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Flow of aqueous suspensions of fine particles in diffusers

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Abstract

The flow of dilute aqueous suspensions of micron-size carbon black particles in diffusers was studied by visualization and by measurements of pressure drop. For particle concentrations from 0.1 to 1.0% by weight and for conical diffusers with half angles of 5 and 11°, the measurements show that pressure recovery was less than that for plain water. The reductions were of order 10% and increased with particle concentration. To understand this effect, the flow was visualized in a two-dimensional diffuser, using computed sonography because of liquid opacity. The sonographic images show that the flow separated earlier than it did with water, which explains the reduced pressure recovery. At the same time, it is not understood how such minute particles at such small concentrations affect flow separation. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Aqueous suspensions of fine particle; Diffusers; Pressure recovery; Flow visualization; Computed sonography

1. Introduction

Recent studies have demonstrated that the drag on a sphere or cylinder in an aqueous suspension of fine particles may be less than the drag for water alone. Watanabe et al. (1991, 1992) and Watanabe and Kui (1995) reported that the drag on a sphere in a dilute suspension of micron-size particles of carbon black or silica dioxide was up to 20% less than that in plain water, at Reynolds numbers in the range of 8×10^3 to 3×10^5. On the other hand, above $3 \times$

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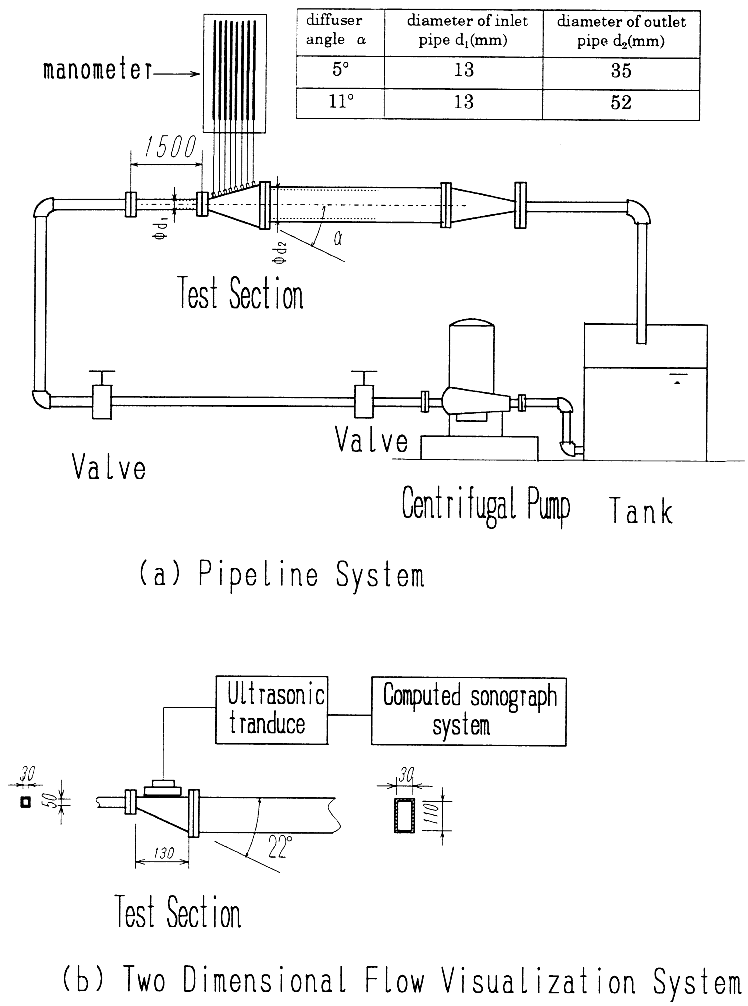
10^5, i.e., above the transition to turbulent flow in the boundary layer, the drag was increased by the particles. A similar reduction in drag was found for circular cylinders (Watanabe et al., 1996). The reduced drag is a remarkable hydrodynamic effect in light of the low particle concentrations: solid volume fractions were of the order of 0.001. In this concentration range, particles of carbon black or silica dioxide are not expected to affect the viscosity and measurements revealed that suspension viscosities were virtually the same as those of water, the difference being less than the measurement error of 2%. Because of these small differences and because of the high Reynolds numbers, the particles must have affected the inertial component of the flow, and the lower drag suggests that the particles influenced flow separation. But a direct examination of the separation zone was difficult because the fluids were opaque and the bodies were moving.



diffuser angle α	diameter of inlet pipe d_1(mm)	diameter of outlet pipe d_2(mm)
5°	13	35
11°	13	52

Fig. 1. Experimental system.

2. Experimental apparatus and method

2.1. The flow system

Fig. 1 shows the experimental system. Test fluids were circulated by a centrifugal pump through a loop, which included an open supply/collection tank. When the diffuser was a conical channel, it was preceded by a long (1.5 m) pipe with an inside diameter to match the inlet diameter of the diffusers (13 mm). The variation of pressure along a channel was monitored by a bank of eight manometer tubes, as illustrated. Two conical diffusers were used and their dimensions are given in Fig. 1. To ensure flow separation, each had a half angle (α) greater than 3.5°; specifically, the angles were 5 and 11°. To generate planar motion for visualizing the flow, the diffuser was a truncated half wedge, as illustrated in Fig. 1. It was made of clear plastic and had a half angle of 22°.

A computed sonography system was attached to the non-oblique wall of the half wedge, as shown in Fig. 1. Since the test fluids already contained particles, tracers were not needed. In this technique ultrasonic waves are sent into the flow by a sonographic probe and reflected by the solid particles. The reflected echo signals are processed by a computer system to create an image of the flow on the screen. The electronic equipment for the system is shown in schematic form in Fig. 2.

Flow in the half-wedge diffuser was designed to generate Reynolds numbers ranging from 1000 to 2000. In this way, the flow was initially laminar and therefore motion in the separation zone was steady and easily observed. In this work, the Reynolds number is defined as $Re = \rho\bar{v}D/\mu$, where $\bar{v}$ is the average velocity at the inlet of a diffuser, D is the diameter (or equivalent diameter) of the diffuser inlet, and ρ and μ are the density and viscosity of the test

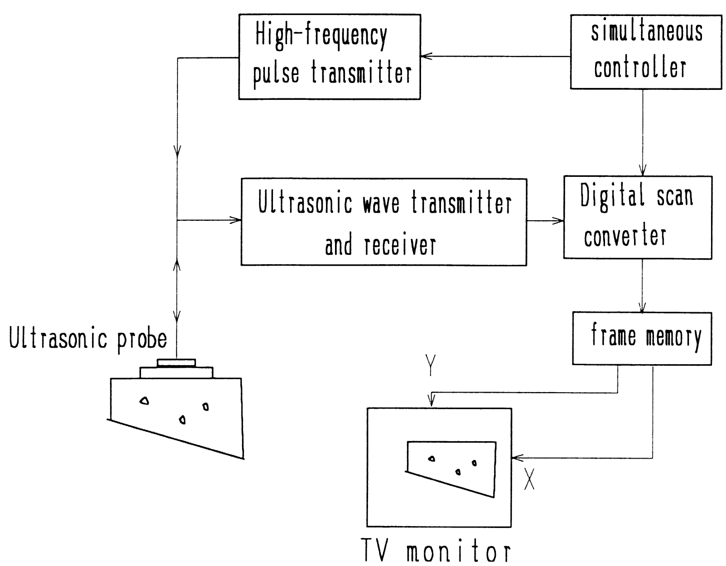


Fig. 2. Block diagram of the computed sonography system.

fluid. The velocity was determined from the flow rate, which was measured by weight collected over a known time. For the conical diffusers, the flow rates were much higher than those in the half-wedge diffuser in order to generate measurable pressure differences. The Reynolds numbers for that work were between 3.5×10^4 and 5.5×10^4.

2.2. The test fluids

The fluids were dilute suspensions of carbon black particles, the same fluids used in the prior work on spheres. These particles had a density of 1950 kg/m^3, and mean diameters were found to vary from 1.29 to 1.40 μm. Mean diameters were determined by measuring particle sizes from electron micrographs, and more than 100 particles were used in the calculation of a mean. Particle shape was not considered to be a factor in this work because, at solid volume fractions of order 0.001, near-spheres have the same hydrodynamic effects as spheres. Four carbon black suspensions were tested in the conical diffusers, and these had weight fractions of 0.1, 0.3, 0.5 and 1.0%, corresponding to solid volume fractions of 0.0005 to 0.005. Two of these fluids, the 0.1 and 0.5 wt% suspensions, were the test fluids in the flow visualization study. At these concentrations, suspension viscosities were not expected to be measurably different from the viscosity of the suspending medium, i.e., of water. As mentioned earlier, prior measurements (Watanabe et al., 1991) of these same fluids established that the viscosities were only a few percent higher than that for water, which is consistent with the known rheology of suspensions (Barnes et al., 1989). However, viscosity is not a factor here anyway. Because of the high Reynolds numbers, inertia dominates and the flow is not likely affected by small changes in viscosity.

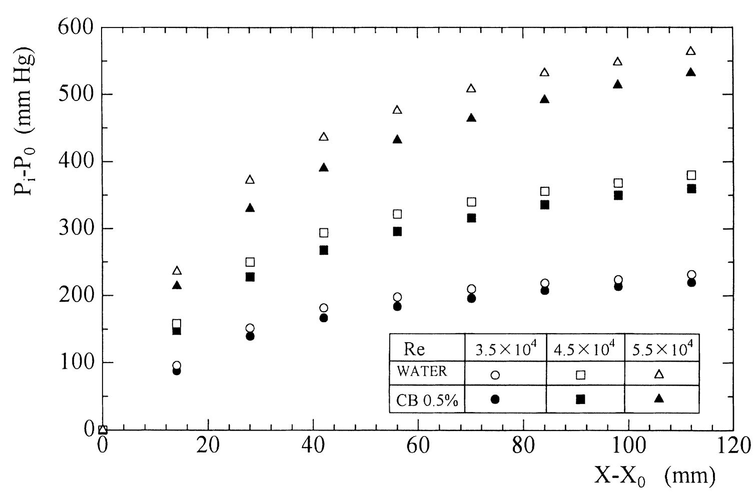


Fig. 3. Comparison of the pressure profiles of tap water and the 0.5% carbon black suspension in the 5° conical diffuser. P_i is the pressure at the ith location in the diffuser (8 locations in all), P_0 is an upstream reference pressure and $X - X_0$ is the distance along the diffuser, from its entrance.

3. Results

3.1. Pressure profiles

Measurements of pressure along the conical channels are reported first to establish that flow in a diffuser can be affected by tiny particles, as we expected. Fig. 3 presents direct measurements for a typical case, the 0.5 wt% suspension in the 5° diffuser. The ordinate is the pressure recovery, defined as $P_i - P_0$, where P_i is the pressure at the ith location in the diffuser (i = 1–8), P_0 is an upstream reference pressure. In the abscissa, X is the axial distance from the extended vertex of diffuser, and X_0 is the distance from the vertex to the entrance. Data are presented for three flow rates (in terms of Reynolds numbers), and the corresponding data for water are given as well. The graph shows that pressure recovery was less for the suspension than for water alone, and increasingly so as the flow rate increased. The reduced pressure recovery with particles suggests that the flow separated earlier in the diffuser.

3.2. Pressure recovery coefficient

The same data are presented in dimensionless form in Fig. 4, along with data for the 11° diffuser. The ordinate is the pressure recovery coefficient, which is the dimensionless quantity normally used in such flows and which is defined as $C_p = \frac{P_i - P_0}{1/2\rho v^2}$. The abscissa is the area ratio $R = S_i/S_0$, where S_i is the cross-sectional area at the ith pressure tap and S_0 is the area at the inlet. R was chosen as the dimensionless axial distance because C_p can be expressed in terms of R for an ideal (inviscid) flow which does not separate, i.e., $C_p = 1 - 1/R^2$. By expressing the results in terms of C_p, the 5° data in Fig. 4 are almost collapsed, which is expected because the Reynolds numbers are of order 10^4. Also shown in the graph are data for the wider-angle

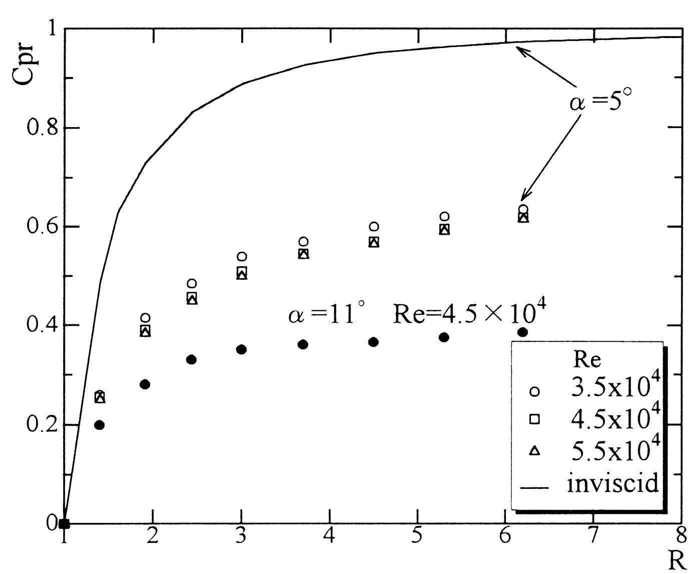
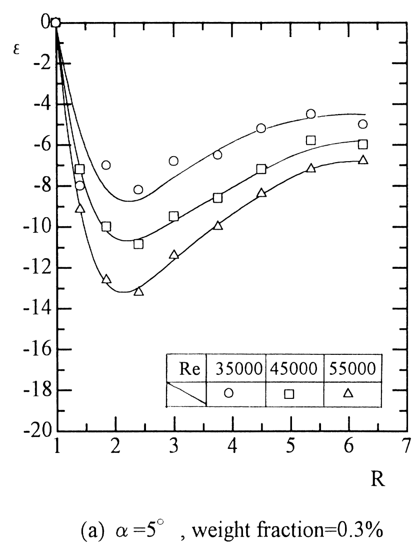


Fig. 4. Relationship between the pressure recovery coefficient C_{pr} and R for a carbon black suspension ($C_w = 0.5\%$).

diffuser ($\alpha = 11°$), as well as the curve for an ideal fluid. With the wider angle, it is expected that less pressure is recovered and the data confirm this expectation.

Particle effects can be seen more clearly if differences between the results for water and the suspensions are presented. To this end, let ε designate the percentage change in the pressure recovery coefficient, defined as $\varepsilon = \frac{C_p - C_{p0}}{C_{p0}} \times 100\%$, where C_{p0} is the pressure recovery coefficient for water. The pressure measurements are presented in this form to illustrate, in Fig. 5, the effect of Reynolds numbers and, in Fig. 6, the effect of particle concentration, for the two half angles respectively. The figures show that the pressure coefficient can be reduced by as much as 13% and that the reduction is more extensive in 11° cone. The influence of Reynolds number, shown in Fig. 5, is surprisingly strong when one considers that the particles are micron-sized and that the flow is dominated by inertia. The graphs of Fig. 6 show that the largest changes in pressure recovery occur with the intermediate concentration, 0.5 wt%, i.e., the maximum effect occurs at a solid volume fraction of about 0.0025. This latter result deepens the mystery as to how the particles affect the flow because, whatever the mechanics, one expects the hydrodynamic effect to increase with concentration in the dilute regime, in the same way that the viscosity increases in that regime. Indeed, because the viscosity is known to increase linearly with concentration for solid volume fractions up to about 0.1, one expects a similar increase for any other hydrodynamic effect. One does not expect the effect to saturate when the solid volume fraction is only 0.0025. The behavior is consistent, however, with the prior results for spheres; the data in Watanabe et al. (1991) show that drag reduction was a maximum for a concentration between 0.5 and 1.0 wt%, for carbon black particles.

Visualization using the computed sonography system confirmed that the particles caused early separation. Figs. 7 and 8 illustrate images obtained by the system for water and the 0.1 wt% suspension. With water, tracer particles had to be added and these were 12-μm metallic



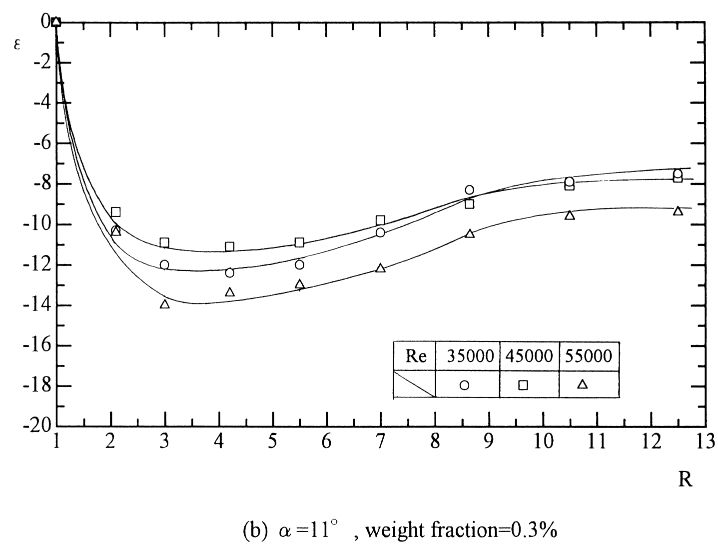
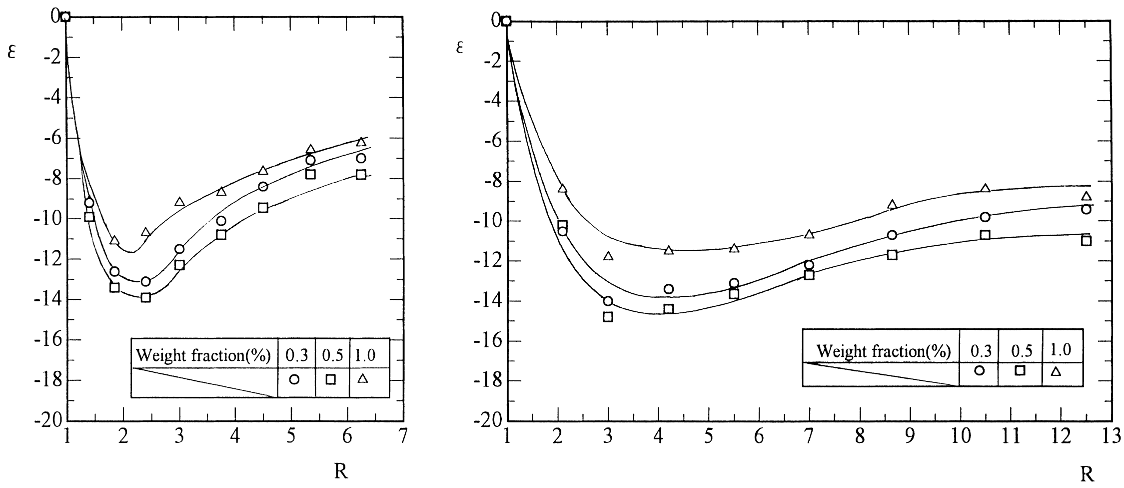


Fig. 5. Relationship between ε and R for a carbon black suspension in the conical diffusers — effects of Reynolds number.



(a) $\alpha=5°$, Re=5.5×10^4

(b) $\alpha=11°$, Re=5.5×10^4

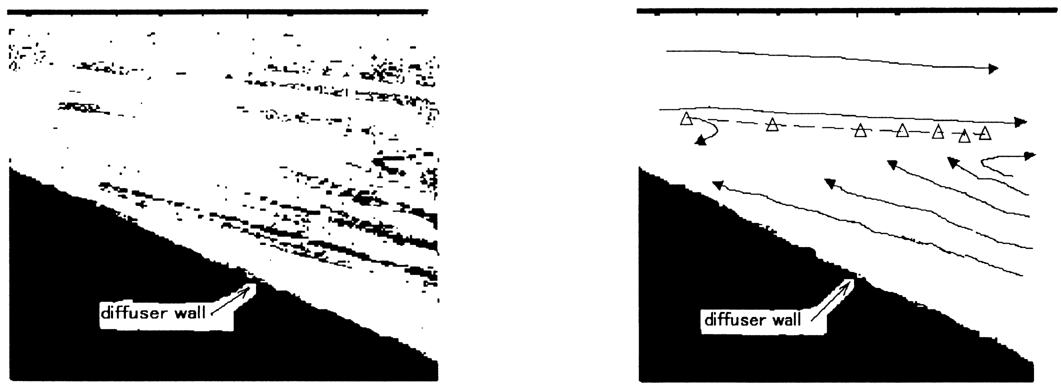
Fig. 6. Relationship between ε and R for a carbon black suspension in the conical diffusers — effects of particle concentration.

coated particles at a weight concentration of 3.2×10^{-3} kg/m^3, which translates to weight concentration of 0.0003 wt%. This value is so far below the minimum carbon black concentration of 0.1 wt% that the tracer particles did not likely affect the flow of water. The first image in Figs. 7 and 8 is a photograph obtained by superposing at least 30 video pictures. The streaks in each photograph were used to construct the streamline pattern, which is the second image of each figure. In each second image, the dividing streamline is shown by a dashed line.

(a) Superposed photograph of 32 images

(b) Particle traces

Fig. 7. Flow visualization photographs of water in the asymmetric diffuser (Reynolds number = 2000).



(a) Superposed photograph of 42 images

(b) Particle traces

Fig. 8. Flow visualization photographs of the 0.1 wt% carbon black suspension in the asymmetric diffuser (Reynolds number = 2000).

Points on the separation streamlines are plotted in Fig. 9, for several particle concentrations and for two Reynolds numbers. In these plots, X is the distance along the upper (non-oblique) wall and Y is the distance perpendicular to that wall. To show the separation streamline clearly, the perpendicular scale is magnified and hence the lower (oblique) wall appears much steeper than its actual 22°. As shown in Fig. 9, curves were fitted through the data points and extrapolated to the wall to identify the points of separation. The plots clearly show that the suspensions separated earlier than water, as anticipated. Furthermore, the 0.5 wt% suspension separated earlier than the 0.1 wt% suspension, consistent with the pressure recovery results in Figs. 5 and 6. Fig. 9 also shows the effect of Reynolds number, which are 1000 and 2000, respectively. As expected, flows at the higher Reynolds number separated earlier, for all three fluids.

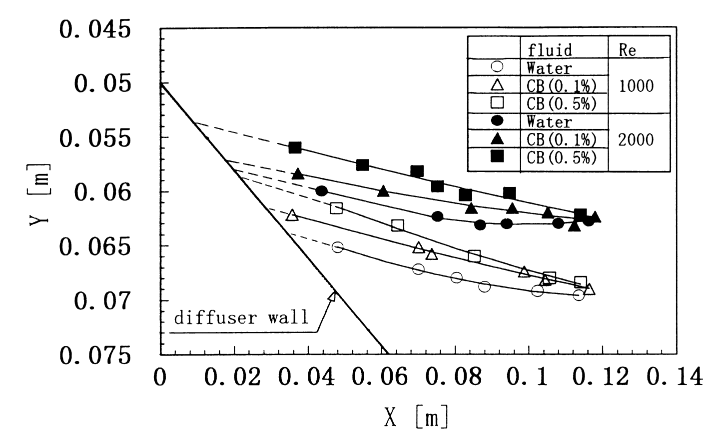


Fig. 9. Separation locations of several test fluids in the asymmetric diffuser.

The separation results are summarized in Fig. 10, in which the distance to the separation point, X_s, is made dimensionless by the length of the diffuser channel, taken along the oblique wall. The graph reinforces how the separation point moves upstream with Reynolds number and with particle concentration.

Fig. 11 shows values of ε for the other diffuser, the half-wedge diffuser, for Reynolds numbers of 1000 and 2000. The results are similar to those for the conical diffusers; numerically they are somewhat larger, perhaps because the entering flow was laminar in the half-wedge case.

4. Discussion and conclusion

The present experiment demonstrates that carbon black particles can cause early flow separation in a diffuser and thus decrease the recovery of pressure. The data show that the particles had a maximum effect at a concentration around 0.5 wt%. At this concentration level, it is remarkable that the particles had any effect at all. Since the particles did not change the viscosity in a significant way, one has to consider other mechanisms. One possibility is that the particles had a roughness effect similar to surface. That is, when particles are attached to a surface to create roughness elements, they can influence flow separation and the transition to turbulence. Classic work by Fage and Warsap (1930), as reported in Schlichting (1968), shows that the drag on a circular cylinders is affected when the size of roughness elements is $O(10^{-3})$ of the cylinder diameter. Their graph (Schlichting, 1968, p. 622) shows that when the Reynolds number is below about 3×10^5, i.e., before transition to turbulence takes place in the boundary layer, roughness elements cause early transition and hence later separation and lower drag. When the Reynolds number is above 3×10^5 and the boundary layer flow is turbulent, the elements cause early separation instead and so the drag is higher. The prior work by Watanabe et al. (1991) shows that small suspended particles can have exactly the same effect: lower drag

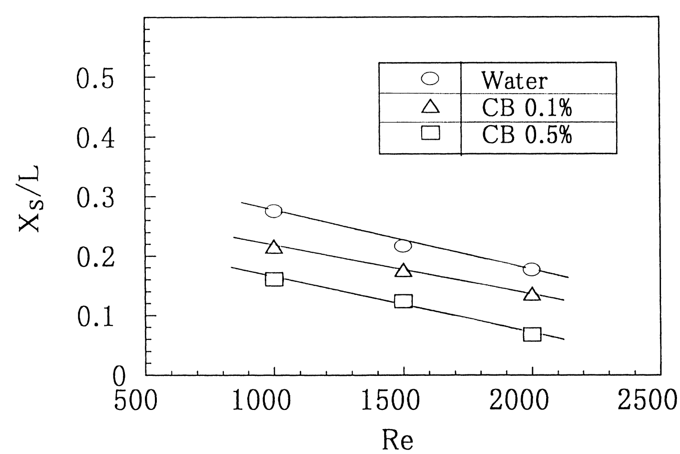


Fig. 10. Dependence of the separation location on the Reynolds number for the asymmetric diffuser.

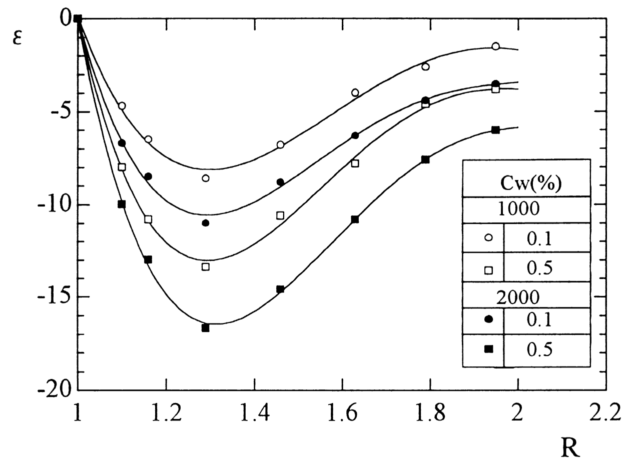


Fig. 11. Relationship between ε and R for carbon black suspensions in the asymmetric diffuser, at a Reynolds number of 1000 and 2000.

before transition and higher drag after. Hence suspended particles can affect the flow in the same way as attached particles.

Another classical work which is relevant is the study of roughness and transition in boundary layer flow on a flat plate (Dryden, 1953, also reported in Schlichting, 1968). Data collected by Dryden (Schlichting, 1968, p. 513) show that transition to turbulence occurs early when the roughness size is of order of the displacement thickness of the boundary layer. This size criterion is the same as that in the studies of Fage and Warsap (1930), where the relative roughness size was of order 10^{-3}. That is, the Reynolds numbers in their cylinder flows were of order 10^5, and, since the boundary layer thickness on a cylinder is of order, $Re^{1/2}$ the relative boundary layer thickness was of order $10^{-5/2}$ and therefore comparable with the relative roughness size of 10^{-3}. Hence, classical work is consistent in showing that boundary layer flow is affected by surface roughness when the irregularities are the size of the boundary layer thickness.

But the particles in the present work were one micron in size and the thickness of the boundary layer in the diffusers was approximately 1/10 of the 13 mm inlet diameter, or about 1 mm. Hence the particles were two or three orders of magnitude below the size known to influence the flow. Furthermore, the particles in the present work were not fixed to the surface but rolled along it, and their effect would be even smaller on that account.

Another mechanism that may be related to the present findings is particle migration. Particle movement across streamlines and away from a wall may be caused by particle interactions or by inertial effects. Interaction-caused migration has been an active research topic recently and a good reference is the seminal paper by Leighton and Acrivos (1987). This type of migration occurs with concentrated suspensions; in the referenced paper and in other such work, solid volume fractions are in the range of 0.1 to 0.5. The fractions in the present work, however, range from 0.0005 to 0.005, and so migration due to particle interactions is negligible in our work. For suspensions as dilute as ours, inertial-driven migration may be relevant. Considerable research on this topic was carried before 1980 and Leal's (1980) review is a good summary of both the mechanics and the work up to that point. Studies of inertial-driven migration have focussed on particle motion in well-defined flow fields with zero or positive pressure gradients. No studies have been carried out in adverse gradients, as occur in our diffusers. Furthermore, prior studies have focussed on the effect of the flow field on a particle, and not on the effect of particles on the flow field. Hence, there is little information to suggest how drifting of widely-spaced minute particles might affect an inertial phenomenon like separation. The best one that can do is to find the order of magnitude of the migration velocity, relative to the local flow velocity. That ratio is of the order of the local Reynolds number (Leal, 1980), which depends on the particle size and local shear rate. The shear rate in a separation zone is difficult to estimate, but it is likely no more than 10^3 s^{-1}. Hence, for micron-size particles in water, the maximum Reynolds number and therefore the maximum relative velocity is of order 10^{-3}. Since there are very few particles in our suspensions, the migration effect is minuscule.

In trying to relate past studies to the present work, it must be remembered that little is known about flow separation on the scale of interest. The present particles are 1/1000 of the thickness of the boundary layer, and there appear to be no studies of separating flow on that scale, with or without particles. Once details of the flow field are known at that micro-scale, the present results may become less mysterious.

Acknowledgements

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