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BRIEF COMMUNICATION

AN EXPERIMENTAL APPROACH FOR THE DETERMINATION OF DEVELOPMENT LENGTH IN PARTICULATE FLOWS

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1. INTRODUCTION

Since Boothroyd (1966), there has been continuing research on the modelling of two-phase particulate flows with special emphasis paid to the associated pressure drop and drag reduction due to the practical importance of the manner. However, complete understanding has not been reached yet, and as Coughran (1988) has suggested in his paper there is need for more experimental information on gas–solid flow systems. Some of the theoretical and experimental investigations conducted up to now are given in the papers of Rossetti and Pfeffer (1972); Pfeffer and Kane (1974); Radin *et al.* (1975); Yang (1978); Garner and Kerekes (1980); Michaelides and Roy (1987); Rizk and Elghobashi (1989); Kennedy and Kollmann (1993). Furthermore, the handbooks by Govier and Aziz (1977) and Hetsroni (1982) should be cited here as direct references to consult for the flow of multiphase systems.

A survey of the related literature has pointed out that the basic parameters influencing the particulate flows are the size and shape of the particle, particle loading ratio, Reynolds number, Re, of flow, and flow direction.

An experimental investigation conducted on the determination of development length of two-phase particulate flows is presented in this Brief Communication. Solid particles of considerably greater size than those referred to in the cited literature were used, directed also towards the simulation of pneumatic conveying of solids in pipelines. Irregular shaped granular solid particles were loaded into air flowing through a horizontal pipe by means of a particle feeder. The development length of a two-phase flow field can be determined either using the velocity profiles (Lodes and Mierka, 1990) or wall static pressure gradients (Obot *et al.* 1993). In this study, the development length, which was treated as the necessary distance downstream of the particle feeder for the attainment of homogeneous particle distribution in air, was estimated by evaluating the variation of local friction factors; $f_{\mathrm{p}+\mathrm{a}}$ calculated from the measurements of local static pressure gradients; $\mathrm{d}P/\mathrm{d}x$.

The measurements were conducted in airflow Re, based on mean air velocity, U, and inner pipe diameter, D, in the range $51{,}500 \leq \mathrm{Re} \leq 109{,}000$ at particle loading ratios, $M_{\mathrm{p}}/M_{\mathrm{a}}$, of $5\% \leq M_{\mathrm{p}}/M_{\mathrm{a}} \leq 30\%$ to determine the influence of $M_{\mathrm{p}}/M_{\mathrm{a}}$ and Re on the development length.

2. EXPERIMENTAL SET-UP AND MEASUREMENTS

The measurements were conducted in an open circuit blower type horizontal flow test set-up shown in figure 1. The set-up consisted of a blower unit, a particle feeder and a pipe system

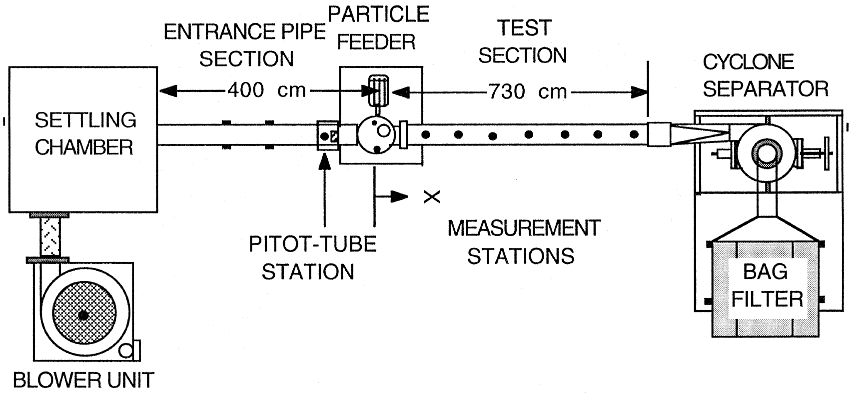

Figure 1. Top view of the set-up.

connected to a cyclone separator–bag filter assembly. The blower was a centrifugal fan coupled to a variable speed control unit. A PVC tube of inner diameter $D = 106$ mm was used in the piping. The 400 cm of the pipe downstream of the settling chamber was called the entrance pipe section, providing sufficient length to have a fully-developed turbulent flow of clean air in the test section. The test section along which the local pressure drops were taken had a length of 730 cm downstream of the solid particle feeder. Solid particles were collected at the cyclone separator. A pitot tube located 30 cm upstream of the particle feeder was used to measure the mean flow velocity in the pipe.

A celled wheel particle feeder was used to induce solid particles. The loading ratio of the solid particles was varied by adjusting the rotational speed of the feeder wheel by means of a variable speed control unit calibrated to cover an M_p/M_a range of $5\% \leq M_p/M_a \leq 30\%$. The particle feeder was such that at Re = 51,500 and Re = 68,600 it was possible to induce particles at a rate of 30% and 20%, respectively. For Re > 85,830 measurements were in the range of $5\% \leq M_p/M_a \leq 15\%$.

Irregular shaped pounded wheat particles with an apparent density, ρ_p, of 746 kg/m^3 measured according to ASTM B212-76 were used. The particle size distribution was determined by weighing the sieved quantities of particles using Endecott's EFL 2 MK 3 test sieve shaker. The particle size range was found to be between 200 μm and 1250 μm, and the average particle diameter d corresponding to 50% weight of sieved particles was taken to be 825 μm.

The local static pressure gradient $\mathrm{d}P/\mathrm{d}x$ on the pipe wall was determined by means of a pressure ring covering the pipe circumference installed according to BS 1042. The measurements were conducted along the test section at different lengths from the particle feeder: $x = 3D$, $x = 12.5D$, $x = 21.86D$, $x = 31.19D$, $x = 40.53D$, $x = 49.87D$ and $x = 59.16D$ shown in figure 1. Inclined leg alcohol micromanometers were used in collaboration with the pressure rings. Local magnitudes of flow friction factor, f, based on the dynamic pressure of clean air were calculated using the well-known equality

$$f = (\mathrm{d}P/\mathrm{d}x)(D/2\rho_a U^2),$$

where ρ_a is the density of air.

3. RESULTS AND DISCUSSION

The local static pressure gradients $\mathrm{d}P/\mathrm{d}x$ were measured along the test section for flows of clean air with $M_p/M_a = 0\%$ and particulates at loadings $5\% \leq M_p/M_a \leq 30\%$. A constant $\mathrm{d}P/\mathrm{d}x$ independent of Re was observed in clean air flow, indicating the fully-developed nature of the flow in the test section. However, in two-phase particulate flows, $\mathrm{d}P/\mathrm{d}x$ had a

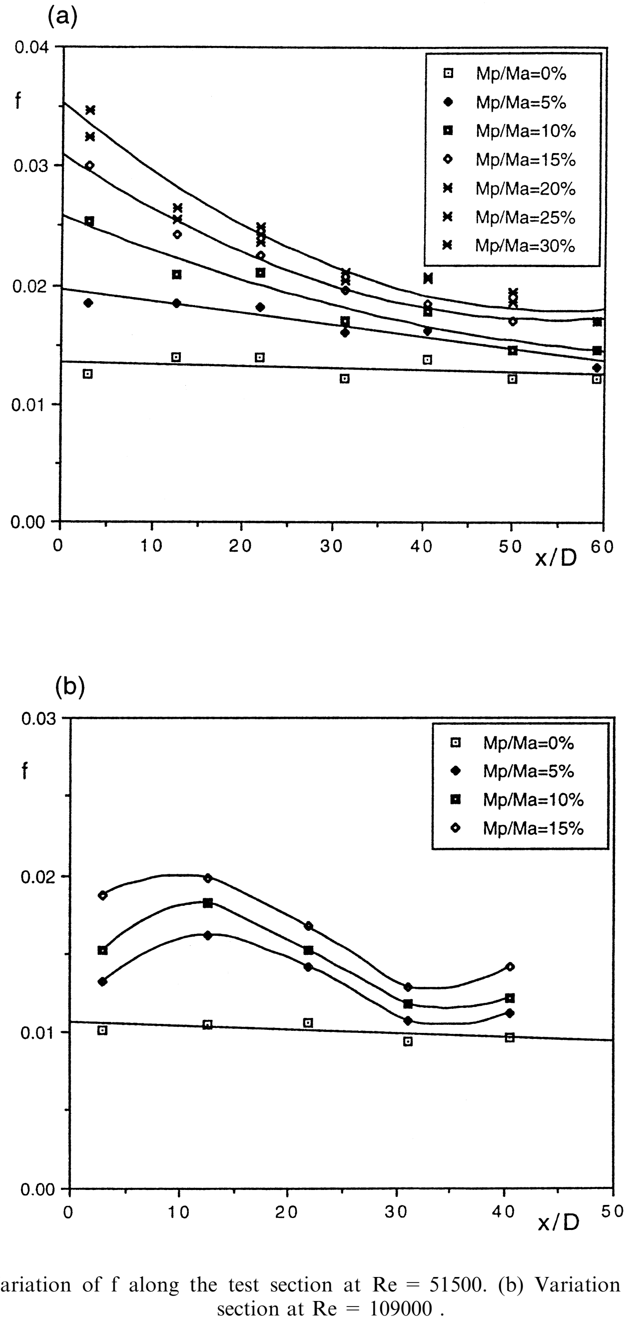

Figure 2. (a) Variation of f along the test section at Re = 51500. (b) Variation of f along the test section at Re = 109000 .

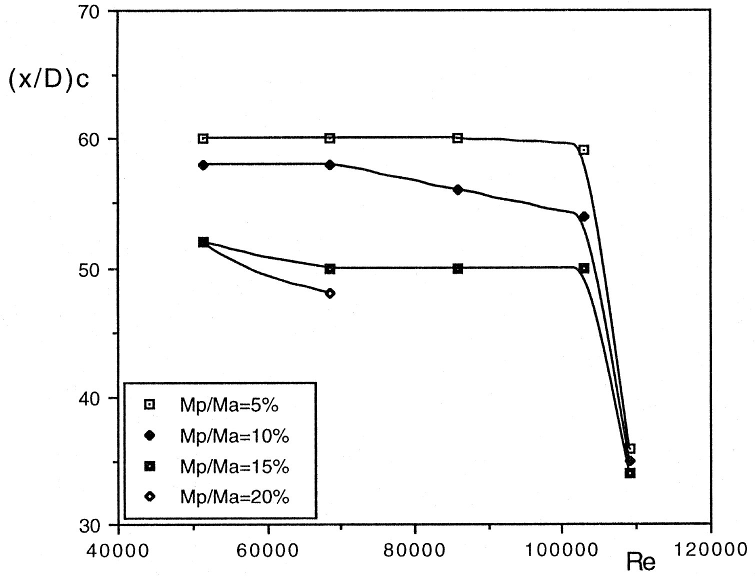

Figure 3. Variation of $(x/D)_c$ with Re.

variation with length, x, from the particle feeder pointing out the absence of an equilibrium reached in the flow field. In accordance with dP/dx measurements, the variation of the flow friction factor f with x/D was such that f_a in clean air did not vary while f_{p+a} in particulate flows had a gradual decrease with x/D along the test section as shown in the sample plots corresponding to Re = 51,500 and Re = 109,000 given in figure 2(a) and (b), respectively. Therefore, based on the behaviour of f_a with x/D, the development length of two-phase particulate flows can be estimated as a length specified by $(x/D)_c$ at which f_{p+a} ceases to decrease rather than taking a constant magnitude with increase in x/D further.

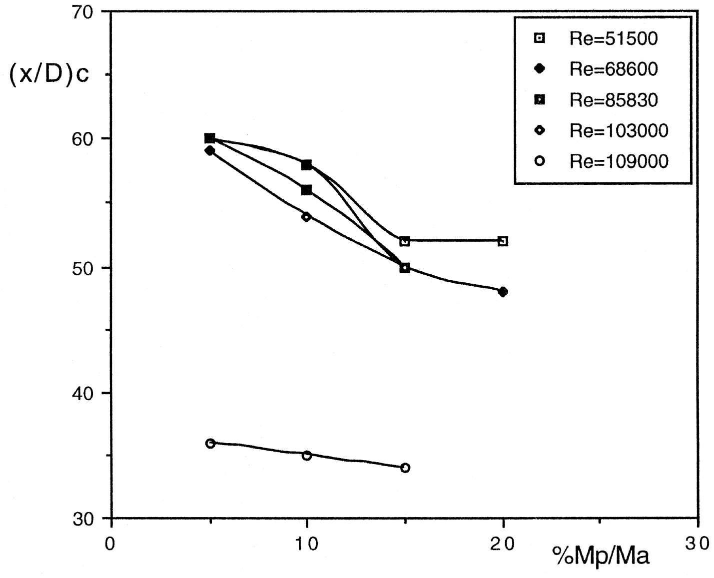

Figure 4. Variation of $(x/D)_c$ with % M_p/M_a.

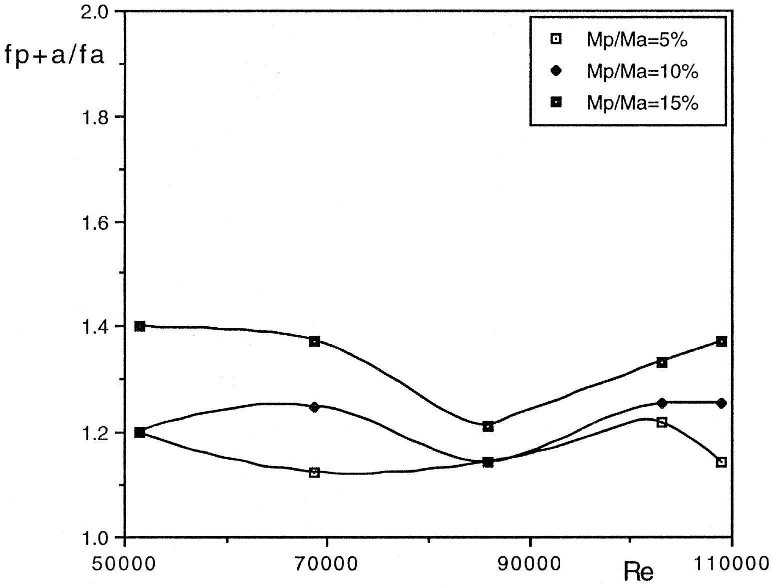

Figure 5. Variation of f_{p+a}/f_a at $(x/D)_c$ with Re.

A superficial analysis indicates that M_p/M_a does not have a strong influence on the extent of the development length, in contradiction to the predictions of Lodes and Mierka (1990), since the curves of f_{p+a} corresponding to different M_p/M_a reach their constant value at almost the same x/D. On the other hand, the increase in M_p/M_a is roughly associated with an increase in the magnitudes of local f_{p+a} values, particularly inside the development region $x/D < (x/D)_c$. However, as Re increases, the magnitudes of f_{p+a} corresponding to different M_p/M_a take closer values inside the development region.

Meanwhile the variation of f_{p+a} with x/D in $x/D < (x/D)_c$ seems to be influenced by M_p/M_a for Re < 109,000, sensed with the behaviour change of f_{p+a} curves from linear at $M_p/M_a = 5\%$ to polynomial for $M_p/M_a > 5\%$.

Furthermore, as can be seen from figure 2(a), the data corresponding to $M_p/M_a > 15\%$ are collapsing and a single curve sketched describes the variation of f_{p+a} with x/D for $M_p/M_a = 20\%$, $M_p/M_a = 25\%$ and $M_p/M_a = 30\%$. This observation implies that loadings with $M_p/M_a > 15\%$ do not cause considerable variation in f_{p+a} at Re = 51,500.

However, the variation of f_{p+a} with x/D corresponding to different particle loadings of air–solid particle suspensions for Re < 109,000 is somehow different from that for Re = 109,000 [figure 2(b)]. For Re < 109,000, f_{p+a} has its maximum at $x/D = 3$; the closest position to the particle feeder with a gradual reduction in magnitude with x/D. On the other hand, for Re = 109,000, f_{p+a} takes its maximum at $x/D = 12.5$. This may be either due to a local flow separation at $x/D = 3$ resulting in a decrease in f_{p+a} for Re = 109,000, or a special feature of flow at this speed.

In order to set the overall influence of Re and M_p/M_a on the development length, variations of $(x/D)_c$ with Re and M_p/M_a are given in figure 3figure 4, respectively. It is seen that, as Re increases, $(x/D)_c$ decreases drastically for Re > 103,000 for the covered M_p/M_a. For Re ≤ 103,000, $(x/D)_c$ does not vary much, taking values between 50 and 60. At Re = 109,000, $(x/D)_c$ is reduced to 35 independent of M_p/M_a.

For the covered cases, no drag reduction was observed since the magnitudes of f_{p+a} were greater than those of f_a in the development region. However, at $x/D > (x/D)_c$ the magnitudes of f_{p+a} indicate a trend of reaching the magnitude of f_a at least. Since the length of the test section was a serious restriction, $f_{p+a} < f_a$ could not be observed. Furthermore, the magnitudes of f_{p+a}/f_a at $(x/D)_c$ take almost constant values in the covered Re, as can be seen from figure 5, justifying the suggested approach for development length determination. Flow resistance in particulate flow is about 1.175, 1.2 and 1.325 of that in clean air, with $M_p/M_a = 5\%$, $M_p/M_a = 10\%$ and $M_p/M_a = 15\%$, respectively, increasing with M_p/M_a due to the drag of the induced particles. Therefore, it can be said that for drag reduction a homogeneous phase distribution should be maintained in the flow field, as was done in the cited investigations of the literature.

4. CONCLUSIONS

Based on the experimental data presented here, it can be said that the development length of two-phase particulate flows is a strong function of Re. As Re increases, the development length decreases. The critical value of Re causing a radical change in flow seems to be $\mathrm{Re} \geq 103{,}000$, since at Re = 109,000 $(x/D)_c$ is on the order of 35 independent of the loading ratio. The loading ratio itself seems not to have much influence on the extent of the development length. However, attainment of flow uniformity inside the development region is affected by both loading ratio and Re. The influence of particle shape and size should be considered in order to evaluate the applicability of the derived conclusions for more general particulate flows.

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