Friction Modification in a Coupled System

Two-phase solids-in-air flow was experimentally studied in a once through flexible wall tube flow system using nominal 25μm and 50μm spherical glass beads. For turbulent flow through the Silastic tube without a damping medium behind the wall, cases of true drag reduction and no drag reduction were found. The rate of addition of the glass beads was seen to be a correlatable parameter for both the flexible and rigid wall systems. A mechanistic model is proposed for interpretation of the results. It was qualitatively observed that the presence of an electrostatic charge on the particles at low relative humidities had a pronounced effect on increasing the drag in the system.

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SCOPE

The ability of modifying a flow system in order to reduce the energy requirements for transport of fluids is a most attractive field both economically and mechanistically. The modification can come from the addition of a drag reducing material to the fluid or by the modification of the boundary surrounding the turbulent fluid stream. By addition of solid particles to turbulent gas streams up to 50% true drag reduction has been obtained (Pfeffer and Rossetti, 1972) while addition of polymers to turbulent liquid streams can yield an amazing 95% true drag reduction (Lee, Vaseleski, and Metzner, 1973). Flexible tubes in conjunction with turbulent liquid streams have shown up to 40% decrease in the drag on the tube (Pelt, 1964). The application of both means are investigated in this study aimed at tuning these mechanisms to produce an optimum design of a flow system for minimal energy expenditure.

CONCLUSIONS AND SIGNIFICANCE

True drag reduction for a solid-gas turbulent flow system is seen to occur in the case of 25μm size beads but not for the 50μm size beads studied. The parameter of solid addition rate differentiates the frictional increase or decrease more markedly in the flexible tube studies than rigid tube studies. In general, the coupling of a flexible boundary with turbulent solid-gas flow increases the turbulence stresses of the coupled flow system.

In the solid-gas flow in flexible tubes at low relative humidities (< 25%), high electrostatic charges build up on the particles; this produces radial and secondary solid flow. High humidity air reduces the electrostatic charge, and the increased frictional effect due to the parameter is decreased such that the frictional regime exhibited for two-phase flow in rigid wall tube experiments is again observed.

Although use of hot film anemometry in solid-gas systems is questionable, the reaction of the hot film to solid addition is to decrease the response, possibly conjecturing decreased turbulence intensity.

Various factors can effect change in the friction factor during turbulent flow. Schlicting (1968) has reviewed these effects, some of which are (a) the existing pressure gradient, (b) suction on the boundary layer, (c) compressibility of the fluid, (d) roughness of the surface, (e) transfer of heat to or from the fluid, (f) flexibility of the boundary, and (g) presence of a dispersed phase within the fluid. Little if any investigation has been done on evaluating the simultaneous effects of two or more of these phenomena. In this work some experimental results on the combined effects of solids addition and flexible boundary on the frictional phenomena during turbulent air flow will be described.

Karmer (1957, 1960a, 1960b, and 1961) was the first to observe that a flexible boundary affected the fluid drag on the surface in his work which involved the towing of projectiles under water. Later work by Pelt (1964) and Klinzing, Kubovcik, and Marmo (1969) on water flow through damped flexible tubes showed fraction reduction of 20% and higher.

The investigations of Blick and co-workers (1968a, 1968b, and 1969) have dealt with flow across flat flexible boundaries with liquid or polyurethane foam damper backups. Reductions in drag coefficient of up to 40% below that of a smooth rigid plate were realized when the boundary layer was turbulent. Hot wire anemometer measurements showed reductions in the turbulence intensities, Reynolds stress distribution, and the spectrum of turbulent energy over the flexible boundary.

Benjamin (1960), Landahl (1962), Hains (1964, 1965), and Gyorgyfalvy (1967) have used the Orr-Sommerfeld equations to analyze the flow stability over a flat flexible boundary. In general, these analyses have indicated that the range of flow stability can be modified if the flexible boundary is ideally designed. The delay in transition is apparently through reduced amplification rates since the critical Reynolds number for flow instability is only slightly increased.

With two-phase systems, friction reduction in turbulent pipe flow can also be realized. Specifically, Boothroyd

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(1966), Boyce and Blick (1970), Mason and Boothroyd (1972), and Pfeffer and Rossetti (1972) reported reductions in the friction factor of 20 to 40% within the particle size range of 10μm to 200μm. Soo and Trezek (1966) reported lesser decreases in the friction factor for air flow with magnesia particles having a mean particle size of 36μm. For aqueous mixtures, the results of Thomas (1960, 1961a, 1961b, and 1962) indicate that some of these phenomena can be attributed to the non-Newtonian characteristics of the suspensions.

Saffman (1962) and Michael (1964 and 1965) have theoretically analyzed the flow stability of a dusty gas. The principal conclusion was that the relaxation time τ_p of the particles is the factor affecting the turbulence. Qualitatively, the relaxation time is a measure of the time required for the particle to adjust to changes in the fluid velocity. If the particles are sufficiently small that τ_p is small compared with a characteristic time scale associated with the flow, then the dust would be expected to follow the fluid velocity fluctuations without time delay. The net result is that the fluid acts as a single-phase of increased density. On the other hand, with increasing size of the dust particles the turbulent eddies begin to interact with the dust, and the flow is stabilized by the dust damping the perturbations in the gas flow; that is, the dust reduces the growth rate of a disturbance.

No data on the simultaneous effects of solids addition and flexible boundary were found in the literature.

EXPERIMENT

A brief description of the experimental apparatus is provided here while more detail can be found in Peters (1971). A schematic of the system is shown in Figure 1. The absolute filter was provided to eliminate any particulate matter which

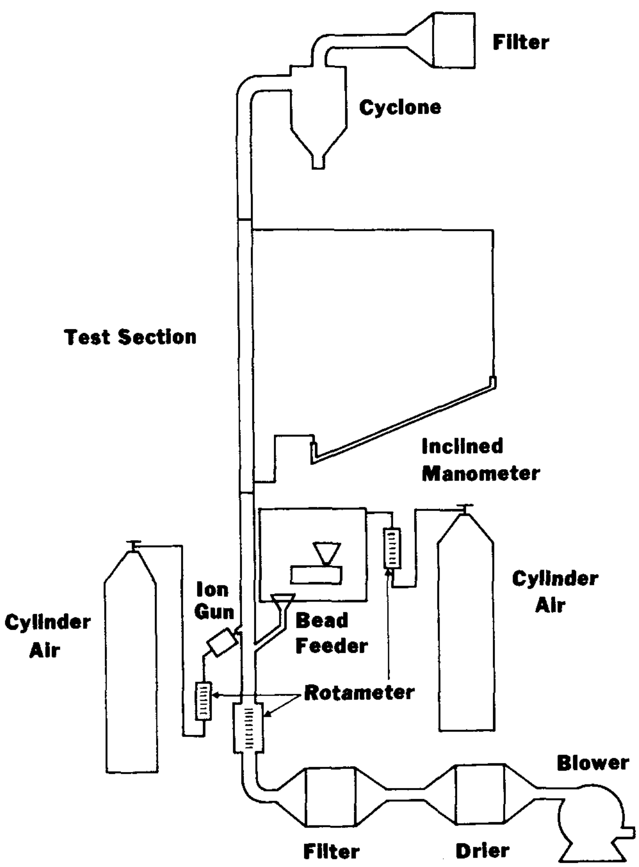

Fig. 1. Schematic of experimental flow system.

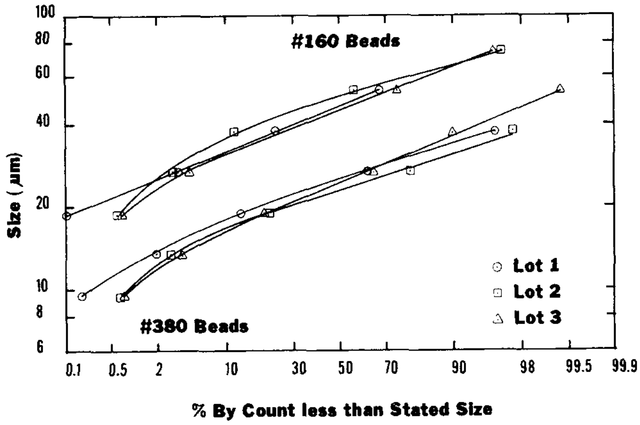

Fig. 2. Particle size distribution of solids used in this study.

might be brought in by the blower intake. The drier section was made available but was only used as such for two runs. In many runs, it was filled with water-saturated cotton to increase the moisture content of the air.

The test section was 0.0254 m I.D. $\times$ 1.59×10^{-3}m wall Silastic tube approximately 2.16 m long and having a modulus of elasticity of 2140 kN/m^2 at low strains. The flexible tube was actually elliptical with a major to minor axis ratio of 1.4. Calculations were therefore based on the cross-sectional area and hydraulic radius of an ellipse. Measurements of the surface roughness of the flexible tube indicated that the test section could be considered smooth over the range of Reynolds number investigated.

To ensure unperturbed developed gas flow and fully accelerated solid flow, the entrance section was 1.27 m long. The exit section was 1.07 m long. Both were made from 0.0254 diameter copper tube. All metal parts were electrically grounded. The companion flanges used for joining the test section to the entrance and exit lengths were soldered to 0.13 m lengths of 0.0254 m I.D. copper tube. The Silastic tube was slipped over these at each end and sealed with hose clamps. Rubber gaskets with precise 0.254 m diameter holes were used to seal the joints between the test section and entrance and exit lengths.

The solids phase used was 3M Company glass beads (#160 and #380 size). Three different lots of each bead size were used during the study, and the size distribution of each lot was determined by optical microscopy. More than 1000 beads of each lot were sized in this manner. Figure 2 shows the particle size distribution plotted on a logarithmic-probability basis. The count median diameters were approximately 25 μm and 50 μm for the #380 and #160 beads, respectively, with σ_g in the range of 1.25 to 1.35. Furthermore, practically all of the beads were spherical and very few were fractured. The density of each lot of beads was also determined using a Le Chatelier flask and found to be in the range of 2.3×10^3 to 2.5×10^3 kg/m^3.

The glass beads were fed into the flowing air stream by a conveyor belt gravity feed system specially designed for this work. With this system, feed rates up to 0.05 kg/s were possible. The glass beads were collected at the exit end of the flow system by a cyclone and another absolute filter. The glass beads were only used one time.

All flow rates were determined with rotameters and the pressure losses across the test section were measured by an inclined manometer having graduations of 0.254 mm (0.01 inches) and a maximum range of 203 mm (8 in.) of water. The solids static head was subtracted from the measured pressure drop to calculate all friction factors. Since the solid flow was completely accelerated, it was assumed that the solids were flowing at essentially the same velocity as the gas. Even in the worst case, the difference would only be 2% based on the gravitational settling velocity of the 50 μm beads. The temperature of the air stream was determined by a calibrated mercury thermometer, and the relative humidity was measured with an Airguide Model 605 humidity indicator which is reportedly accurate to within $\pm 5\%$ relative humidity.

ANALYSIS AND DISCUSSION

The analysis of the study of solid-gas flow through flexible tubes was done on a comparative basis to that through a rigid tube and single phase flow in a flexible tube. The frictional effect of single phase flow through the flexible tube at 1380 kN/m^2 tension could not be distinguished from that of a rigid tube at the 95% confidence limit level. The effect of tension in the flexible tube on the frictional effect of flow showed a minimum in the friction factors with increasing tension but the overall effect was only a 2% change. It is felt that a damping material behind the flexible tube would have made this effect more pronounced. Data of Pelt (1964) and Klinzing (1969) for this type of tube and the results of Blick (1968a, 1968b, 1969) substantiate this conjecture.

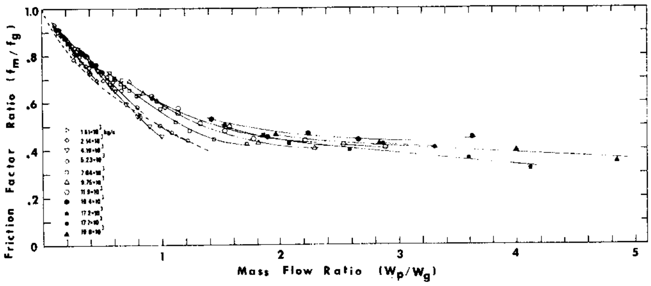

Fig. 5. Ratio of two-phase friction factor to single-phase friction factor as a function of the mass flow ratio in the flexible tube for 25μm beads. Two-phase friction factor was based on the mixture density.

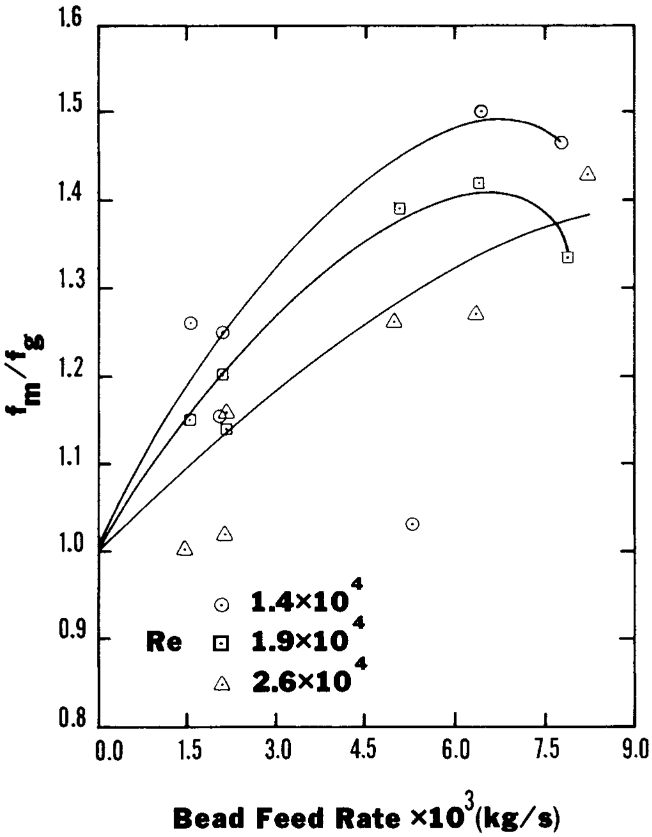

Fig. 3. Ratio of two-phase friction factor to single-phase friction factor as a function of bead feed rate for 25μm beads in silastic tube (40 kN/m^2 tension). Two-phase friction factor was bsed on the density of the mixture. These results were obtained at low relative humidities.

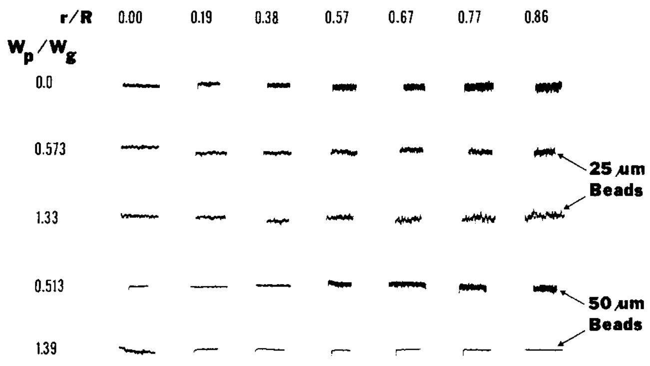

Fig. 4. Graphical representation of the axial velocity fluctuations in the absence and presence of beads. All data were taken at air Reynolds number of about 1.5 × 10^4.

In the two-phase flexible tube studies at low relative humidities (< 25%), unusual solids flow patterns and high electrostatic charge build up occurred on the flexible tube walls. This charge buildup did not occur on the rigid wall copper tube since it was effectively grounded. The particles would strike the compliant tube wall, and a layer of particles would buildup until gravitational forces would pull them down. These particles would then be reentrained by the upflowing airstream. This pattern would be repeated, apparently at random positions and time intervals. As a result of this behavior the two-phase friction factor f_m increased much above that for the rigid tube. Figure 3 shows these results for 25μm particles. It was found by increasing the relative humidity above 75% the data for the two-phase friction factor for the flexible system returned to the regime of the rigid wall tube indicating effective dissipation of the electrostatic charge by the increased humidity.

The use of hot film anemometry in the solid-gas system is generally unsuitable. However, for two-phase flow through the tube, hot film anemometer tracings were obtained and are shown in Figure 4. As can be seen, the fluctuations of the hot film output were significantly decreased when the 50μm particles were added to the flow in the flexible tube. The hot film output in the two phase system is, of course, not only proportional to the air velocity but also depends on the solid beads in the flow system. Looking at the mass ratio of 1.39 of the two size beads at the centerline positions, similar hot wire tracings were observed. Toward the wall the tracing for the 50μ_m beads decreased while the tracing with 25μm beads increased. It is felt that since the 25μ_m beads exhibited such vastly different behavior, the turbulence intensity in the 50μm diameter bead case was truly damped and that this depends on delicate coupling conditions of the flexible boundary, particle size, and bead concentration. It should also be noted that no true drag reduction was found with the 50μm particles.

In the analysis of the two-phase flow system, the ratio of the friction factor of the mixture to that of the gas can be written as (Peters, 1971)

$$\frac{f_m}{f_g} = \left[\frac{1}{1 + \dfrac{W_p}{W_g}} \right] (1 + \varphi) \qquad (1)$$

The factor φ is a measure of the modification of the turbulence stresses by the presence of the solid particles and flexible boundary. Figures 5 and 6 are plots of f_m/f_g as a function of W_p/W_g for the flexible tube. If the data points lie above the dash lines in these figures, the turbulent stresses are increased by the presence of the solids and flexible boundary. If the points are below this

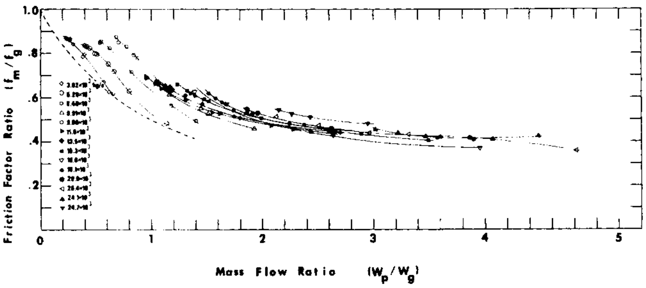

Fig. 6. Ratio of two-phase friction factor to single-phase friction factor as a function of the mass flow ratio in the flexible tube for 50μm beads. Two-phase friction factor was based on the mixture density.

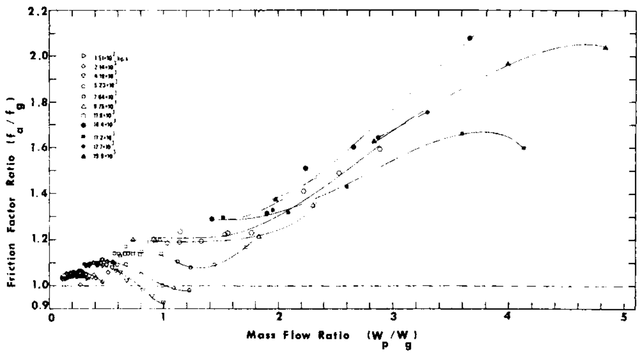

Fig. 7. Ratio of two-phase friction factor to single-phase friction factor as a function of the mass flow ratio in the flexible tube for 25μm beads. Two-phase friction factor was based on air density.

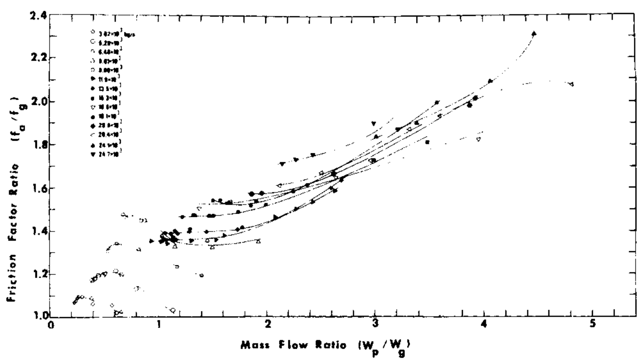

Fig. 8. Ratio of two-prase friction factor to single-phase friction factor as a function of the mass flow ratio in the flexible tube for 50μm beads. Two-phase friction factor was based on air density.

curve, there is drag reduction. As can be seen from the curves, the effect of the solid addition is pronounced and differentiates the data precisely. This high degree of differentiation is not found to exist in the rigid tube data of Peters (1971) and Bender (1972). It also can be noted that no minimum in the ratio f_m/f_g was noted with the mass flow ratio over the region studied up to 7 kg solids/kg air. This minimum, however, has been predicted by other investigators.

The factor φ can be written as

$$\varphi = \frac{\mu\left(\frac{\partial \overline{u}}{\partial r}\right) - \rho(\overline{u'v'}) - m_p N(\overline{u_p'v_p'})_\Delta}{\mu \frac{\partial \overline{u}}{\partial r} - \rho(\overline{u'v'})_\Delta} \tag{2}$$

The subscript delta Δ refers to change in these quantities by the addition of solids and the presence of a flexible boundary. If the two-phase friction factor is based on the air density (designated f_a) rather than the density of the mixture, then Figures 7 and 8 show plots of $(1 + \varphi) = f_a/f_g$ as a function of W_p/W_g indicating true reduction for only low loading ratios and low bead flow rates. Both figures exhibit the S shape character as mass flow ratio increases. From the analysis φ is mostly positive indicating an increase in the Δ terms of Equation (2). In general, it can be stated that the presence of the flexible boundary in this study increased the turbulence stresses of the two-phase solid-gas system.

NOTATION

f = tube friction factor
m = mass of single particle
N = particle number density
p = static pressure
r = radial coordinate
u = axial component of velocity
v = radial component of velocity
W = mass flow rate

Greek Letters

μ = viscosity
ρ = density
σ_g = geometric standard deviation of particle size distribution

Subscripts

a = based on air density
g = gas or fluid phase
m = mixture
p = particulate phase
Δ = added stresses caused by particulate phase

Superscripts

— = average or mean quantity
$'$ = fluctuating quantity about mean value

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Pressure Drop and Holdup in Stratified Gas-Liquid Flow

A mathematical model and an iterative procedure to calculate holdup and pressure drop in horizontal gas-liquid flow is developed. The predictions of the model agree with well over a hundred data points collected with air-water and air-glycerine solutions in 0.0254-, 0.0381-, and 0.0508-m. diameter pilot pipelines. A design procedure using the verified model is presented.

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SCOPE

Over the past three decades, pressure drop and holdup data have been collected for horizontal gas-liquid systems, and many attempts have been made to develop from the data general procedures for predicting these quantities. The current state of this art has been discussed in review articles by Anderson and Russell (1965, 1966), Simpson (1968), DeGance and Atherton (1970), and in texts by Govier and Aziz (1972), Scott (1964), and Wallis (1969). All came to essentially the same conclusion: No satisfactory general correlation exists. Errors of about 20 to 40% can be expected in holdup or pressure-drop prediction, and even this range is optimistic if one attempts to use the various predictive schemes without applying a generous measure of experience and judgment. A major difficulty in developing a general correlation based on statistical evaluation of data is deciding on a method of properly weighing the fit in each flow regime. It is difficult to decide, for instance, whether a correlation giving a good fit with annular flow and a poor fit with stratified flow is a better correlation than one giving a fair fit for both kinds of flow.

Although general correlations must continue to be used by those faced with two-phase flow problems, alternate procedures should be developed if we are to improve our ability to predict holdup and pressure drop. The complicated fluid motions in most two-phase flows of pragmatic interest make it impossible to develop the kinds of mathematical description that have proven so useful in single-phase flow analysis and design. Nevertheless, useful insights into the more complex problem are obtained by analyzing simple two-phase flow, as illustrated in this paper. In addition, this study provides a simple, tractable model of the flow and a clearcut, easy-to-use computational procedure for determining pressure drop and holdup. This analysis was also motivated by a need to establish a simple mathematical description for stability analysis to predict flow-pattern transition and has proven most useful in this regard.

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