow, resulting from the presence of the dust, in the ratio of the orifice plate differentials. There were generally fluctuations in pressure readings and the amplitude of the fluctuations increased with increasing dust concentration. Normally, the average value of the reading was taken within five seconds of purging. After a longer period, the reading steadily increased until the probe eventually blocked. (A possible explanation for this is the formation of a plug of material which was being pushed forward into the probe by incoming particles.)

The dust flow rate was obtained from the difference between the initial and final weights of the material in the feed-hopper, and the duration of feeding. For each dust used, tests were conducted at various mass concentrations of dust in air up to 0.4, and at three different average air velocities of 15, 20 and 36 m s^{-1}, approximately.

5 RESULTS AND DISCUSSION

The experimental data are plotted in Figure 4 as h against μ. Straight lines passing through the origin have been fitted to the data of each dust. The average values of k are given by the slopes of these lines. It can be seen that:

a The value of k is dependent on the type of dust used. The finest of the three dusts tested gives the largest value of k while the coarsest dust has virtually no effect.

b For $\mu < 0.15$, the finer dusts show k to increase with increase in dust concentration.

c The data show no apparent dependence on gas velocity.

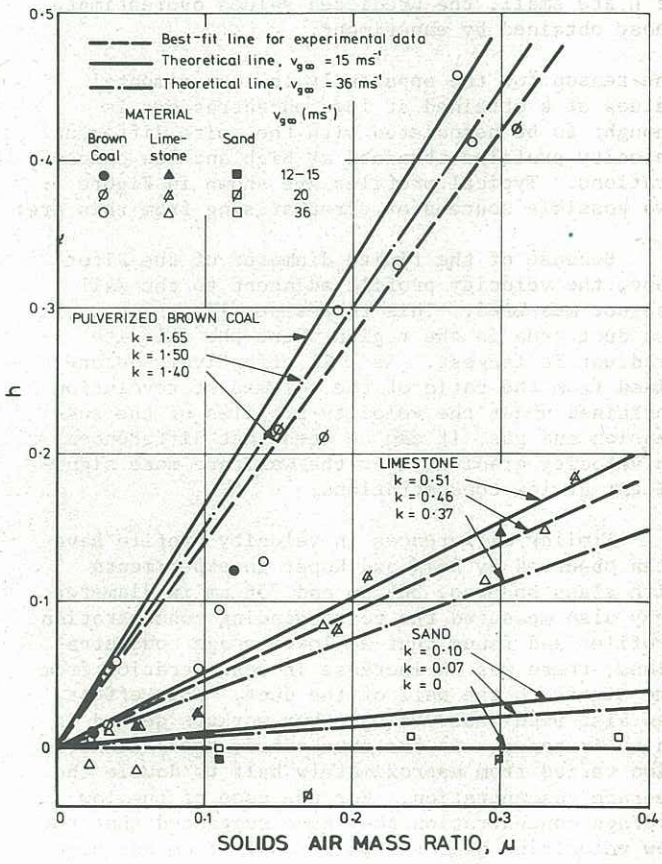

Figure 4 : Graph of h versus particle concentration μ.

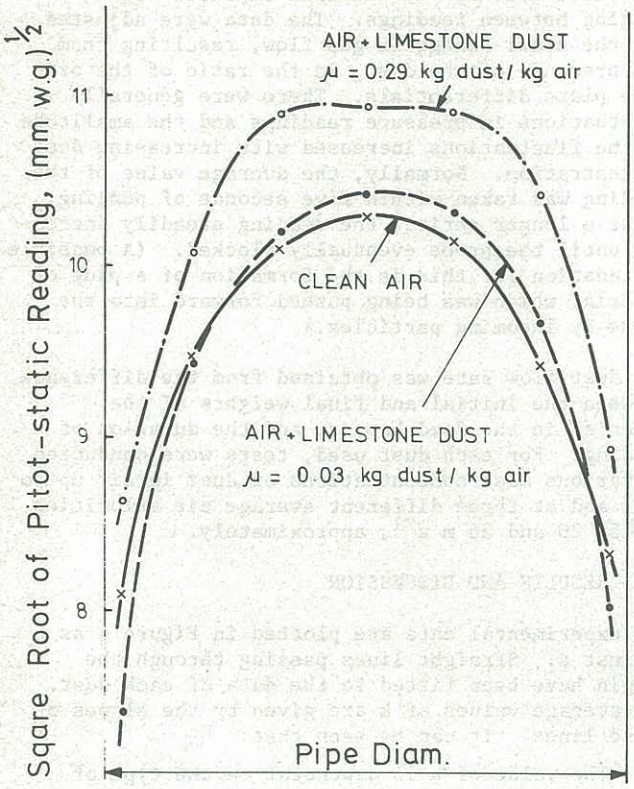

Figure 5 : Velocity profiles in 74 mm i.d. pipe

For each dust, the predicted values of k obtained at the extremes of the range of experimental velocities, viz. 15 and 36 m s^{-1}, have been superimposed onto the figure. For the two finer dusts, the predicted values of h for $\mu > 0.15$ are contained within the scatter of experimental data. For the coarser sand, however, although the values of h are small, the predicted values overestimate those obtained by experiment.

The reason for the apparently low experimental values of k obtained at low concentrations is thought to be associated with the quite different velocity profiles obtained at high and low concentrations. Typical profiles are shown in Figure 5. Two possible sources of error arising from this are:

a Because of the finite diameter of the Pitot tube, the velocity profile adjacent to the wall was not measured. This represents 13 per cent of the duct area in the region where the velocity gradient is largest. As k is effectively determined from the ratio of the volumes of revolution contained under the velocity profiles of the suspension and gas, it can be seen that differences in velocity gradient near the wall are more significant at low concentrations.

b Similar differences in velocity profile have been observed by Doig and Roper in experiments with glass spheres, 304 μm and 756 μm in diameter. They also measured the corresponding concentration profiles and found that at low average concentrations, there was an increase in concentration from the centre to the wall of the duct. This effect has also been observed by other workers quoted in in their paper. In the case cited, the concentration varied from approximately half to double the average concentration. For the case of the low average concentration they have suggested that the low velocities near the wall result from the high concentration of dust near the wall. The effect of this would be to invalidate (9), from which h is calculated, as this assumes μ is constant across the duct. Qualitatively, however, the effect would be to reduce the concentration at which the data was evaluated, hence improving the agreement with the predicted values of h.

At high concentrations, Doig and Roper found little variation in concentration across the duct. Assuming that the flatter velocity distributions found in the present investigation are associated with an evenly distributed dust, then (9) wil give a good estimate of k.

The major assumption in the theoretical analysis is that particles exchange their momentum only with the stagnant gas in the probe until they reach the bend, whereupon they lose their remaining momentum by contact with the probe. It would be expected, for example, that large particles would have a higher probability of contact with the probe walls before reaching the bend, so that the theoretical value of k would be over-estimated. On the other hand, these particles might also be expected to navigate the bend without losing all of their momentum. The influence of the head length of the probe will require further investigation before this can be resolved.

6 CONCLUSIONS

An effective density equal to $\rho_g (1 + k\mu)$, where $0 \leq k < 2$, has been used to interpret the Pitot-static readings taken in a dust-laden gas stream. A method for evaluating k based on an existing theoretical analysis has been found to give predictions which were in general agreement with experimental results. Within the range of the experimental conditions, k was found to be a function of the density and size distribution of the dust and was independent of the gas velocity.

7 ACKNOWLEDGEMENT

This paper is published with the permission of the State Electricity Commission of Victoria.

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