Transport Processes in the Two-Dimensional Near Wake

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Theme

TESTS were conducted to characterize the two-dimensional recirculation zone downstream of circular cylinders and wedges, in the Reynolds number range 8×10^3 to 3×10^5. In this effort, a tracer material consisting of NO_2 in a mixture of $NO_2 - N_2O_4$ was injected through holes in the bluff-body wall into the recirculation zone where tracer residence times and concentration distributions were determined using a fiber-optic probe. Vortex shedding and wake geometrical parameters were found from spark schlieren photographs taken with helium tracer injected into the zone. Measurements were taken at numerous approach flow velocities in the range 15 – 150 m/sec, at the three freestream densities of 0.41, 0.67, and 1.20 kg/m^3, and at several initial levels of turbulent intensity up to 11%. The data indicate that the vortex shedding phenomenon associated with two-dimensional bluff-bodies exerts a major influence on the transport of mass in the near-wake.

Contents

The experimental facility employed consists of a 10×10-cm cross-section test chamber in which any one of several two-dimensional bodies can be installed with axis normal to the air flow. Cylindrical bluff-bodies are constructed of concentric inner and outer shells. In the normal open position, injector ports in both cylindrical shells are aligned, thereby allowing unimpeded tracer flow through the ports into the recirculation zone. Rotation of the inner cylinder 20° seals off all ports in the outer shell to stop tracer flow. Closure is accomplished pneumatically in about 0.001 sec. The cylinder body is traversable as a unit in the transverse (z) direction to allow the acquisition of data at locations removed from the test section centerplane. Four two-dimensional bluff-body models were considered including 1.58 cm and 2.54 cm diam circular cylinders, and two v-gutter-type wedges. One wedge has a 39° included angle with a (maximum) base height of 3.53 cm, while the other is a 26° wedge with a 2.2 cm base. The 1.58-cm cylinder is installed in a fitted recess in the base of the wedges to provide tracer injection capability. Details of the apparatus are provided in Ref. 1.

An assembly for installation of screens is incorporated in the design of the test facility at a location 1.25 cm upstream of the cylinder centerline. Screens with various mesh spacing to wire diameter ratios provide initial freestream turbulence levels from 3 to 11%.[1] Recirculation zone geometrical parameters are determined from spark schlieren photographs after injection of helium tracer to establish large density gradients. $NO_2 - N_2O_4$ tracer concentration distributions and residence times are determined using traversable fiber-optic probes which consist of a pair of 0.25 cm diam sheathed bundles of glass fibers. One bundle of fibers serves as a transmitter and the other as a detector of visible light above 4000 Å. Spacing between the probes is maintained at 0.32 cm.

High-intensity light for the fiber-optic probe system, made available from a tungsten-halogen lamp, is directed to a narrow band pass optical filter which passes light in the range 4550-4690 Å, wavelengths near optimum for absorption by $NO_2 - N_2O_4$ tracer. The filtered light is channeled into the test chamber via the transmitter unit of the fiber-optic probe. Subsequently, a fraction of the light is absorbed by the tracer material and the remainder is channeled through the detector unit of the probe to a photomultiplier tube; the photomultiplier output is displayed on an oscilloscope.

The light transmitted as a fraction of the delivered intensity is an exponential function of the product of the tracer absorption coefficient, the tracer concentration, and the spacing between the transmitter and detector units of the fiber-optic probe, according to the Beer-Lambert law. For the equilibrium mixture of NO_2 and N_2O_4, absorption above 4000 Å is due exclusively to NO_2. Hence, increasing NO_2 in the tracer mixture by raising the temperature results in increased absorption. Satisfactory absorption levels necessitated operation at about 310°K where the NO_2 mole fraction in the mixture is 0.28 and the transmission is 0.675 (vs 0.80 at 295 K).

Schlieren photographs of the near-wake reveal a region extending for a length of approximately 2.5 bluff-body characteristic heights (2.5d); this region encompasses the recirculation zone. The intersection of this region with the center plane of the flow locates the rear stagnation (closure) point. Vortices which are shed from the near-wake region result in significant local agitation of the flow and a marked distortion of the half of the recirculation zone from which the vortex issues. Recirculation zone length L measured from the body trailing edge to the closure point, and the maximum zone

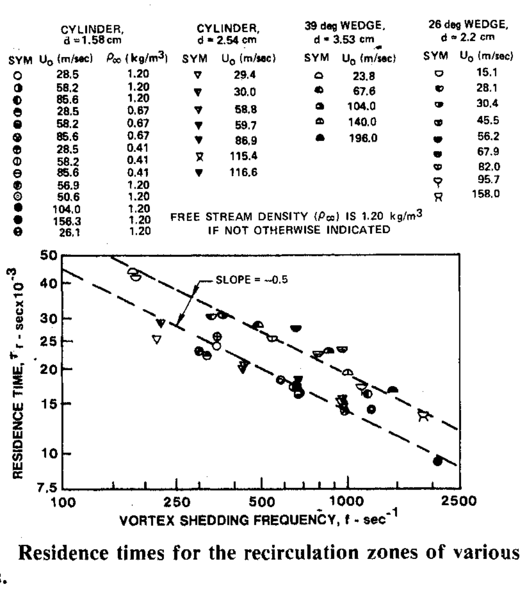

Fig. 1 Residence times for the recirculation zones of various bluff-bodies.

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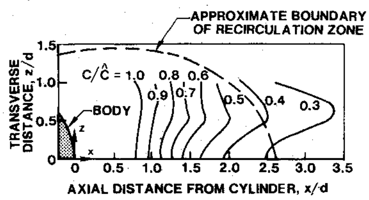

Fig. 2 Tracer concentration contour map: $d = 1.58$ cm, $U_\infty = 24$ m/sec, $P = 1$ atm. (P and U_∞ are freestream pressure and velocity, respectively).

width, B, determined by doubling the maximum half-width of the undisturbed portion of the recirculation zone, do not change materially with flow conditions for a given body. For the $d = 1.58$ cm cylinder, $L/d \cong 2.3$, and $B/d \cong 1.6$.

The increase in photometer system light transmission with time following the cessation of tracer injection is used to determine relative tracer concentration variations with the use of the Beer-Lambert law. The concentration is found to decrease in an exponential fashion with time until most of the tracer material has been transported out of the recirculation zone. The time required to reduce the tracer concentration to $1/e$ of its original concentration is taken as the tracer residence time τ_r.

Residence time data was acquired for variations in freestream velocity, density and turbulence level, and body type and diameter (see Fig. 1). The vortex shedding frequency f is a natural selection as the independent variable to emphasize the influence of the periodic nature of the bluff-body flow on near-wake transport. Shedding frequency was found from the Strouhal number, $S \equiv fd/U_o$, where U_o is the velocity at the body shoulder location, computed from the approach velocity and the blockage ratio. A variation of residence time with sheddding frequency to the -0.5 power is displayed independent of the outer flow velocity and density (for given mean flow conditions, τ_r was independent of turbulence intensity levels to 11%).[1] This successful residence time correlation supports the view that body-related turbulent transport is the dominant mechanism for the near-wake region in the subcritical Reynolds number regime which extends from 300 to 3×10^5. Note that the ratio of the intercepts of the parallel lines in Fig. 1 is 1.4, which is also the ratio of the Strouhal number for the wedge ($S = 0.26$) to that of the cylinder ($S = 0.185$) in the subcritical regime. Thus, a relationship which correlates all residence time measurements obtained can be written as

$$\tau_r = 2.37\, S \cdot f^{-1/2} \tag{1}$$

a result which may be useful for predicting the τ_r associated with other types of bluff-bodies.

Equation (1) can be faulted as being dimensional and, hence, intuitively unsatisfying. Attempts to introduce appropriate dimensionless groupings, e.g., $\tau_r U_o/d$, did not result in successful data correlation. Clearly, understanding of the physics of the two-dimensional, near-wake region is yet to be established. Nevertheless, analytical justification for the form of Eq. (1) can be provided. The transport coefficient ϵ for the near-wake region may be taken as the product of a characteristic disturbance length ℓ and a characteristic disturbance velocity. Identifying the source of flow agitation with the transition waves of Bloor,[2] then

$$\epsilon \sim \ell \cdot \ell f_t \tag{2}$$

Note that transition waves (turbulent bursts) having a frequency f_t may be detected in the near-wake using hot wire anemometry. In the Ref. 2 study for low-speed airflow over circular cylinders at subcritical Reynolds numbers, it was determined that the frequency of transition waves has the following dependencies:

$$f_t \sim U_o^{3/2} d^{-1/2} \tag{3}$$

Since the Strouhal number is approximately constant for the range of parameters considered in Ref. 2, it is possible to restate Eq. (3) in alternative, equivalent forms, e.g., at Reynolds number Re,

$$f_t \sim U_o^2/d\, f^{1/2} \sim Re\ U_o/d^2 f^{1/2} \tag{4}$$

where f is the vortex shedding frequency. Furthermore, if the characteristic length is taken as the (laminar) boundary-layer thickness at the point of separation,

$$\ell \sim d/Re^{1/2} \tag{5}$$

$$\epsilon \sim U_o/f^{1/2} \tag{6}$$

One additional manipulation is required to introduce the residence time. This is accomplished by making a tracer material balance for the recirculation zone, by equating the volumetric mass flux leaving the zone to that transported from the zone:

$$V/\tau_r = \epsilon \cdot d \tag{7}$$

Noting that the volume (V) of the two-dimensional zone can be expressed in terms of the maximum width and length of the recirculation zone

$$V \sim BL \sim d^2 \tag{8}$$

it follows that

$$\tau_r \sim d \cdot f^{1/2}/U_0 \tag{9}$$

Finally, for any two-dimensional bluff-body, i.e., Strouhal number, Eq. (9) can be rewritten as

$$\tau_r \sim S/f^{1/2} \tag{10}$$

Thus, Eq. (1) is at least consistant with existing observations.

Tracer concentration distributions in the two-dimensional recirculation zone downstream of the 1.58 cm diam cylinder were obtained by taking axial traverses with the fiber-optic probe at each of five transverse positions of the bluff-body. All axial tracer concentration distributions measured display common features. Initially, there is a gradual reduction in concentration to a point approximately one diameter in length downstream of the bluff body. Thereafter, the concentration (C) normalized with reference concentration ($\hat{C}$) decreases rapidly with axial distance (x) according to the familiar power law distribution associated with free jet centerline concentration decay:

$$C/\hat{C} \sim (x/d)^{\theta} \tag{11}$$

where θ, the decay exponent, is found to vary between -1.0 and -1.4 independent of freestream conditions and transverse location (z) in the range $0 \leq z/d \leq 1$. An obvious change in the decay rate occurs at distances from the bluff-body of 2 to 3 diameters, i.e., distances which correspond approximately to the longitudinal extent of the recirculation zone.

The distribution of tracer material throughout the recirculation zone is displayed in the contour map of Fig. 2. It is significant that the transverse distributions of tracer material are quite flat. Evidently, the motions within the recirculation zones operate to minimize transverse gradients and, therefore, a conceptually useful model of a one-dimensional recirculation zone characterized using Eq. (11) might be appropriate.

References

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[2] Bloor, M. S., "The Transition to Turbulence in the Wake of a Circular Cylinder," *Journal of Fluid Mechanics*, Vol. 19, June 1964, pp. 290-304.