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An experimental investigation of the detention of airborne smoke in the wake bubble behind a disk

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Experiments have been performed in a low-speed wind tunnel to determine the detention time of airborne smoke particles that become trapped in the wake vortex (or bubble) region behind flat disks placed perpendicular to the flow. Using a laser transmissometer to detect the smoke, its detention time was obtained from the time-dependent decay of the smoke in the disk bubble during the time immediately following the removal of the source of smoke. The dimensionless group H, the product of the detention time and the mainstream air velocity divided by the disk diameter, is seen to be a constant equal to $7{\cdot}44 \pm 0{\cdot}52$ for Reynolds numbers in the range 2000–40000. This result is compatible with a simple fluid-mechanical model which describes the transport of fluid-borne scalar entities across the bubble boundary by turbulent diffusion. The investigation suggests that H should be unique for the flow about a disk over a wide range of conditions, and further suggests the possibility that similar unique values for H can exist for flow about other obstacles. The number H has potential applications in a number of physical and engineering research areas.

1. Introduction

Some experiments have been reported which investigated the electrostatic precipitation of charged dust particles on to the downstream surface of a metallic perforated plate placed perpendicular to a stream of dusty air (Vincent 1971). In order to explain the results a mechanism was invoked whereby charged dust particles passing through the holes in the plate were said to be entrained into the zones of recirculating air on the immediate downstream side of the solid portions of the perforated plate. During their resulting entrapment particles were swept back towards the downstream surface of the plate under the influence of an externally applied electric field. Whether or not a given dust particle thus trapped reaches the solid boundary and is deposited was said to depend on the balance between the detention time and the time required to sweep the particle to the collecting boundary in the applied field from some mean stationary position. The complicated geometry of the perforated plate did not allow formal analysis, but by drawing a parallel between the three-dimensionality of the flow around the individual elements that make up the perforated plate and that around a single isolated disk, and using experimental fluid-mechanical data published for the disk by Carmody (1964), a rough quantitative model was constructed which showed reasonable agreement with experiment. Extensions of this work led to the development of the grid-type electrostatic dust precipitator (Vincent & Przygocki 1971; Vincent 1972*a*, *b*; Bevans & Vincent 1974).

Such ideas may have application in other systems involving suspended particulates, for example in the design and use of snow fences, the formation of sand-dunes and the silting of rivers. Further, the recirculating flow pattern behind flow obstacles has an important bearing on the performance of many heat-transfer and chemical-processing systems. A fundamental mechanism of interest in all such systems is the transfer of scalar entities (e.g. particulates, heat and chemical species) across the boundary of the recirculation zone. Associated with this transfer mechanism we have the detention time, which may be defined as the characteristic time during which a given entity remains trapped inside this boundary.

In this paper we report experimental measurements of the detention time of smoke tracer particles in the wakes of flat disks placed at right angles to the main air flow, and relate these to a simple fluid-mechanical model of the physical system.

2. Theory

The main features of the wake flow behind disks in air have been studied experimentally by Fail, Lawford & Eyre (1959) and Carmody (1964), and such investigations provide a rich source of empirical data to aid future work. At sufficiently high Reynolds numbers, fluid separation takes place at the edge of the disk, leading to the formation of a shear (mixing) layer which spreads out under turbulence and closes behind the disk at about two to three diameters downstream (see figure 1). As a result of this mixing, a recirculatory flow is induced in the region immediately behind the disk. The mean flow of the fluid can be represented by a streamline pattern, the main feature of which is the closed streamline which separates the recirculating flow from the mainstream flow (i.e. $\Psi' = 0$, where Ψ' is $8\Psi/D^2U$ and Ψ the stream function (from Carmody)). This limiting streamline is referred to as the *bubble* boundary, extending about two to three disk diameters downstream. By the definition of a streamline there can be no net transport of fluid across the bubble boundary, and exchange of individual batches of fluid can take place only by molecular or turbulent diffusion. Some bubble instability, leading to random vortex shedding, is present but is less marked than in the case, say, of some two-dimensional flows (e.g. about a cylinder) where strong periodicity is observed.

The detailed structure of the flow about a disk is very complicated and cannot be fully described formally. However, important results can be obtained by assuming that the turbulence characteristics can be described in terms of two quantities only: the kinetic energy and the length scale (or mixing length) of the turbulent motion (Kolmogorov 1942; Prandtl 1945; Launder & Spalding 1972). If the fluid carries scalar entities (e.g. aerosol particles), then similar quantities can be used to describe their motion.

Dimensional analysis can give useful insight into the nature of the problem and

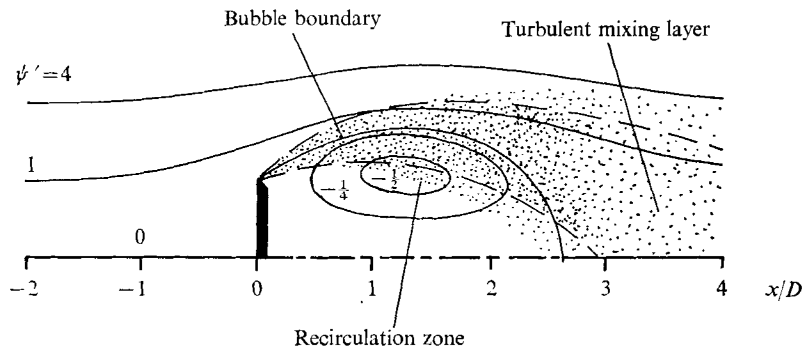

FIGURE 1. Axisymmetric flow pattern about a disk (from Carmody 1964).

act as a guide to experimentation, provided that a correct choice of variables is made (Pankhurst 1964). For a reasonably general description of the entrapment of scalar entities in the bubble behind the disk, an appropriate set of variables is: t_d (detention time), D (disk diameter), U (mainstream air velocity), k_{sc} (characteristic energy of turbulence for the scalar), l_{sc} (characteristic mixing length for the scalar), ν (molecular kinematic viscosity of the fluid), D_B (molecular diffusion coefficient for the scalar), f (frequency of vortex shedding), where it is assumed that, if there were no molecular or turbulent diffusion, the scalar entities would move along streamlines (i.e. with no deviation from the mean motion as a result of inertia or settling). These lead to six independent dimensionless groups, so that

$$\phi\left(\frac{Ut_d}{D}, \frac{DU}{\nu}, \frac{l_{sc}}{D}, \frac{k_{sc}}{U^2}, \frac{D_B}{\nu}, \frac{Df}{U}\right) = 0. \tag{1}$$

The characteristic wake variables for the scalar, l_{sc} and k_{sc}, are included to account generally for turbulent transport of the scalar without having to specify its detailed physical properties. In dealing specifically with aerosol particles it might be more appropriate to specify particle size and density, while for the turbulent transport of heat, chemical species or other entities, other physical variables could be specified. Equation (1) covers all these possibilities.

If we now assume that molecular diffusion and vortex shedding are of negligible importance over the range of conditions of interest, then we may rewrite (1) as

$$\phi\,(H, Re, l_{sc}/D, k_{sc}/U^2) = 0, \tag{2}$$

where $H = Ut_d/D$, the detention time expressed relative to the time scale for flow past the disk, and $Re = DU/\nu$, the disk Reynolds number. Equation (2) may be re-arranged to give

$$H = \phi_1\,(Re, l_{sc}/D, k_{sc}/U^2). \tag{3}$$

If we can perform an experiment to determine H as a function of Re for a given fluid–scalar system, then we can investigate the importance of l_{sc}/D and k_{sc}/U.

The next step is to obtain an expression for H based on a physical model. For the transport of scalar entities in a turbulent flow field, the continuity equation is

$$\partial\bar{c}/\partial t + \operatorname{div}(\bar{\mathbf{v}}\bar{c}) = \operatorname{div}(\overline{D_B \operatorname{grad} c}) - \operatorname{div}(\overline{\mathbf{v}'c'}), \tag{4}$$

where c' and $\mathbf{v}'$ are the fluctuations in the scalar's concentration and velocity respectively, and an overbar denotes a time-averaged value. The instantaneous values of the concentration and velocity are $c(t) = \bar{c}+c'(t)$ and $\mathbf{v}(t) = \bar{\mathbf{v}}+\mathbf{v}'(t)$ respectively. The first term in (4) represents the rate of change of concentration, the second term convection, the third term molecular diffusion and the fourth term turbulent exchange. This last term effectively represents an added diffusional flux, which in practice usually outweighs the molecular diffusion term and so becomes the main term of interest. The actual flux by turbulent diffusion is therefore

$$\mathbf{j} = -\overline{\mathbf{v}'c'}. \tag{5}$$

Launder & Spalding (1972, p. 67) have constructed a two-flux model which takes into account the flux of scalar entities in opposite directions across a boundary. If the y direction is defined locally so as to be perpendicular to this boundary, then, provided that l_s is not too large, we can use their result to write the local net flux across the boundary as

$$j_y = -l_s\frac{\partial}{\partial y}((\overline{\mathbf{v}'^2_y})^{\frac{1}{2}}\,\bar{c}), \tag{6}$$

which leads to

$$j_y = -(2b)^{\frac{1}{2}}\,l_s\left(k_s^{\frac{1}{2}}\frac{\partial\bar{c}}{\partial y}+\bar{c}\frac{\partial k_s^{\frac{1}{2}}}{\partial y}\right), \tag{7}$$

where b is the fraction of the total kinetic energy of the turbulence carried by motion of the scalar in the y direction and where l_s and k_s are local values.

In the steady state the total number of entities contained within the bubble behind the disk is constant, those that leave by turbulent transfer across the bubble boundary being replaced by new ones entering likewise. If at some time $t = 0$ the source is removed, the bubble will empty at a rate

$$\frac{dN}{dt} = \int_A j_y\,dA, \tag{8}$$

where we have taken the y direction to be always perpendicular to the bubble boundary, where A is the surface area of the bubble across which the entities can escape (not including the downstream face of the disk) and where we have assumed that the bubble is stable so that losses due to vortex shedding can be neglected.

Inserting (7) into (8) gives

$$\frac{dN}{dt} = -\int_A\left((2bk_s)^{\frac{1}{2}}\,l_s\frac{\partial\bar{c}}{\partial y}\right)dA, \tag{9}$$

where it is assumed that $\bar{c}\,\partial k_s^{\frac{1}{2}}/\partial y \ll k_s^{\frac{1}{2}}\partial\bar{c}/\partial y$ on the basis of Carmody's experimental data for the spatial distribution of turbulent velocities, which suggest that the turbulent kinetic energy is a maximum over most of the bubble surface. We see now that the flux term in (9) is in the form of Fick's law, where $(2bk_s)^{\frac{1}{2}}l_s$ is the equivalent of a turbulent diffusion coefficient along the y direction. This diffusion coefficient depends more on the prevailing flow conditions than on any of the fundamental properties of the fluid itself. (More generally, care must be exercised in any application of the Fick's law approximation to problems involving turbulent exchange, since it is only valid if the spatial distribution of turbulent energy varies slowly in comparison with the scalar quantity of interest; this condition might not always be satisfied.)

There is not enough available theoretical or experimental information to enable a rigorous evaluation of (9). Therefore, in order to proceed, let us consider the system in terms of 'characteristic' (i.e. averaged over the bubble surface) values for the properties of the turbulence, and also assume a simple functional form for the concentration gradient. Thus

$$\frac{dN}{dt} \sim -l_{sc}(2bk_{sc})^{\frac{1}{2}}\frac{\bar{C}_t}{\delta}A, \tag{10}$$

where $\bar{C}_t$ is the mean spatial concentration inside the bubble at time t, and δ is a length scale indicating the mean distance over the turbulent mixing layer across which the concentration drops to zero (on the outside).

If the volume of the bubble is V, then the number of entities inside the bubble at time t is given by $N_t = \bar{C}_t V$. The ratio V/A depends on the shape of the bubble and hence on the streamline pattern; therefore V/A can be expressed in the form $Df_1(Re)$. It is difficult to evoke such a firm physical basis for the length scale δ, having introduced it somewhat artificially for the purpose of allowing a quantitative evaluation of (9). One approach, however, is to consider δ as some proportion of the mean width of the mixing layer around the bubble boundary, and so possibly dependent on D and U as well as on the properties of the turbulent motion of the entities as represented by k_{sc} and l_{sc}; therefore we can replace δ with the form $Df_2(Re, l_{sc}/D, k_{sc}/U^2)$. By inserting these suggestions into (10) and integrating, we see that the number of entities trapped in the bubble decays exponentially with time. The time constant of this decay represents the average detention time, which we can write down in the form

$$H \equiv \frac{Ut_d}{D} = \left(\frac{k_{sc}}{U^2}\right)^{-\frac{1}{2}}\left(\frac{l_{sc}}{D}\right)^{-1} f_1(Re)f_2\left(Re, \frac{l_{sc}}{D}, \frac{k_{sc}}{U^2}\right)\Big/(2b)^{\frac{1}{2}}, \tag{11}$$

or

$$H = \phi_1(Re, l_{sc}/D, k_{sc}/U^2), \tag{12}$$

which is consistent with the dimensional analysis.

It is convenient to separate the fluid and scalar terms in this expression, and this can be achieved by assuming particle properties $\sigma = l_c/l_{sc}$ and $\alpha = k_c/k_{sc}$, where l_c and k_c are the characteristic wake turbulence variables for the fluid. Equation (11) can therefore be re-written as

$$H \equiv \frac{Ut_d}{D} = \sigma\alpha^{\frac{1}{2}}\left(\frac{k_c}{U^2}\right)^{-\frac{1}{2}}\left(\frac{l_c}{D}\right)^{-1} f_1(Re)f_2\left(Re, \sigma, \alpha, \frac{l_c}{D}, \frac{k_c}{U^2}\right)\Big/(2b)^{\frac{1}{2}}. \tag{13}$$

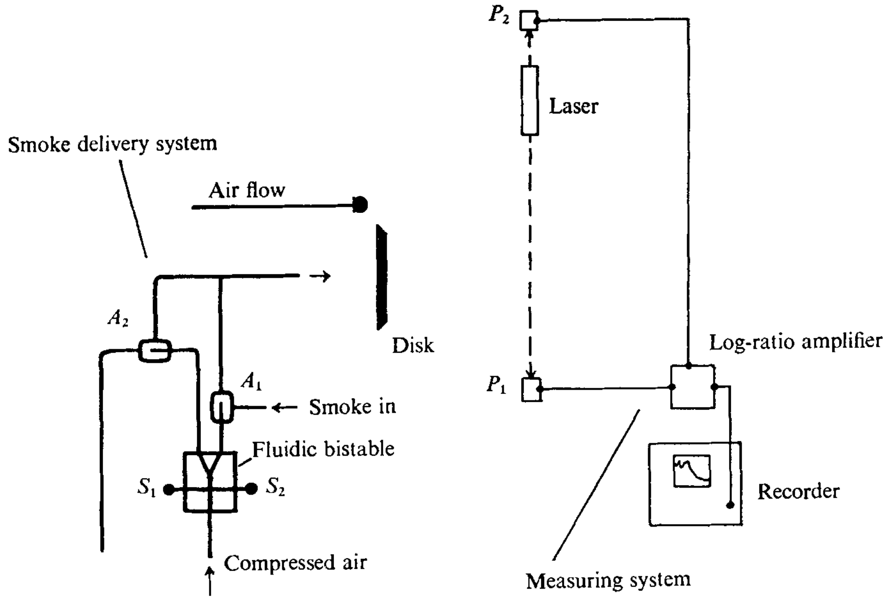

FIGURE 2. Schematic diagram of experimental system.

3. Experimental system

In the experiments we set out to create the situation described in the theory; that of a wake bubble behind a disk filled with airborne scalar entities whose external supply is suddenly removed, and the subsequent monitoring of the emptying of the bubble. In these experiments the entities consisted of tracer smoke particles from a conventional wind-tunnel smoke generator. The experiments were carried out in an open-cycle, low-speed, low-turbulence wind tunnel whose working volume measured $1 \times 1 \times 1$ m. The experimental arrangement is shown schematically in figure 2. The experimental disks were suspended one at a time in the middle of the wind-tunnel test section from an iron frame by means of piano wires. Each disk had a 30° bevelled edge and the ratio of disk thickness to diameter was kept constant from one disk to another. Smoke was delivered to the air stream axial to and just upstream of the test disk, entering the delivery system through an aspirator $A1$ connected to a supply of compressed air. The injection of smoke into the air stream could be interrupted at will by triggering a fluidic bistable in the compressed-air line ahead of the aspirator. To ensure a clean cut-off of the injected smoke at the outlet nozzle, the second output arm of the bistable was connected to another aspirator A_2 arranged such that, on triggering the bistable, the injection nozzle experienced a sharp back pressure which prevented smoke already inside the smoke delivery system from bleeding into the main air stream. Motion pictures taken of the operation of this system showed that the smoke-off fall-time was substantially less than the 50 ms, which roughly corresponded to the exposure time per frame.

The amount of smoke in the bubble behind the disk was monitored by means of an optical transmissometer system incorporating an He–Ne laser and two diode photodetectors, one in front of the laser to detect the light transmitted through the smoke and the other mounted into the back of the laser and set up so as to give a reference signal. The signals from these two photodiodes were fed into a logarithmic-ratio amplifier whose final output voltage was directly proportional to the actual amount of smoke intercepted by the laser beam. This output was recorded as a function of time using a fast-response chart oscillograph, thus enabling the decay of smoke in the bubble behind the disk to be observed when the source of smoke was suddenly removed.

4. Results

Experiments were performed using four disks of diameters 2, 5, 10 and 15 cm for mainstream air velocities ranging from 1 to 5 m s^{-1}, covering a range of *Re* from about 2000 to 40000. Visual observation of the smoke trapped in the disk bubble indicated that the bubble shape and general physical appearance did not change appreciably with *Re* and that there was no large-scale vortex shedding. Figure 3 (plate 1) shows a typical photograph of the smoke just after the supply has been interrupted. Comparison with figure 1 suggests that the length of the bubble may be somewhat shorter than the 2·6 disk diameters calculated by Carmody.

An oscillograph display for a single typical event is shown in figure 4, where the absence of a significant periodic perturbation confirms that large-scale vortex shedding is not occurring. Logarithmic plotting of a large selection of such events chosen over a wide range of experimental conditions indicated excellent exponential behaviour, as predicated by the theory. Therefore for each recorded event we could with confidence determine the time constant of the decay (and hence t_d) from just two points on the oscillogram. The 'dead time', as indicated on the graph in figure 4, is the time delay between the instant at which the smoke is cut off at the injection nozzle and the time at which the bubble 'sees' the resultant step-wise change in the smoke supply. It is determined by the mainstream air velocity and the distance of the injection nozzle upstream of the disk.

In the theory we discussed the decay of smoke in the bubble with respect to the *total* number of entities in the bubble. In the actual experiments, the smoke was monitored only along a narrow pencil of laser light, and we must decide whether the decay time constant thus measured was representative of the whole bubble. From the motion pictures, the smoke concentration throughout the bubble appeared to be reasonably uniform at all times during the decay, with thorough and continual mixing of the trapped smoke, no doubt as a consequence of the strong recirculation and the turbulence. This suggests that the decay time constant should *not* be very sensitive to the position of the laser beam with respect to the disk. Figure 5 shows the results of some experiments in which t_d was measured as a function of x/D, where x is the distance of the vertical plane containing the laser beam downstream from the plane of the disk. The degree of constancy of t_d with x/D confirms our conclusion.

The detention time t_d was measured from over 260 separate events covering the

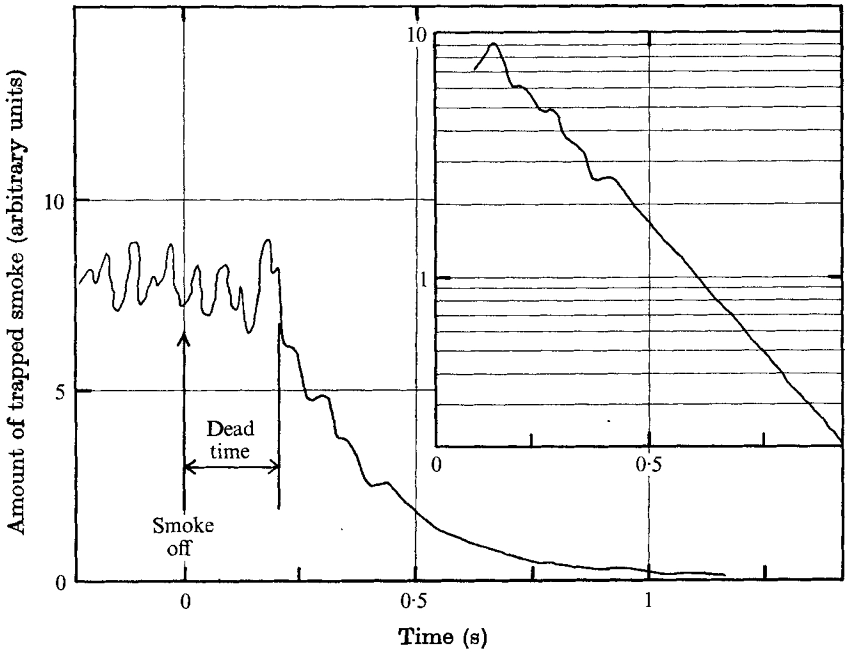

FIGURE 4. Oscillogram for a typical event. (D = 10 cm, $Re \simeq 20000$.)

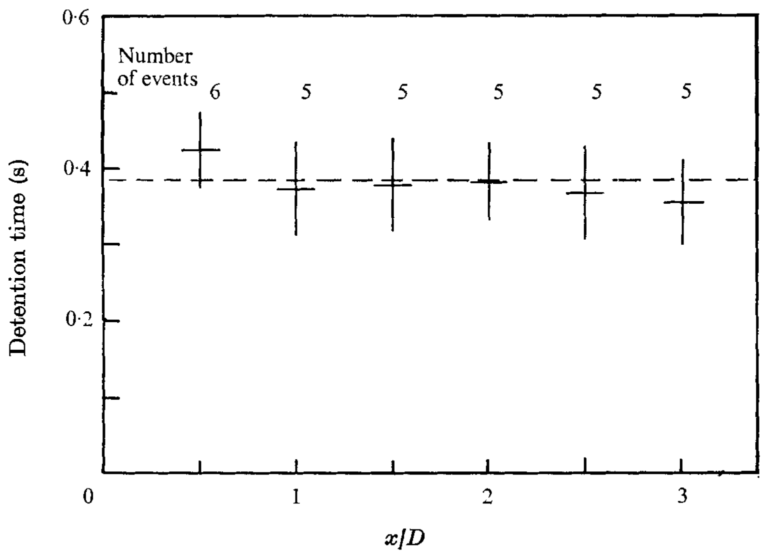

FIGURE 5. Measurements of detention time as a function of x/D. (The dashed line is consistent with the best straight line in figure 6; Re = 13700, D = 10 cm.)

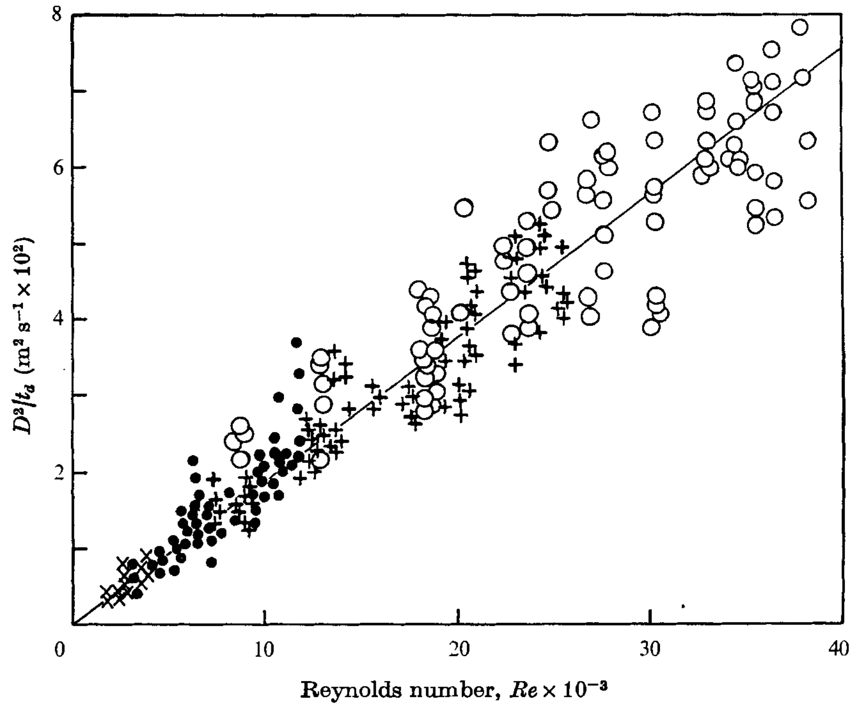

FIGURE 6. Experimental plot of D^2/t_d as a function of Reynolds number also indicating the best straight line. ○, D = 15 cm; +, D = 10 cm; ●, D = 5 cm; ×, D = 2 cm.

range of conditions referred to already and where $x/D = 1$. Although the quantity of interest is the number H, there is some virtue (from the point of view of clearly illustrating functional behaviour) in presenting the data in the form of a graph of D^2/t_d *vs.* Re. Reconsider (13). If $\sigma, \alpha, k_c/U^2$ and l_c/D turn out to be either constants or functions of Re, then (13) becomes of the form

$$H = \phi_2(Re), \tag{14}$$

which leads directly to

$$D^2/t_d = \phi_3(Re), \tag{15}$$

showing that, for a given fluid, D^2/t_d should be a unique function of Re. Figure 6 shows the experimental data plotted on these axes. The scatter in the points appears to be largely random, stemming from the turbulence-induced noise on the original oscillograms, from random vortex shedding and from the limitations on time resolution. However it is fair to say that the scatter is no worse than would be normally expected from this type of experiment. Despite the scatter, the outstanding feature of the results is that (15) does indeed appear to be satisfied. Furthermore, the function ϕ_3 closely resembles a straight line through the origin, from whose slope we obtain the interesting result that the number H is constant, with a value $7{\cdot}44 \pm 0{\cdot}52$.

5. Discussion

For the fixed fluid–scalar system in our experiments, it can be assumed that σ and α were constant. The constancy of the experimental value of H suggests therefore that l_c/D and k_c/U^2 were also constant for the range of Re covered. This is not unreasonable since it is a well-known fact for a disk in a smooth air flow that the base pressure coefficient, and hence probably the dimensionless properties of the turbulence, is constant over a wide range of Re (including the range of our experiments). Therefore the detention time of smoke particles trapped in the wake bubble behind the disk in our experiments was determined only by the diameter of the disk and the mainstream air velocity. The more general implications of this result will be discussed shortly. First, however, an order-of-magnitude evaluation of (13) will allow a check on whether our theory can sensibly predict H; use is made of the following estimates for the various terms in the equation.

(i) From the photograph in figure 3, the bubble appears to be shorter than was calculated by Carmody. We can roughly estimate that $f_1(Re) \sim 0{\cdot}35$.

(ii) The term k_c/U^2 can be estimated from Carmody's experimental data for the local distribution of the velocity of turbulence, assuming similarity with the present experiments. Thus $k_c/U^2 \sim 0{\cdot}045$.

(iii) The fraction of turbulent energy carried in particle motion perpendicular to the bubble boundary is estimated as $b \sim 0{\cdot}50$.

(iv) It is assumed that the individual smoke particles are so small as to behave essentially like particles of the fluid everywhere within the volume of interest. Therefore we estimate that $\sigma \sim 1$ and $\alpha \sim 1$.

(v) The ratio of the characteristic mixing length of the fluid to the diameter of the disk is estimated to be a constant somewhere within the range $0{\cdot}01 \leqslant l_c/D \leqslant 0{\cdot}10$.

(vi) The length scale over which the concentration of particles drops to zero across the bubble boundary has as its lower limit the length scale of the turbulent motion of the particles and as its upper limit the width of the mixing layer. The latter can be estimated from Carmody's data for the spatial distribution of turbulent velocities. Therefore we can estimate that the ratio δ/D has a constant value somewhere within the range $l_s/D \leqslant f_2 \leqslant 0{\cdot}10$.

These are felt to be physically reasonable estimates of the quantities of interest. When they are inserted into (13), we obtain a constant value for H somewhere within the range $1{\cdot}5 < H < 15$. This covers the value obtained experimentally. The general nature of the agreement between theory and experiment supports the validity of the physical picture presented and the various assumptions made in formulating it.

Over the range of Re covered by the experiments, the number H, describing the detention time of the given smoke particles in the wake bubbles behind disks in atmospheric air, is throughout equal to $7{\cdot}44 \pm 0{\cdot}52$. We can conclude that H should be unique for all turbulent fluid–scalar flows about disks, provided that $\sigma \sim 1$ and $\alpha \sim 1$. More generally, however, we must write H in the form

$$H = \phi_4(\sigma, \alpha) \tag{16}$$

in order to allow for the situation where the scalar entity exhibits characteristics which might affect σ and α. The obvious example is that of aerosols, where σ and α must depend on the properties (i.e. mass and size) of the individual particles, to a greater or lesser extent depending on their size. Tchen (1947) has argued on a general basis that the turbulent diffusion coefficient for aerosols is the same as that for the suspending fluid, so that, in our notation, $\sigma\alpha^{\frac{1}{2}} = 1$. His theory states that, as the particle size increases, the decrease in random particle velocity is compensated for by a corresponding increase in the length scale of the turbulent motion of the particle. This means that in (13) the only term which implies dependence of H on the properties of the aerosol system is

$$\frac{\delta}{D} \equiv f_2\left(Re, \sigma, \alpha, \frac{l_c}{D}, \frac{k_c}{U}\right) \sim f_2(\sigma, \alpha). \tag{17}$$

If, as seems plausible, δ is in some way directly linked with the characteristic mixing length *for the particles*, then we should expect δ/D to be a function of at least σ. Therefore δ/D, and hence H, *are* likely to depend on the properties of the aerosol system. In addition, the motion of finite-sized aerosol particles can be influenced by inertial and settling effects, thus further complicating their dynamical behaviour in the flow field of the bubble. These matters, and hence the important question of the universality of the number H for all fluid–scalar flows about disks, are subjects for further work.

Nevertheless, H for a disk *should* be unique for a wide range of situations of practical interest. We may go further and suggest that similar characteristic H numbers might exist for flows about obstacles of other geometrical shapes, despite the added complication of vortex shedding, which we might find in many cases. If there existed a catalogue of such H numbers dependent only on the shape of the flow obstacle for wide ranges of Re, potential applications might be found in such areas of research as the mechanics of aerosol deposition, heat transfer and chemical processing. It is noted that the number H is similar in some respects to the dimensionless homochronicity number which has already been used elsewhere to describe the time needed for the establishment of a steady-state heat exchange process after a step-wise change in the temperature of a stream of fluid around an obstacle (e.g. Parnas 1965).

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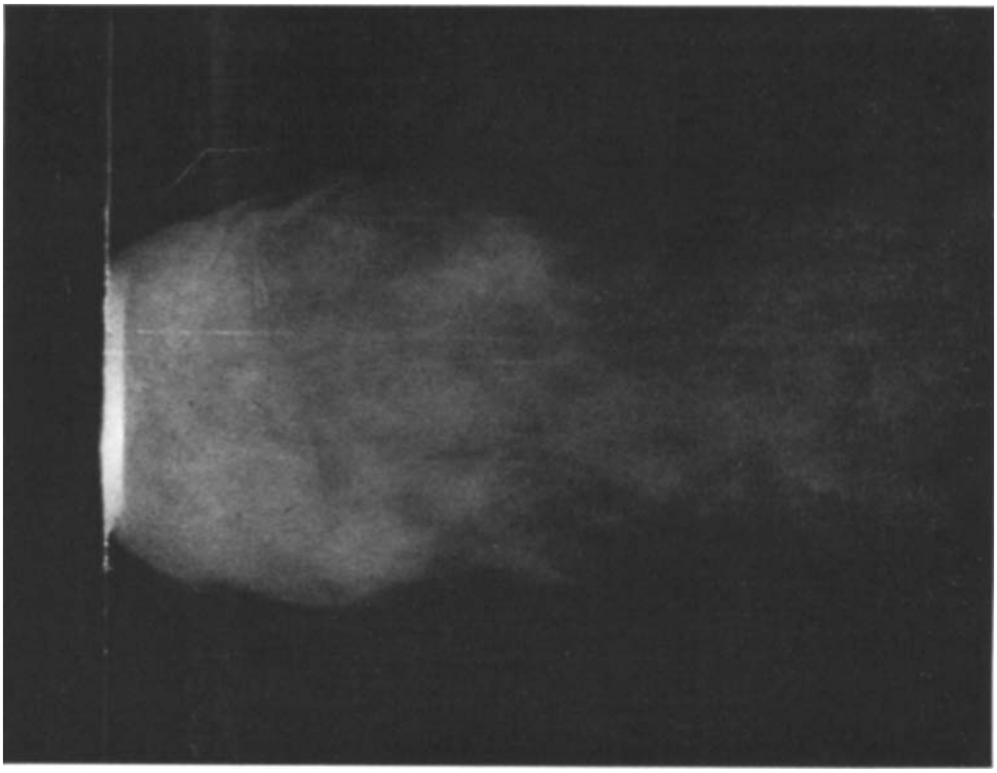

FIGURE 3. Photograph of a typical event, showing smoke trapped in the wake bubble behind a disk shortly after interruption of the smoke supply. ($D = 5$ cm, $Re \simeq 10000$.)