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Transport in the near aerodynamic wakes of flat plates

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An experimental investigation has been carried out into the nature of the transport of airborne material in the near aerodynamic wakes of bluff bodies with simple shapes. The main attention was focused on the essential differences existing between axisymmetric flows (as about disks) and two-dimensional flows (as about rectangular long thin flat plates). Measurements were made for such bodies of the near-wake residence time of injected small particles, along with other and more familiar near-wake properties such as the vortex-shedding frequency and base pressure. It was concluded for disks that the transport of material into and out of the near-wake region is dominated by turbulent diffusion, and is strongly influenced by free-stream turbulence, especially for free-stream turbulence whose length scale is substantially smaller than the disk diameter. For rectangular flat plates, transport is dominated by the periodic shedding of vortices, and to only a secondary extent by turbulent motions, and is not strongly influenced by free-stream turbulence.

1. Introduction

A number of papers have recently been published on the subject of the transport of suspended airborne material in the near aerodynamic wakes of bluff bodies (Humphries & Vincent 1976*a*, *b*, *c*, 1978). The overall aims of the research programme were concerned in one way or another with air pollution, either with dust-control devices such as electrostatic precipitators (Vincent 1977*a*) or with the transport and build-up of atmospheric pollution near buildings (Vincent 1977*b*, 1978). However, the flow configurations investigated for the most part were simple, chosen to enable the development of a basic physical framework for the subsequent understanding of more-complicated systems. So far, most have been flows that could be described as axisymmetric; for example about disks, square plates and triangular plates, in smooth and turbulent air streams. Some work was also carried out with surface-mounted cubes.

The common predominant feature of the near-wake flows just described is the *cavity*, the separated near-wake zone of recirculating fluid. A simplistic, but workable, view is that airborne material from the free stream can enter or leave this cavity by turbulent diffusion. In certain cases (e.g. surface-mounted cubes) coherent swirling motions can also contribute significantly to this transport. A physically meaningful

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quantity for describing the transport of airborne material into and out of the near-wake cavity is the dimensionless *residence-time parameter* H ($\equiv Ut_{\mathrm{R}}/D$, where t_{R} is the characteristic residence time, U the free-stream air velocity and D the characteristic bluff-body diameter). Experiments were carried out in which light-extinction apparatus was used to monitor tracer smoke trapped inside the near-wake cavity and to allow determination of the time constant of the exponential decay (equivalent to the mean residence time, t_{R}) of the amount of smoke trapped during the period following abrupt removal of the source of smoke. The *residence*-time concept is thus similar to that which featured previously in theories and experiments relating to bluff-body flame stabilizers (Bovina 1959; Winterfield 1965). For disks and other simple axisymmetrically shaped bodies, H was found to be independent of the body Reynolds number R ($\equiv UD$/kinematic viscosity) for $R > 2000$. Measurements were also made of base-pressure coefficient $C_{p\mathrm{b}}$, cavity-length parameter X/D (where X is the cavity length), and cavity-shape parameter f_1 (the non-dimensionalized ratio of cavity volume to surface area); these quantities displayed similar characteristics. The introduction of grid-induced free-stream turbulence was found to have a strong effect on each of H, $C_{p\mathrm{b}}$, X/D and f_1. For conditions where the integral length scale l_{f} of the free-stream turbulence was always substantially less than the bluff-body size, all of these quantities were found to be unique functions of the free-stream turbulence parameter Λ_{f} ($\equiv k_{\mathrm{f}}^{\frac{1}{2}} l_{\mathrm{f}}/UD$, where k_{f} is the kinetic energy of free-stream turbulence). This is consistent with the flow model that was proposed. The model goes on to suggest that there should be unique and relatively simple relationships between H, $C_{p\mathrm{b}}$, X/D and f_1 for each shape of bluff body; this was also borne out by the experimental results. In relating the results for one body shape to those for another, it was found necessary to introduce one other quantity in order to complete the similarity picture of the near wake; namely *bluffness*, as characterized by the front-face pressure coefficient $C_{p\mathrm{f}}$. For the simple bluff bodies in question, it was concluded that the wake cavity can be regarded as a closed volume with no mean flow by which material can enter or leave it; thus the transport of material into and out of the cavity can only be by turbulent diffusion.

The first part of this paper describes new experiments that set out to further investigate the interaction between a turbulent free stream and the near wake of a simple axisymmetric bluff body. The second part follows on to describe how the work has been extended to include simple flow configurations that are essentially two-dimensional (as opposed to axisymmetric); for example long flat plates. Here the character of the near-wake flow is very different from that that we have so far been discussing, being dominated much more by the periodic shedding of vortices. Although the phenomenon of vortex shedding in the fluid-dynamical wakes of bluff bodies has been the subject of extensive theoretical and experimental investigations for the 100 years since it was first reported by Strouhal (1878), it is still far from being completely understood. An important quantity which must be introduced for describing such flows, one which it was not found necessary to invoke during the earlier work on axisymmetric flows, is the Strouhal number, S ($\equiv Df_{\mathrm{s}}/U$, where f_{s} is the vortex-shedding frequency). We have set out to investigate how our earlier ideas on the *residence-time* concept need to be modified when such flows are being considered.

Bar width b (cm)	1	2·5	4	5·5
Mesh size, M (cm)	4·5	10	17	19
Blockage ratio	0·40	0·44	0·42	0·49
Working distance from screen x (cm)	50–160	100–160	160	160

TABLE 1. Description of screens for turbulent generation

2. Experimental apparatus and techniques

The experiments were carried out in an open-cycle, low-speed, low-turbulence wind tunnel with working cross-section 1×1 m. The required range of turbulent free-stream conditions was obtained by means of rectangular lattice-type screens placed across the inlet to the working section. The relevant screen data are given in table 1. According to Baines & Peterson (1950), stable and reasonably well-established turbulent flow conditions may be obtained, provided that the screen blockage does not exceed 50 % and at a working distance from the screen of at least five mesh sizes. Our experimental arrangement was chosen to satisfy these requirements. The experimental data of Baines & Peterson were used to allow determination of the intensity and length scale of the turbulence thus generated at various distances downstream from each screen. These are adequately represented by the empirical relations

$$\frac{u'}{U} = 1{\cdot}12\left(\frac{x}{b}\right)^{-0{\cdot}71}, \tag{1}$$

$$\frac{l_y}{b} = 0{\cdot}114\left(\frac{x}{b}\right)^{0{\cdot}46}, \tag{2}$$

where u' is the root mean square of the instantaneous velocity fluctuations along the axis of the tunnel, l_y the length scale of turbulence perpendicular to the axis of the tunnel, b the screen bar width, and x the working distance downstream from the screen. It is encouraging that these data are in good agreement with those obtained independently elsewhere at around the same time (Dryden *et al.* 1947). In the absence of appropriate instrumentation for accurately measuring the required turbulence properties ourselves, they were considered as acceptable alternatives for the purposes of the present paper.

The disks used in the first part of the investigation were each made from aluminium, with diameters 2, 5, 10 and 15 cm respectively, and with 30° bevelled edges. These were suspended in turn in the working section by thin piano wires and placed at normal incidence to the air flow (bevelled edge facing downstream).

The long plates used in the second part of the investigation were also made from aluminium, of widths 3, 4, 5, 7 and 10 cm respectively, and again with 30° bevelled edges. These were mounted at normal incidence to the air flow and, unless otherwise stated, across the width of the tunnel. In order to allow control of the effective plate aspect ratio (length to width Δ) each plate carried Perspex end plates as recommended by Cowdrey (1962) to minimize the introduction of three-dimensional effects due to end leakages. These end plates were capable of sliding along the aluminium plates so that Δ could be varied in the range 5–18.

The experimental apparatus and techniques used for determining the near-wake residence-time parameter H, base-pressure coefficient C_{p_b}, and wake cavity-shape parameter f_1 have been described in detail elsewhere (Humphries & Vincent 1976*a*, *b*). In the long-plate experiments, the vortex-shedding frequency was measured by monitoring, by means of a static pressure probe mounted just outside the near-wake region, the pressure 'ripples' caused by the shedding of the vortices. It should be noted that the frequency thus obtained is in fact the frequency of vortex shedding *from one side only.*

3. Near-wake flows of disks

3.1. *Physical background*

The main features of the near-wake flow of air behind a flat disk have been discussed in earlier papers (Humphries & Vincent 1976*a*, *b*). The mean flow of the fluid can be represented by a streamline pattern, the main feature of which is the limiting closed streamline that separates the mainstream external flow from the recirculating base flow. This limiting streamline is referred to as the *cavity boundary.* Although there is evidence that the disk sheds loops of vorticity at fairly regular intervals (Fail, Lawford & Eyre 1959), this cavity may be regarded for present purposes as stable. Therefore it is a fair working hypothesis to assume that the transport of fluid into and out of the cavity across this boundary takes place predominantly by the random motions associated with turbulent diffusion. The same is basically true for airborne scalar entities such as solid particles, although their individual motions might differ from that of local air packets owing to their inertia (Humphries & Vincent 1978). However, in this paper we shall be concerned only with small, virtually inertialess, particles, and these will reflect the transport of the air itself.

If it is now assumed that the wake cavity contains N particles at time $t = 0$, whereupon the source of their supply is abruptly cut off, the number of particles trapped inside the cavity subsequently decays with time as particles are transported across the cavity boundary by turbulent diffusion. This decay should be an exponential function whose time constant is the characteristic residence time t_R referred to previously. This leads to the expression for the dimensionless residence time parameter

$$H \equiv \frac{Ut_R}{D} = f_1 f_2/\Lambda_c, \tag{3}$$

where Λ_c is the characteristic *near-wake* turbulence parameter ($= k_c^{\frac{1}{2}} l_c/UD$, where k_c and l_c are characteristic near-wake values of the turbulence quantities in question averaged over the cavity surface), f_1 the dimensionless shape factor for the cavity, and f_2 a dimensionless quantity relating to the distance a particle must be carried by turbulent motion across the cavity boundary before it can be considered as having escaped.

In common with other properties of axisymmetric bluff-body flows, H was found by Humphries & Vincent (1976*b*) to be a unique, but weak, function of R for $R > 2000$. It was argued that when there is free-stream turbulence, f_1, f_2 and Λ_c (and hence H itself) are all functions of the *free-stream* turbulence parameter, Λ_f ($= k_f^{\frac{1}{2}} l_f/UD$, where k_f and l_f are the properties of the free-stream turbulence). This assumes that the integral length scale of the free-stream turbulence is substantially smaller than the size of the disk, and that the mean period of the fluctuations in the turbulent free stream is small compared with the time associated with the mean-flow distortion. It says nothing about the distortion of the free-stream turbulence due to the presence of the bluff body as described by Hunt (1973). Thus we can write

$$H(\Lambda_f) = f_1(\Lambda_f)f_2(\Lambda_f)/\Lambda_c(\Lambda_f). \tag{4}$$

The two quantities Λ_c and Λ_f are effectively dimensionless turbulent diffusion coefficients for the near wake and the free stream respectively. Their interrelationship is closely bound up with the physical nature of the interaction that takes place between the free stream and the shear layers of the near wake.

In (4), the quantities H and f_1 can be measured for a given particular set of experimental conditions. The quantity f_2 is much more difficult to assess. We would expect its lower limit to be the length scale of the turbulence in the shear layers around the wake-cavity boundary, and its upper limit the thickness of the shear layer, but it cannot be measured directly and so must be assessed qualitatively. By analogy with classical diffusion theory, we can argue that f_2 is comparable with the mean excursion (due to random motions) from some axis, and so should be a function of the product of the coefficient of diffusion and time. In the present case, the time in question is proportional to the length of the wake cavity. So f_2 should vary with the product of Λ_c and X/D. As the level of free-stream turbulence (as reflected by Λ_f) increases, we know that Λ_c increases but that X/D decreases. Therefore f_2 should vary relatively weakly with Λ_f. So we may estimate the variation of Λ_c as a function of Λ_f from

$$\Lambda_c \propto f_1(\Lambda_f)/H(\Lambda_f), \tag{5}$$

and experimental measurements of f_1 and H.

When the scale of free-stream turbulence substantially exceeds the thickness of the free shear layer, then velocity fluctuations are correlated over a substantial part of the near wake and the turbulence appears to the disk as an unsteady mean flow. Insofar as this could effect the shedding of vorticity, then this could influence the residence time. However, it is reasonable to expect that any such variation would not necessarily follow the simple diffusion model we have proposed for the situation where l_f is substantially less than D. Previous measurements of H and f_1 by Humphries & Vincent (1976*b*) *were* carried out only for conditions where l_f was substantially smaller than D. In the present paper we present results for a wider range of conditions, including some where $l_f > D$.

3.2. *Results and discussion*

Measurements were made of the residence-time parameter H and of the wake-cavity shape parameter f_1 for a range of free-stream turbulence intensities and length scales, using disks of diameters 2, 5, 10 and 15 cm respectively, and techniques that have been fully described elsewhere (Humphries & Vincent 1976*b*). Reynolds number was in the range 3000–30000. The ratio f_1/H (proportional to Λ_c) is plotted as a function of the free-stream turbulence parameter (Λ_f) in figure 1. Each value of H is that obtained from the average of 20 separate measurements, and the error bars shown are indicative of the typical accuracy with which the physical quantities in question

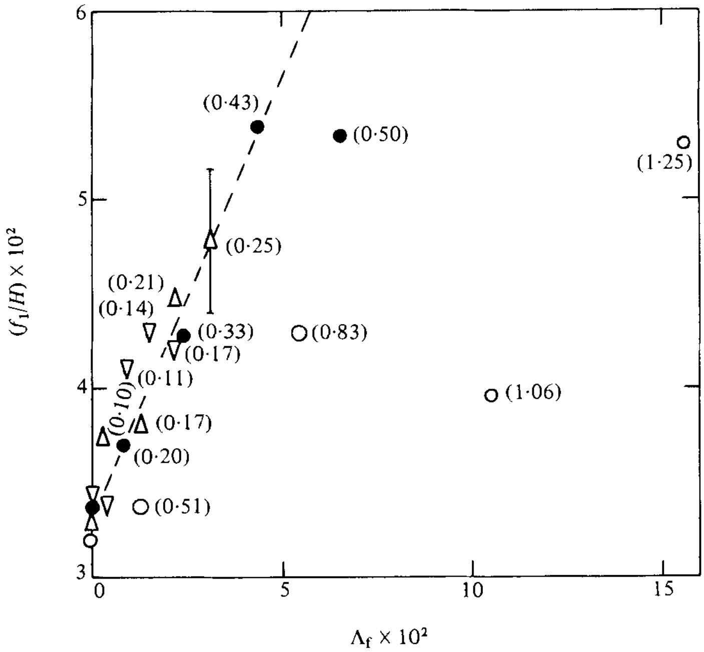

FIGURE 1. f_1/H as a function of Λ_f for disks in turbulent flow (the figures in brackets indicate l_f/D). ○, $D = 2$ cm; ●, 5 cm; △, 10 cm; ▽, 15 cm.

could actually be measured. The figures in brackets beside each point indicate the ratio of the length scale of the free-stream turbulence to the disk diameter (l_f/D). The most important single trend is that Λ_c increases with Λ_f, an expected result since free-stream turbulence increases mixing by reinforcing the existing shear-layer turbulence. For $l_f/D < 0{\cdot}50$, the data plotted in this way show a reasonable collapse (within experimental error), supporting our earlier statement that Λ_c should vary uniquely with Λ_f. Furthermore, the relationship between the two turbulence parameters appears to be roughly linear. It is also seen from figure 1 when $l_f/D > 0{\cdot}50$ that f_1/H (and therefore Λ_c) is obviously no longer uniquely dependent on Λ_f. This result might be expected from the arguments expressed earlier.

In the part of the study just described, useful further experimental information has been obtained about the effect of free-stream turbulence on the near-wake flow about a disk, broadly consistent with qualitative physical explanations. While it may be tempting to draw the conclusion that the observations suggest a simple explanation for the nature of the interaction between the turbulent free stream and the near wake, we follow the advice of Bradshaw (1974), who warned against the use of over-simple arguments in incorporating free-stream turbulence effects in calculation methods. It is fair to say, however, that the experiments have not yet allowed much illumination of the actual detailed processes which take place.

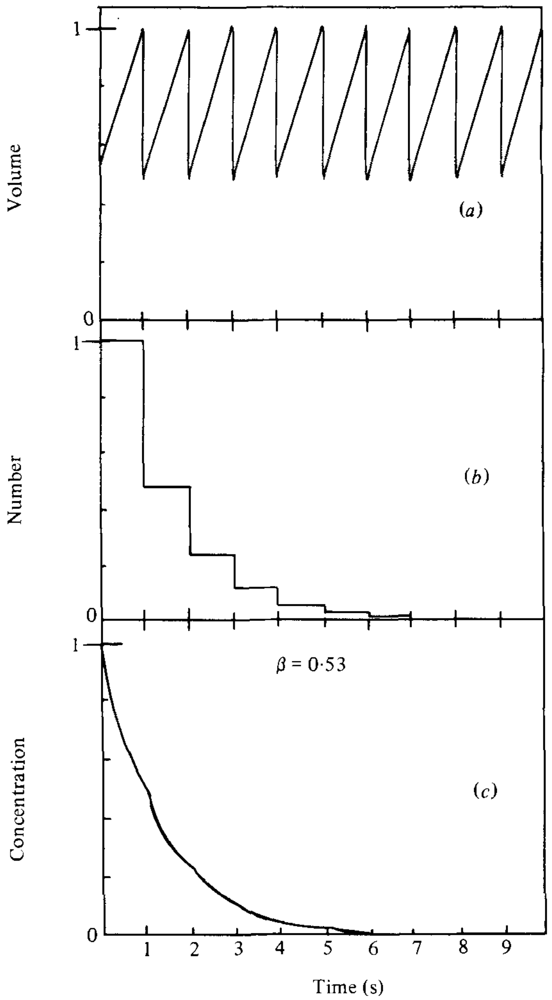

FIGURE 2. Model for the loss of particles from the near-wake regions of long flat plates predominantly by vortex shedding. It shows (*a*) the effective volume of the near-wake entrapment region, (*b*) the number of particles effectively trapped, and (*c*) the particle concentration, all as functions of time.

4. Near-wake flow of ractangular flat plates

4.1. *Physical background*

In the case of the disk and other axisymmetric bluff bodies, the predominant mechanism for transport of airborne particles into and out of the base region of the near wake is turbulent diffusion. The situation in the case of two-dimensional flow about a long flat plate is very different, however; while turbulent diffusion still plays a role, especially in helping to maintain a homogeneous spatial distribution of particles trapped in the near-wake region, predominance now shifts to vortex shedding.

The phenomenon of vortex shedding itself has been extensively documented elsewhere, so does not require detailed description here. It is sufficient to say, for the present purposes of discussing the near-wake transport of airborne particles, that the idea of a closed wake cavity (as invoked for the disk) is not a satisfactory working hypothesis for two-dimensional flows. A simple model may be constructed to describe the transport of airborne particles into and out of the near wake of a long flat plate, where it is assumed that the main gain process is associated with the formation of each new vortex, the main loss process is associated with the shedding of that vortex, and turbulence acts to continually mix and remix the trapped particles. It is assumed that the net rate of particle entrainment into the near-wake entrapment region is constant with time, and that the volume of air contained in it oscillates during the vortex-shedding cycle between a fixed maximum (just prior to the shedding of a vortex) and a fixed minimum (just afterwards). This implies, quite reasonably, that the volume of air carried away with a shedding vortex is always the same. Figure 2(*a*) shows how the effective near-wake entrapment region varies with time during a number of vortex-shedding cycles. Next it is assumed that the region is filled with Q particles at time $t = 0$, whereupon their source of supply is abruptly removed. Particles can only escape from the region when a vortex is shed. If it is further assumed that the turbulent mixing is at least adequate to distribute the particles evenly throughout the region between shedding events, then the fraction of trapped particles lost at each event will be the same as the fraction of the air in the region which is carried away with the shedding vortex, say β. Thus the number of trapped particles will decay with time as shown in figure 2(*b*). The actual concentration of trapped particles, as would be measured for example by the light-extinction apparatus already described, is equal to their number divided by the volume of the entrapment region. Consequently, the variation of particle concentration with time is as shown in figure 2(*c*). This hypothetical curve has an envelope that is exponential and, interestingly, does not exhibit any strong periodic component which might be associated with the vortex shedding.

The time constant of the envelope of the decay curve in figure 2(*c*) is determined by β and f_S, although not in a simple way which can be expressed analytically owing to the discontinuous nature of the loss process. However, bearing in mind that

$$HS = t_R f_S, \tag{6}$$

we can, for given conditions, choose a value of β which, after numerical calculation, gives a value of HS which may be compared with the corresponding experimental value.

4.2. *Results and discussion*

Figure 3 shows a typical single event describing the decay of the smoke concentration in the near wake of a rectangular long thin flat plate, using essentially the same apparatus and techniques as in the corresponding experiments with the disks. As for the disk (also shown for comparison), the trace displays a considerable randomly fluctuating component which is clearly associated with the turbulent motions in the near-wake region. But the envelope of the curve is, under inspection, clearly exponential. As predicted by the simple model, there is no obvious oscillatory component to be associated with the vortex shedding.

Figure 4(*a*) shows the experimental variation of residence time parameter H in smooth free-stream flow as a function of plate Reynolds number R for a number of plate sizes D and plate aspect ratios Δ. Within the limits of experimental error, and

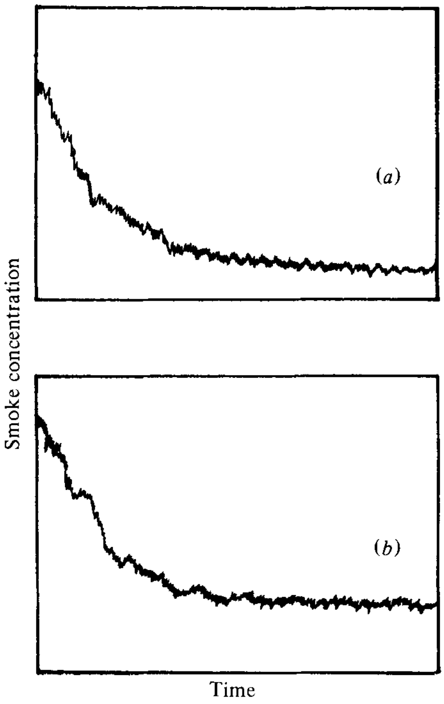

FIGURE 3. Records of typical experimental events, describing the decay of smoke concentration in the wakes of (a) a disk and (b) a long flat plate, located in a smooth free stream.

over the ranges of conditions indicated, the relationship appears to be a unique one, independent of D, Δ, or whether the plate is placed vertical or horizontal in the wind tunnel. For $R > 4000$, H appears to be more or less constant at around 5, low compared to the value > 7 obtained for the disk (Humphries & Vincent 1976*a*), suggesting a more powerful near-wake removal mechanism. For R decreasing below 4000, H rises more and more steeply, reaching a value around 24 at $R = 1000$.

The variation of Strouhal number S with R is shown in figure 4(*b*). The wide scatter at low R can be attributed to the experimental difficulties in detecting low amplitudes in the pressure 'ripples'. With this in mind, no attempt is made to attach any significance to variations of S with R in this range.

Having noted for $R > 4000$ that both H and S are independent of R, we can specify $HS = 0{\cdot}7$ for that range from the data in figure 4. By iterative calculation, it is found that this corresponds to a value for the fraction of the near-wake entrapment region removed during a single vortex-shedding event:

$$\beta = 0{\cdot}53 \pm 0{\cdot}03.$$

Following on from this discussion, it would appear that we cannot attribute the sharp rise in H at low R to any corresponding change (i.e. a decrease) in vortex-shedding frequency as reflected by S. It must therefore be associated with a decrease in β. Gerrard's (1966) qualitative discussion about the near wakes of long circular cylinders, many of the features of which will be similar to those for long flat plates, may be useful in helping to explain this. He notes that the length of the vortex-

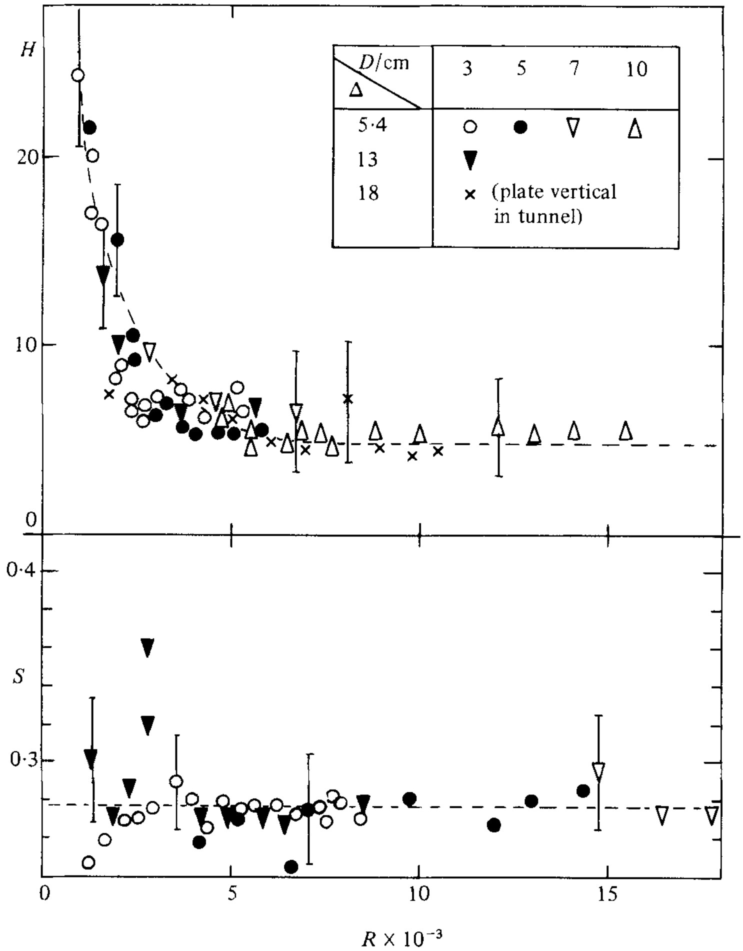

FIGURE 4. H and S as functions of R for rectangular flat plates in smooth flow.

formation region, determined by the position where fluid from outside the wake first crosses the wake axis, increases as R is decreased in the range of interest. This is controlled by where the shear layers become turbulent, being further away from the cylinder as R decreases. The result as the vortex formation length increases is that the proportion of the near-wake entrapment region which is occupied by the vortex (β itself) decreases. For long flat plates, we note (Flachsbart 1935) that the drag coefficient decreases with R for $R < 4000$, suggesting that the rate of entrainment of fluid into the near wake is also decreasing, consistent with the increase in the length of the vortex formation region. But, for $R > 4000$, the drag coefficient becomes relatively independent of R, suggesting that the rate of entrainment and hence the vortex-formation length, and in their turn β and H, also level off. This is consistent with what we observed.

Measurements of H and S as functions of the free-stream turbulence parameter Λ_t are plotted in figures 5(a) and (b) respectively, covering the ranges $0{\cdot}3 < l_t/D < 0{\cdot}9$ and $0{\cdot}01 < k_t^{\frac{1}{2}}/U < 0{\cdot}11$, and for $R \simeq 6500$. The results for H are markedly

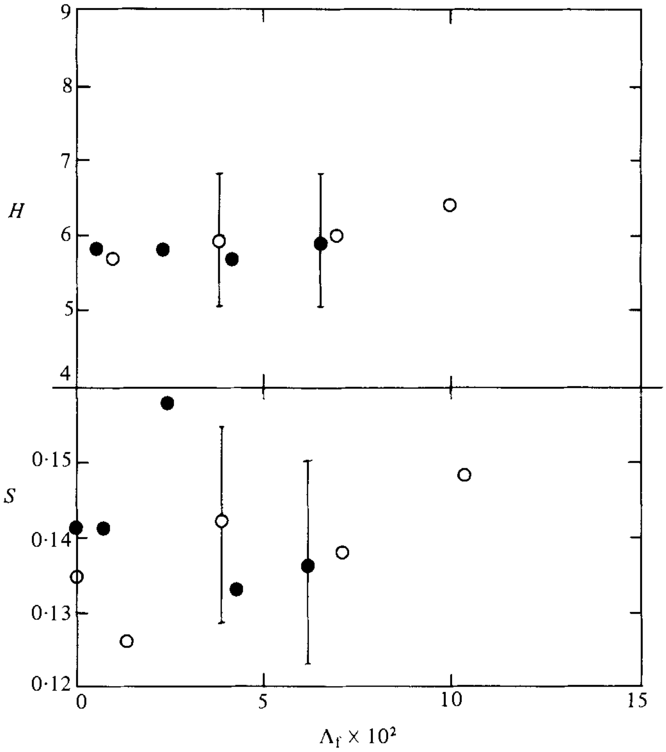

FIGURE 5. H and S as functions of Λ_f for rectangular flat plates in turbulent flow (R = 6500 ± 400, Δ = 10). ○, D = 3 cm; ●, 5 cm.

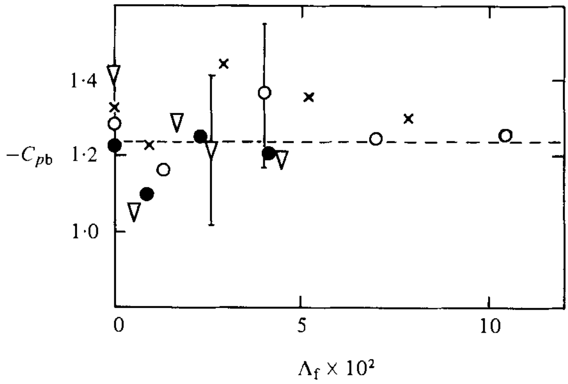

FIGURE 6. C_{pb} as a function of Λ_f for rectangular plates in turbulent flow (R = 7000 ± 300, Δ = 5·4). ○, D = 3 cm; ×, 4 cm; ●, 5 cm; ▽, 7 cm.

different from those obtained for the disk (and other three-dimensional flow configurations) and reported in earlier papers; here, within experimental error, there is no significant variation at all in H with Λ_f. The results for S also show no significant trend and so agree in essence with the findings of Bearman (1978, private communication). These data therefore support our earlier hypothesis that the transport of particles into and out of the base region of the plate is controlled largely by vortex shedding and only to a secondary degree by turbulent diffusion.

Measurements have also been made of base pressure coefficient $C_{p\mathrm{b}}$ as a function of Λ_f for the same ranges of conditions. For the disk and other axisymmetric bodies, $C_{p\mathrm{b}}$ was seen to decrease markedly as Λ_f increased. But for the rectangular flat plates (figure 6), there is no significant variation, consistent with the behaviour of H and S.

5. Conclusions

The study set out to investigate further (following on from previous published work) the transport of fluid and particles in the near aerodynamic wakes of disks in smooth and turbulent free streams, and then to examine related effects for the case of rectangular flat plates. The results enable interesting comparisons to be made between the properties of three-dimensional and two-dimensional near-wake flows respectively. The main conclusions are as follows.

(i) The results of experiments performed with disks in a turbulent free stream confirm that turbulent diffusion is the primary mechanism for the transport of airborne particles into and out of the near-wake *cavity*, so long as $l_\mathrm{f}/D \lesssim 0{\cdot}5$ where Λ_c appears to be uniquely controlled by Λ_f. In this range, the relationship between Λ_c and Λ_f appears to be relatively simple, even linear.

(ii) The transport of particles into and out of the near-wake zone of a long rectangular flat plate is controlled primarily by vortex formation and shedding. In this case, it is inappropriate to talk in terms of a closed wake *cavity*. Turbulent diffusion now plays a secondary role in mixing the particles throughout the recirculation zone. For this type of wake, H is constant over a wide range of R, but increases sharply for R decreasing below about 4000. The latter increase is associated with the decrease in the proportion of the near-wake entrapment region β, which is occupied by a vortex at the instant it is shed, which in turn is associated with an increase in the length of the vortex-formation region. For $R > 4000$, H is relatively insensitive to free-stream turbulence.

(iii) Over the ranges of conditions examined for the rectangular plates, Strouhal number S is insensitive to both R and Λ_f. Not surprisingly, the base-pressure coefficient $C_{p\mathrm{b}}$ also does not vary with Λ_f.

As can be seen from these conclusions, a marked contrast exists between the near-wake transport of fluid and particles behind axisymmetric and two-dimensional thin flat plates respectively. In practical extensions of this work, these ideas have been applied to considerations of the treatment time of particle-laden gases in air-pollution control devices such as electrostatic precipitators, and to examine the possible enhancement of particle collection efficiency by the deployment of suitably designed flow baffles (Vincent & MacLennan 1980; MacLennan & Vincent 1981).

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