Wake Structure of a Cube in a Quasihomogeneous Turbulent Flow

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Introduction

THE turbulent wake formed downwind of a building is characterized by a decrease in the mean velocity and an increase over background levels of the turbulence intensity of the flow. The initial turbulent near-wake region very near the building is dominated by the influence of the structure, whereas at some distance downstream, in the far-wake region, background turbulence dominates. The turbulence characteristics and extent of the near wake is of particular interest to the safe operation of light aircraft that taxi near structures like aircraft hangers. In addition, models of contaminant dispersion in the building wake must account for the transition from building-dominated turbulent dispersion to ambient turbulent dispersion when attempting to describe the concentration field. Since the character of the turbulence in the near wake depends on the approaching ambient mean shear and turbulence levels (Castro and Robins[1]), one would suspect that the extent of the near-wake region would also. Castro and Robins[1] added mean shear and turbulence to the approach flow and examined the effects on the turbulent dispersion and velocity profiles in the wake of a cube. They reported a significant increase in mixing in the near wake over that of the uniform, low-turbulence case as may be expected.

Huber and Snyder[2] reported on dispersion studies of contaminants released from a ground source at the center of the leeward edge of a modeled building with a width twice its height and depth. They found the transition to occur at a downstream distance of typically 10 model heights and subsequently proposed a model based on this value. It is suspected, however, that the transition point will vary depending on ambient turbulence levels and/or building dimensions. More recently, Huber[3] attempted to study the effect of ambient turbulence levels and building dimension on the near-wake zone, and although recognizing the influence of both on the extent of the near wake, he did not attempt to quantify the effects.

Ramsdell[4] also recognized the importance of both building dimension and ambient turbulence levels on the transition from the near wake to the far wake and subsequently attempted to account for these effects in his mathematical model of building wake dispersion.

The present Note reflects part of some recent work on the investigation of the effects of building dimension and ambient turbulence levels on the character of the turbulence in the wakes of model cubes in a water channel. The objective of this work was to identify the extent of the near wake and its dependence on both building dimension and ambient turbulence levels. Also, since one would expect that the principle scales of interaction between the wake turbulence and ambient turbulence would scale with the building dimension, an attempt was made at providing quantitative evidence of this.

Experimental Methods and Design

Laser Doppler anemometry (LDA) was used for measurements of the instantaneous turbulent velocity field in a water channel both without and with a square bar turbulence generating grid. Longitudinal turbulent intensities of less than 2% and to 10%, respectively, resulted in the ambient flow. Cubes of dimension $h = 2$, 3.5, and 5 cm were used to produce the wake flows of interest.

Flow velocities combined with the above cube dimensions to give a Reynolds number range of $1.3 \times 10^3 \leq Re_h \leq 3.5 \times 10^3$. Because of the maintenance of clean sharp edges on the aerodynamically rough cube surfaces, Reynolds number independence was maintained. Maximum blockage of the working cross section of the flume was less than 2%.

Experimental Equipment

The experiments were conducted in the fluid mechanics laboratory at the University of Waterloo, Waterloo, Ontario, Canada. The water channel is 12.2 m long with a working cross section 1.2 m wide and a nominal water depth of 0.8 m. It has a Plexiglas walled test section 2.4 m in length. Steady flow is maintained from a constant head tank. An intermediate velocity of 0.071 m/s (±0.002 m/s) was chosen for the present study. The apparent unsteadiness of approximately 3% in the mean flow of the flume was of sufficiently low frequency to not affect the rms measurements in the experiments. Flow straightners and metal screens were utilized at the head of the water channel to minimize all scales of turbulence in the ambient flow.

All velocity measurements were made using a nonintrusive four-beam, two-component LDA system with a 500-mW nominal output argon-ion laser. The optical system was used in forward scatter mode. Adequate seeding of the flow was a natural consequence of selecting water as the flow medium. Further details of the experimental equipment may be found in Musselman.[5]

The models were placed two cube dimensions downstream of the leading edge of a false floor placed well above the naturally occurring boundary layer of the water channel. This allowed for a nearly uniform approach flow at the leading edge of the model. The depth of the new boundary layer at the leading edge of the model was in all cases more than an order of magnitude less than the model dimension.

Since the intensity of the turbulence striking the face of all cubes would be approximately equal, the primary criterion used in sizing the cubes was the ratio of average longitudinal integral length scale of approach turbulence to characteristic dimension of the cube (L_u/h). The three cube sizes of $h = 5$, 3.5, and 2 cm had corresponding ratios L_u/h of 0.40, 0.56, and 0.98.

Measurements

Instantaneous velocity data were collected at various points downstream of each cube along the lateral centerline of the wake, at two different heights, $z/h = 0.5$ and 1.0. Several lateral profiles were used to verify symmetry of the wake, and additional vertical profiles were taken at various points downstream of the largest cube corresponding to the measurement locations used by Castro.[6] These data were used for comparison purposes for the case of a low-turbulence, uniform background flow. To ensure dependable spectra data and repeatable turbulence parameters, data sets of 40,960 points, sampled in 40 blocks of 1024 at 250 Hz even sampling, were taken at all locations, with and without the turbulence generating grid.

Results

Appropriate comparisons between the mean velocity and longitudinal turbulence intensity profiles of this study using LDA with that of Castro,[6] who used pulsed wire anemometry, revealed almost identical results, giving a degree of credibility and confidence in the present data set (see Musselman[5]).

Decay of Longitudinal Turbulence Intensity

Figure 1 illustrates the effect of the level of background turbulence on the longitudinal turbulence intensity in the wakes of the cubes.

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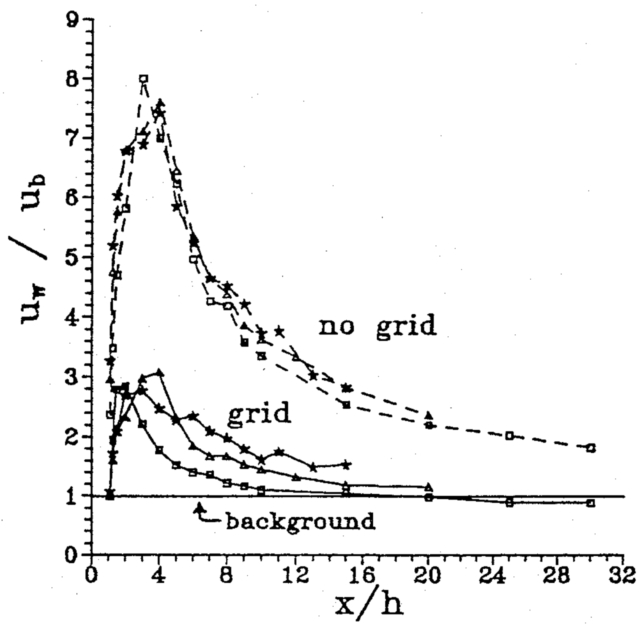

Fig. 1 Nondimensional decay of longitudinal turbulence intensity, z/h = 0.5. ■-■-■-■-■ 2-cm cube, ▲-▲-▲-▲-▲ 3.5-cm cube, ★-★-★-★-★ 5 cm cube.

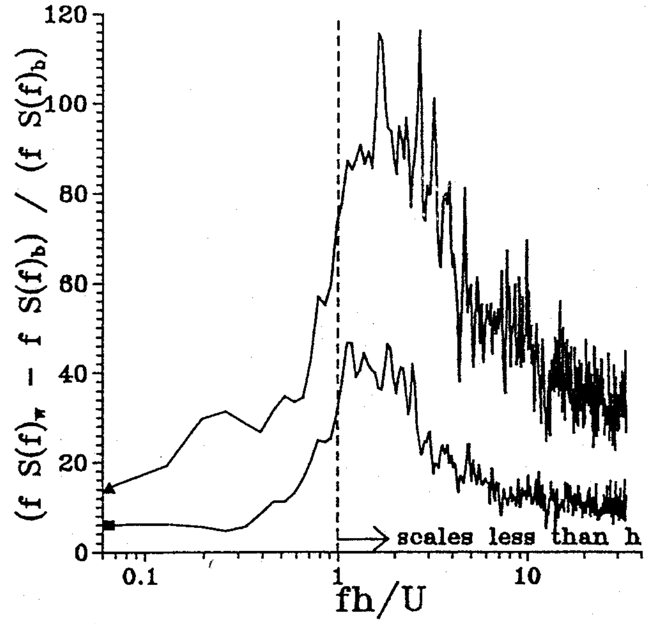

Fig. 2 Nondimensional energy spectra, 2-cm cube, high-turbulence approach, x/h = 1.5. ▲ z/h = 1.0, ■ z/h = 0.5.

The solid line at unity represents background turbulence levels, with u_w and u_b representing the rms velocity in the wake and background, respectively. There is a sharp increase in turbulence intensity from near zero very near the back edge of the cube to a peak at $x/h \approx$ 1.5–4 due to the strong shear flows close to the cube. The intensity ultimately decays to background levels. Turbulent eddies produced in the immediate wake primarily scale with the cube dimension h, and as the wake subsequently grows in size downstream, the turbulent energy redistributes itself over the larger scales of the wake dimension, resulting in the decay of turbulence intensity with downstream distance.

It is clear from Fig. 1 that the rate of decay to background turbulence levels increases with increasing background turbulence. Also, the rate of decay to background for all these cubes is similar in the low-turbulence background but decreases with increasing cube dimension in the higher background turbulence. This is indicated by a power law fit beyond $x/h = 4$, of the form $u_w/u_b \propto (x/h)^n$, $-0.70 < n < -0.40$ for 2- to 5-cm cubes in the high-turbulence grid flow. Clearly, the higher background turbulent energy is, as one would suspect, more effective at diminishing the influence of the near wake. From Fig. 1 one can see that for $L_u/h \approx 0.4$ (5-cm cube) the rate of decay is low, whereas for $L_u/h \approx$ unity (2-cm cube) the rate of decay is much faster. For the case not studied directly in this study, $L_u/h \gg 1$, the integral scales of background turbulence are much greater than that generated by the cube, and one would expect these low-frequency oscillations to affect the bodily movement of the wake but contribute little to the relative diffusion of momentum deficit. This effect is adequately illustrated by the behavior of the low-turbulence, almost laminar, no grid case. Thus the background turbulence has the most influence on the wake when the turbulent scales correspond to those of the wake dimension.

Spectral energy plots at downstream locations proved that the structure of the background turbulence was also recovered in the far wake at rates indicated by the turbulence intensities of Fig. 1.

Redistribution of Turbulent Energy in the Wake

The redistribution in the wake of the scales of the background turbulent kinetic energy to scales on the order of the cube dimension has been discussed previously in the literature (see Castro and Robins,[1] for example). The data obtained in the present experiment have allowed for a clear demonstration of this phenomenon. By normalizing the turbulence spectra in the near wake by the background turbulence spectra, the common shapes at the ends of the spectra are minimized and the differences are highlighted. Figure 2 clearly shows that in the near-wake region the scales of turbulence created are primarily at the scales of the cube dimension h or less.

Conclusions

The present data suggest that the location of the transition from the near wake to the far wake is a function of both the ratio of the integral scale of background turbulence to building dimension L_u/h as well as the intensity of the background turbulence. Further, as $L_u/h \to 1$, the rate of decay of wake turbulence to background is maximized and diminishes as $L_u/h \to 0$ or infinity.

Acknowledgment

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