

Local flow field of a surface-mounted finite square prism

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ABSTRACT: The local flow field of a surface-mounted finite-height square prism was studied experimentally in a low-speed wind tunnel using particle image velocimetry (PIV). The prism was mounted normal to a ground plane and was partially immersed in a flat-plate turbulent boundary layer. Four finite square prisms of aspect ratios $AR = 9, 7, 5$ and 3 were tested at a Reynolds number of $Re = 4.2 \times 10^4$. PIV velocity field measurements were made in a vertical plane parallel to the mean flow direction on the flow centreline, within two diameters upstream and five diameters downstream of the prism, and also above the free end. In the near-wake region, the large recirculation zone contains a vortex immediately behind and below the free end; the size and strength of this vortex increases as the aspect ratio of the prism decreases. A second vortex is found behind the prism near the prism-wall junction; this vortex was not observed for the prisms of $AR = 5$ and 3 , indicating a distinct wake structure for these prisms compared to those of $AR = 9$ and 7 .

KEYWORDS: Bluff body, finite square prism, near wake, recirculation zone, vortex structures, particle image velocimetry

1. INTRODUCTION

The flow around surface-mounted circular cylinders of finite height is more complex than the familiar case of a two-dimensional or “infinite” circular cylinder [1]. Surface-mounted cylinder-like or prismatic structures are found in many engineering applications, such as the flow past high-rise buildings, oil storage tanks, chimneys and cooling towers. For these bluff bodies, the flow field is strongly influenced by the flow around the free end and the flow around the junction between the cylinder and the surface.

The flow around a finite square prism of side length, D , and height, H , mounted normal to a ground plane (Fig. 1) is influenced by the aspect ratio, $AR (= H/D)$, the Reynolds number, $Re (= DU_\infty/\nu$, where U_∞ is the freestream velocity and ν is the kinematic viscosity), and the relative thickness of the boundary layer on the ground plane, δ/D (where δ is the boundary layer thickness at the location of the prism). The flow around the prism-wall junction (at the ground plane) and over the free end cause the local flow field to become strongly three-dimensional. Some of the most extensive insight into the wake vortex dynamics (vortex shedding, streamwise vortex structures) of the finite square prism comes from recent experimental studies by Wang et al. [2, 3], Wang and Zhou [4], and Bourgeois et al. [5]. These studies used a variety of experimental techniques, including flow visualization, thermal anemometry, laser Doppler velocimetry (LDV), and particle image velocimetry (PIV).

Because of the complexity of the flow field around the surface-mounted finite-height square prism, and the many influencing parameters, further study is needed to obtain a complete physical understanding of the wake behavior, especially very close to the prism, i.e., the local

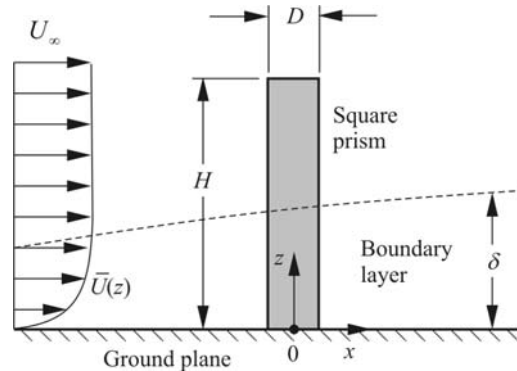


Figure 1. Schematic representation of the flow past a finite-height square prism mounted normal to a ground plane and partially immersed in a flat-plate boundary layer.

flow field. In the present study, the local flow fields of surface-mounted finite-height square prisms were investigated in a low-speed wind tunnel using the PIV technique. Of particular interest in the present study were the flow in the near-wake region and the effect of aspect ratio.

2. EXPERIMENTAL APPARATUS

The experiments were conducted in a low-speed closed-return wind tunnel with a test section of 1.96 m (length) $\times$ 0.91 m (height) $\times$ 1.13 m (width). The streamwise freestream turbulence intensity was less than 0.6% and the mean velocity non-uniformity outside the test section's wall boundary layers was less than 0.5%. An aluminum ground plane was installed on the floor of the wind tunnel test section and a fully developed turbulent boundary layer was produced on the ground plane at the location of the finite square prism.

Four different, smooth, aluminum square prism models, all of the same width, $D = 31.5$ mm, were tested. The free end of each prism was a flat surface with sharp perimeter edge. Each prism had a different height, giving prisms with AR = 9, 7, 5, and 3, similar to the earlier experiments of [1,6]. The prisms were anodized flat black to minimize unwanted reflections from the laser light sheet used for the PIV measurements. Each prism was partially immersed in the turbulent boundary layer on the ground plane. The experiments were conducted at a freestream velocity of $U_\infty = 20$ m/s, giving a Reynolds number, based on prism width, of $Re = 4.2 \times 10^4$.

The wind tunnel data were acquired using a computer with a 1.8-GHz Intel Pentium 4 processor, a National Instruments PCIe-6259 16-bit data acquisition board, and LabVIEW software. The freestream conditions were obtained with a Pitot-static probe, Datametrics Barocell absolute and differential pressure transducers, and an Analog Devices AD590 integrated circuit temperature transducer. To characterize the boundary layer on the ground plane, a boundary layer Pitot tube and an X-wire boundary layer probe were used to measure its mean velocity profile. At the location of the prism (with the prism removed), the boundary layer thickness was $\delta = 54$ mm providing a thickness-to-width ratio of $\delta/D = 1.7$ and a thickness-to-height ratio ranging from $\delta/H = 0.2$ (for AR = 9) to $\delta/H = 0.6$ (for AR = 3).

Velocity field measurements in the vicinity of the finite square prism were made with a PIV system. The laser light (532 nm) was supplied by a 200-mJ/pulse dual Nd:YAG Gemini PIV 15 laser from New Wave Research, which had a maximum pulse frequency of 15 Hz. A TSI

light arm was used to deliver the laser beam from the laser to the light sheet optics. The light sheet optics included either a -50-mm or -25-mm cylindrical lenses and 500-mm , 750-mm , or 1000-mm spherical lenses, depending on the location of the field of view. Images were acquired with a CCD camera (MegaPlus ES4020, double frames, 2048×2048 pixels) and captured by a 64-bit EDT PCI DV C-Link frame grabber on a computer workstation. The timing of the laser, camera, and frame grabber was controlled by a Berkeley Nucleonics 505-8C digital delay generator synchronizer. The flow was seeded by atomized propylene glycol droplets produced by a theatrical fog machine.

PIV measurements were made in vertical (x - z) planes located on the centreline of the test section ($y = 0$). The light sheet optics were located above the wind tunnel test section and the laser light was directed through a small aperture in the test section roof and towards the ground plane. The field of view was $61\text{ mm} \times 61\text{ mm}$ ($1.9D \times 1.9D$) yielding an image resolution of about $30\text{ }\mu\text{m/pixel}$. For the tallest prism (of $AR = 9$), more than 25 fields of view were used to build a composite picture of the flow field upstream and downstream of the prism. For each field of view, an ensemble of 1,000 sample images was acquired from which the mean velocity vector field was determined. Image pairs were processed with a half-padded FFT cross-correlation algorithm, a relative maxima peak detection algorithm, and a Gaussian sub-pixel interpolation algorithm. A Hart correlation-based (CBC) validation method [7] with 50% overlap was used for reducing the sub-pixel errors and eliminating spurious vectors from the PIV results. The cellular neural network (CNN) method [8] together with dynamic threshold outlier identification was used as a post-interrogation algorithm to detect spurious vectors in PIV measurements. Most fields of view were analyzed with initial interrogation areas of 32×32 pixels. Owing to large pixel displacements in some limited regions of the flow, initial interrogation sizes of 64×64 pixels were used in the remaining fields of view. In all cases a two-level analysis technique was used that halved the interrogation area size during the second pass. In addition, a 50% interrogation area overlap was used in all cases. The resulting velocity vector fields contained approximately 127×127 and 63×63 velocity vectors with a vector spacing (spatial resolution) of approximately $0.015D$ and $0.03D$, respectively. This spatial resolution is significantly greater than the seven-hole probe experiments of Sumner et al. [1], the X-probe measurements of Adaramola et al. [6], and the PIV studies of Wang and Zhou [4] and Park and Lee [9] in the literature. The uncertainty in the mean velocity measurements was estimated to be about 2%.

3. RESULTS AND DISCUSSION

Figure 2 shows the local mean velocity vector field on the wake centerline ($y/D = 0$) for each of the four prisms (of $AR = 9, 7, 5$, and 3); the corresponding mean flow streamlines are shown in Figure 3. In Figure 2, the in-plane mean velocity components are made dimensionless with the freestream velocity ($\bar{U}/U_\infty, \bar{W}/U_\infty$). The mean fields are calculated from an ensemble of 1,000 instantaneous PIV velocity fields.

Upstream of the prism, for all four aspect ratios, part of the approach flow moves up and over the tip and separates from the leading edge of the free end. No flow reattachment occurs on the free end (Figs. 2 and 3). The other part of the approach flow, closer to the ground plane, moves downwards as it nears the prism and recirculates upstream of the prism-wall junction. It is in this region where the familiar horseshoe vortex is located (although it cannot be discerned in Figs. 2 and 3). In the near-wake region, a strong downwash flow (downward-directed velocity vectors in Fig. 2) is observed immediately downstream of the free end in the near wake of the

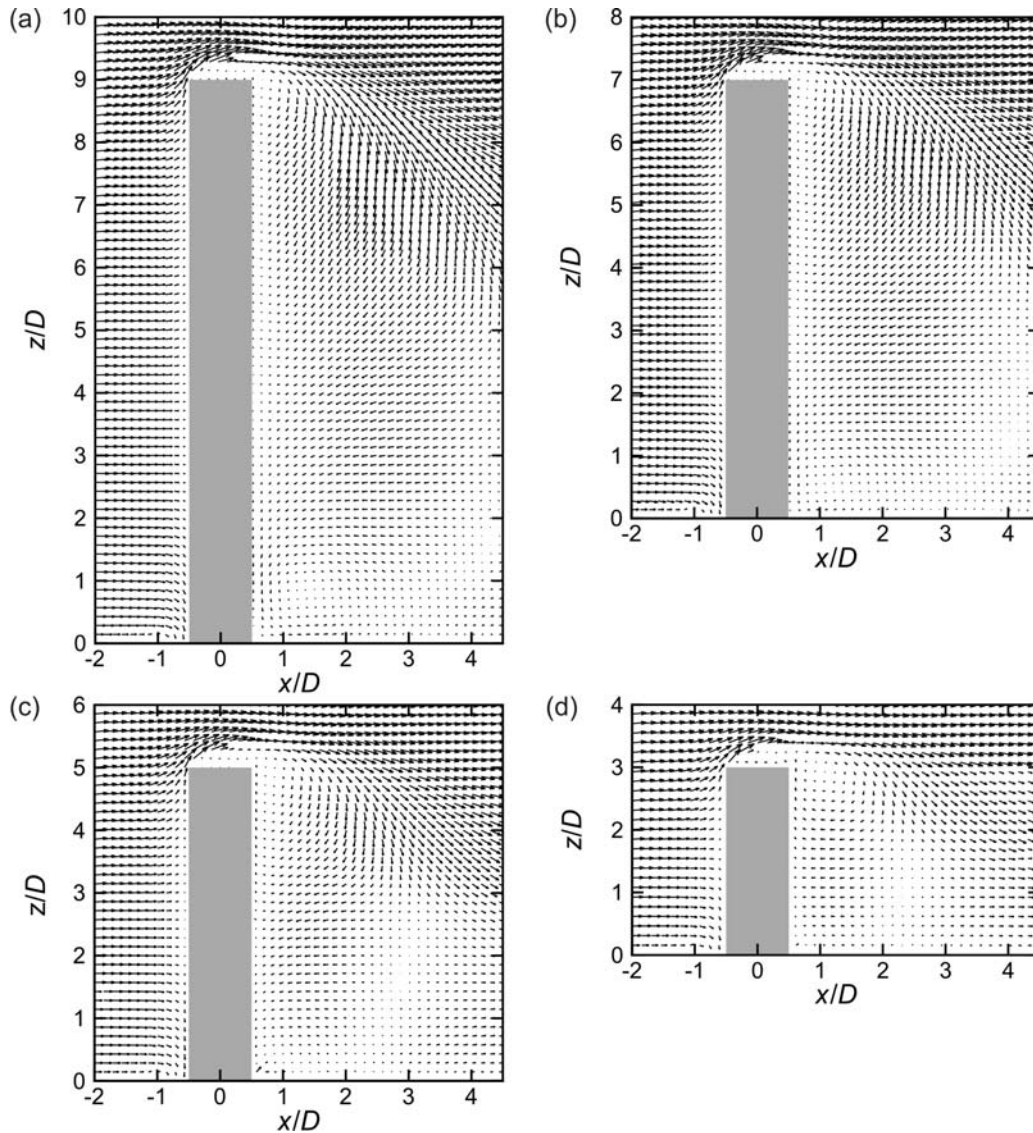


Figure 2. Mean velocity vector field ($\bar{U}/U_\infty$, $\bar{W}/U_\infty$ components) in a vertical plane on the wake centerline ($y/D = 0$, the symmetry plane): (a) AR = 9; (b) AR = 7; (c) AR = 5; (d) AR = 3.

prism (Fig. 2). The downwash originates downstream of the free-end recirculation zone, persists in the streamwise direction and descends into the central portion of the wake.

In the mean streamlines shown in Figure 3, part of the downwash flow is directed towards the ground plane and returns upstream to stagnate onto the rear surface of the prism; a large recirculation zone forms behind the prism. The rest of the downwash flow moves away from the prism into the far wake. As seen in Figure 3, a small vortex forms immediately downstream of the trailing edge of the free end. The size of the vortex is a function of the prism aspect ratio, such that the largest vortex occurs for the smallest aspect ratio (AR = 3, Fig. 3d). According to Figures 3a,b,c, for AR = 9, 7 and 5, respectively, some of the downwash flow is directed along the prism wall toward the ground plane, whereas for AR = 3 (Fig. 4d), flow moves upwards along the prism wall toward the free end, resulting in a larger vortex just below the free end.

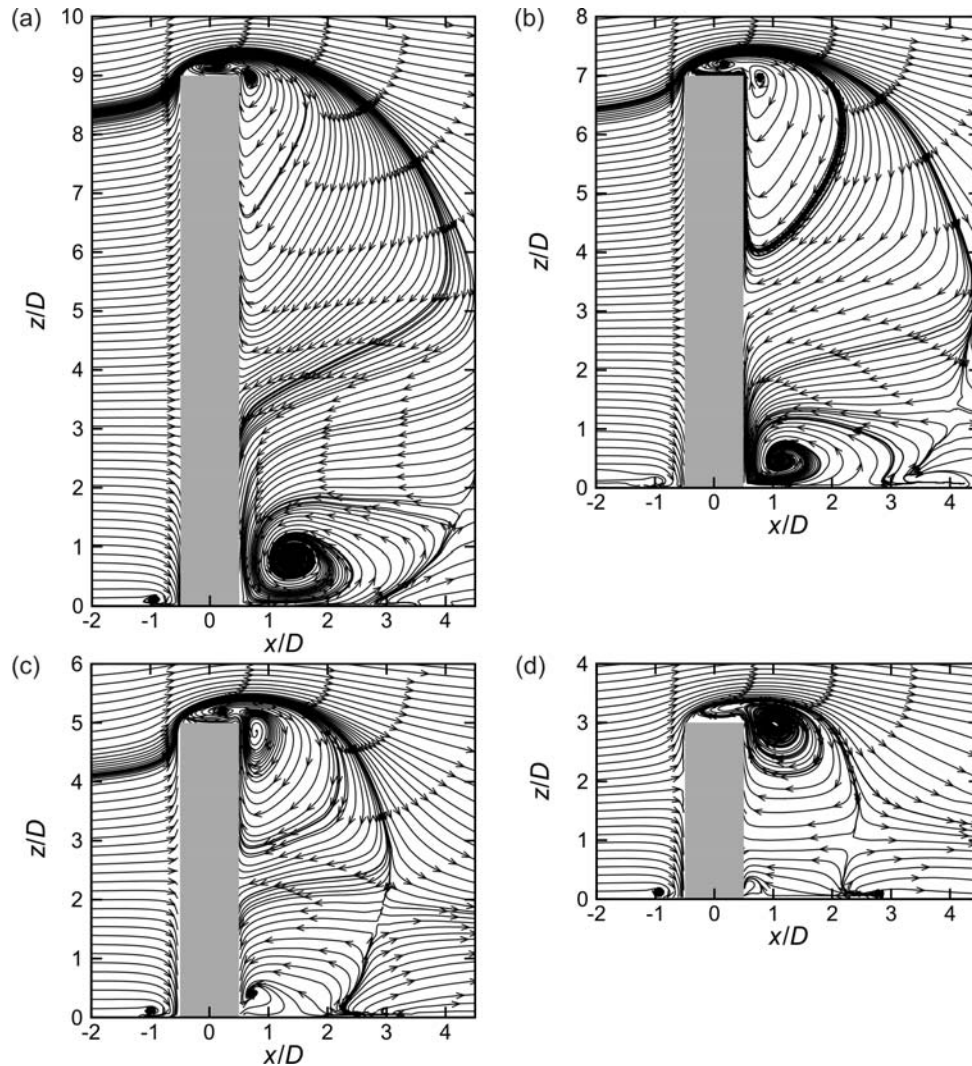


Figure 3. Mean streamlines in a vertical plane on the wake centerline ($y/D = 0$, the symmetry plane), corresponding to the mean velocity fields in Figure 2: (a) $AR = 9$; (b) $AR = 7$; (c) $AR = 5$; (d) $AR = 3$.

According to Figures 2 and 3, another vortex, with CCW sense of rotation, can be found immediately behind the prism, near the prism-wall junction, for $AR = 9$ and 7 (Fig. 3a,b); enlargements of these vortices are shown in Figure 4. This vortex is much weaker and nearly absent for the prisms of $AR = 5$ and 3 (Figs. 3c,d and 4c,d). The distinct near-wake structure for $AR = 3$, and to some extent for $AR = 5$, suggest the critical aspect ratio for these prisms is between $AR = 5$ and $AR = 3$.

Figure 5 shows how the maximum length of the recirculation zone is dependent on the square prism's aspect ratio. According to this figure, the maximum length of the recirculation zone increases from $L_{\max}/D = 2.3$ for $AR = 3$ to $L_{\max}/D = 4.2$ for $AR = 9$. In Figure 5, the present data are compared to the square prism data of Wang and Zhou [4] and Bourgeois et al. [5]. Good agreement can be seen between the present data and the other studies for prisms of $AR = 3, 5$, and 7 .

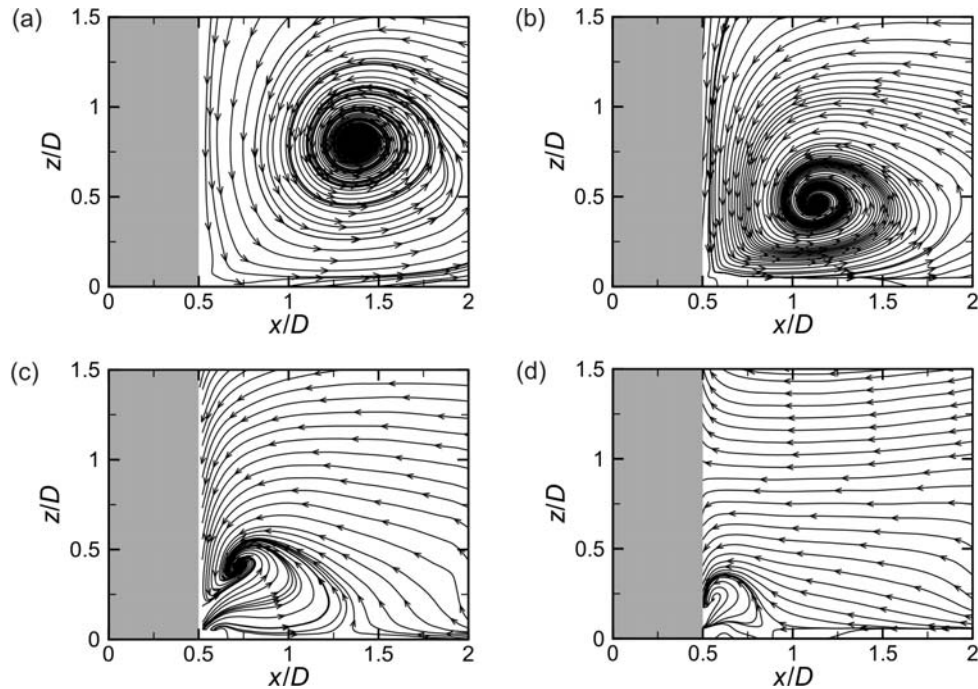


Figure 4. Mean streamlines immediately behind the prism at the junction with the ground plane: (a) AR = 9; (b) AR = 7; (c) AR = 5; (d) AR = 3.

A contour plot of the streamwise turbulence intensity (u'/U_∞), on the wake centreline, is shown in Figure 6. The highest values of streamwise turbulence intensity are encountered above the free end of the prisms of AR = 9, 7, and 5 (Figs. 6a,b,c), while the highest value of u'/U_∞ for AR = 3 (Fig. 6d) occurs farther downstream, showing a distinct turbulence structure for AR = 3. For all four prisms, the highest values of wall-normal turbulence intensity (w'/U_∞ , not shown) are encountered within the recirculation zones of the prisms. The location of highest wall-normal turbulence intensity in the near-wake region tends to move downward and towards the prism as the aspect ratio of the prism decreases.

The Reynolds shear stress field on the wake centreline for AR = 3 (Fig. 7d) is distinct from those for AR = 9, 7, and 5 (Fig. 7a,b,c). For the three most slender prisms, the near-wake region is characterized by two regions of elevated Reynolds shear stress: a region of negative shear stress at the top of the wake and a region of positive shear stress closer to the ground plane. For AR = 3 (Fig. 7d), however, the region of positive shear stress below the free end is almost absent, showing a distinct wake structure for this prism. Furthermore, the positive Reynolds shear stress just below the prism free end decreases in size and level as the aspect ratio of the prism decreases; it disappears for AR = 3.

The mean cross-stream vorticity ($\omega_y D/U_\infty$) fields for the four finite square prisms are shown in Figure 8. Upstream of the prism, the negative (CW) vorticity near the ground plane reveals the presence of the boundary layer and horseshoe vortex. For all four aspect ratios, negative vorticity is generated as the flow moves around the free end and downward into the near-wake of the prism. It is apparent that as the square prism aspect ratio decreases, the region of mean cross-stream vorticity behind the prism becomes larger in area and extends farther downstream. Close to the prism-wall junction, and immediately behind the prism, a small region of positive (CCW) vorticity is found for the prisms of AR = 9, 7 and 5 (Figs. 8a,b,c). This corresponds to the small recirculation shown earlier (Figs. 3a,b,c and 4a,b,c). Compared to AR =

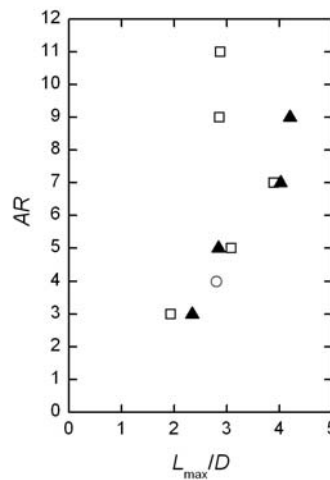


Figure 5. Maximum streamwise length of the mean recirculation zone for different aspect ratios. ▲, Present study, square prism, $Re = 4.2 \times 10^4$; □, Wang and Zhou [4], square prism, $Re = 9.3 \times 10^3$; ○, Bourgeois et al. [5], square prism, $Re = 1.2 \times 10^4$.

9, 7, and 5, no region of positive vorticity is found in the region immediately behind the prism at its junction with the wall for the prism of $AR = 3$ (Fig. 8d).

4. CONCLUSIONS

In the present study, the local flow field and near wake of a surface-mounted finite square prism were investigated in a low-speed wind tunnel at $Re = 4.2 \times 10^4$ using PIV. The prism was mounted normal to a ground plane and was partially immersed in a flat-plate turbulent boundary layer with $\delta/D = 1.7$ at the location of the prism. Four prism aspect ratios were considered, $AR = 9, 7, 5$, and 3 . PIV velocity measurements were made in a vertical plane on the flow centreline, upstream and downstream of the prism, with a special focus on the near-wake recirculation zone. The results of the present study have improved the limited state of information on the local flow field of a surface-mounted finite square prism and the influence of aspect ratio.

In the near-wake region, a large recirculation region forms behind the prism. Downwash flow enters the central portion of the wake where some flow from the free end reverses and moves toward the rear surface of the prism. A small vortex is located just downstream of the free end behind the prism and below the main downwash flow. This vortex is found for all four aspect ratios. Near the ground plane and close to the prism-wall junction, a second vortex forms; this vortex is weak or nearly absent for the prisms of $AR = 5$ and 3 . The maximum length of the recirculation zone (L_{max}/D) increases with the prism aspect ratio from $2.3D$ for $AR = 3$ to $4.2D$ for $AR = 9$. Elevated levels of wall-normal turbulence intensity and Reynolds shear stress also occur above the free end of the square prism. Cross-stream vorticity production also occurs around the free end and into the downwash region behind the prism. This region of mean vorticity extends farther downstream as the aspect ratio decreases.

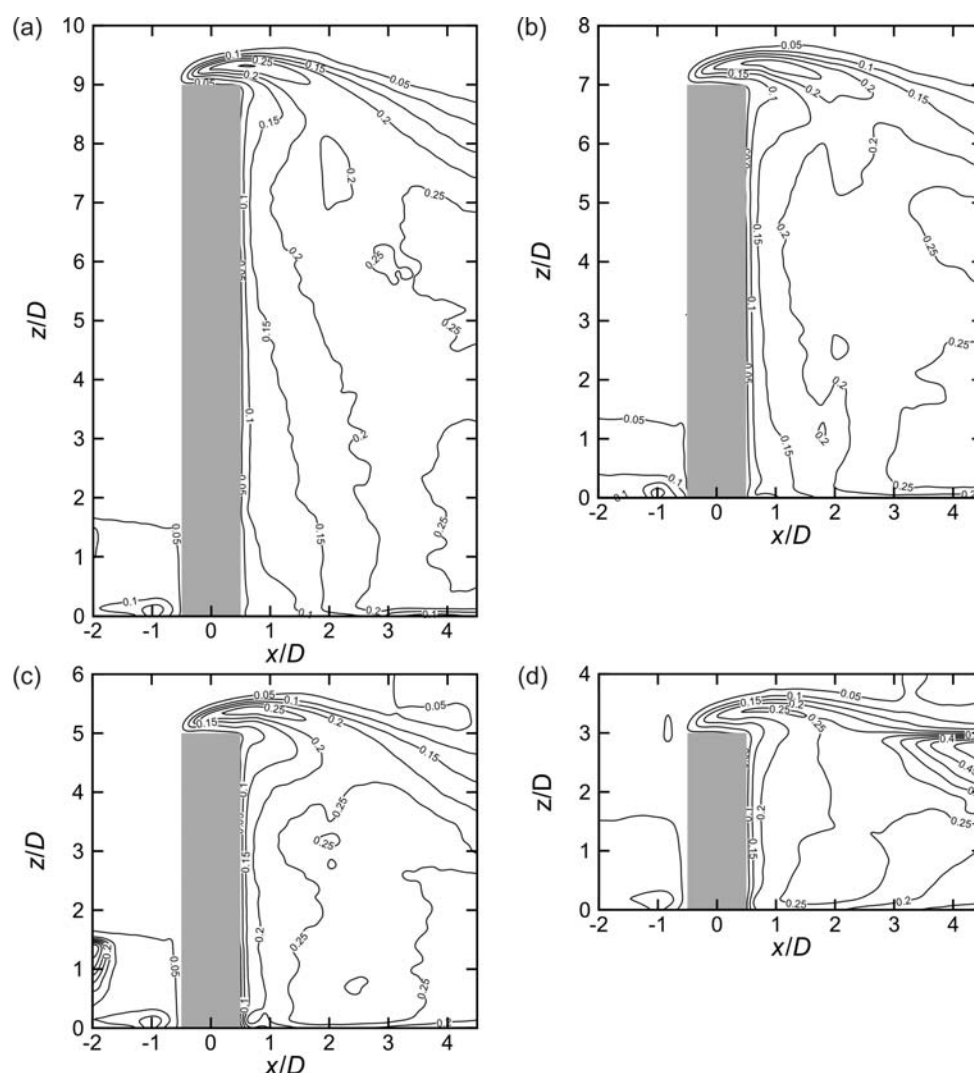


Figure 6. Streamwise turbulence intensity contours in a vertical plane on the wake centerline ($y/D = 0$, the symmetry plane): (a) $AR = 9$; (b) $AR = 7$; (c) $AR = 5$; (d) $AR = 3$.

ACKNOWLEDGMENTS

The authors acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC). The assistance of D.M. Deutscher and Engineering Shops is gratefully acknowledged.

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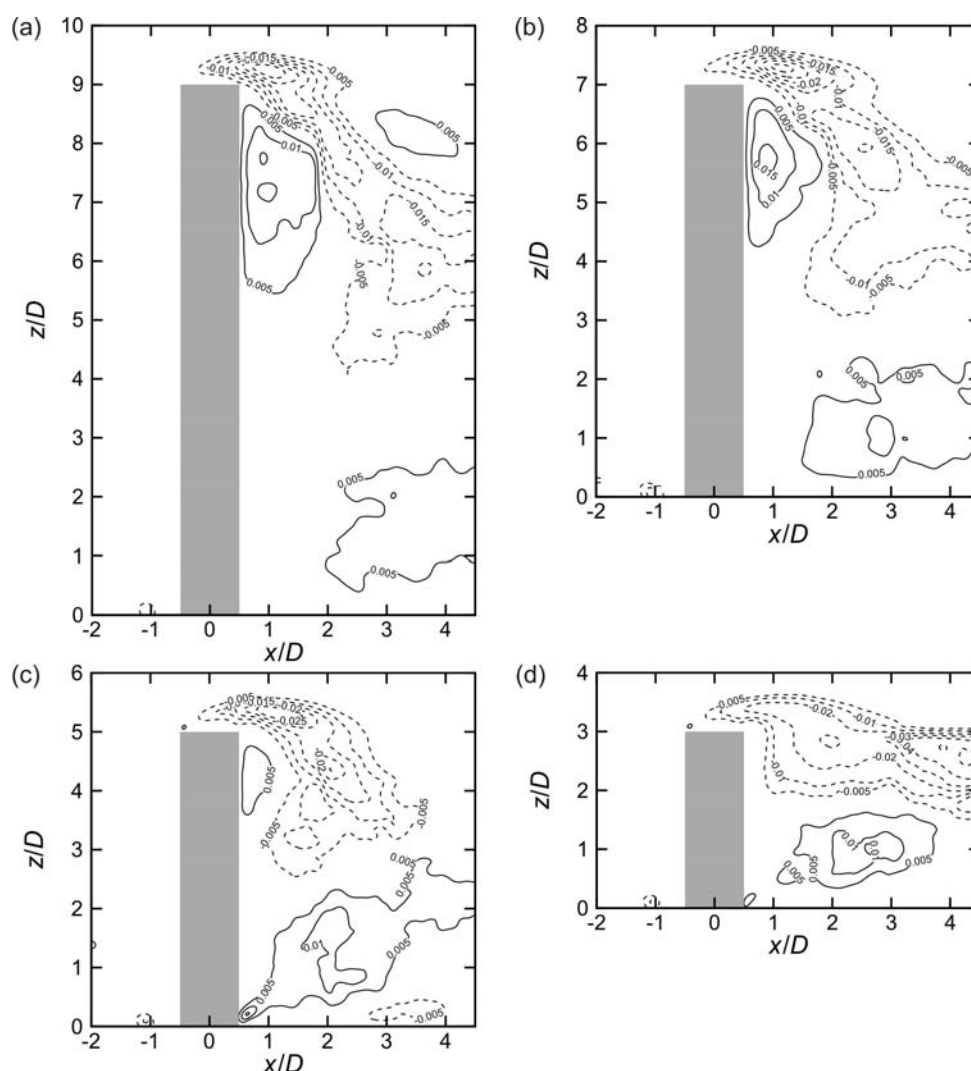


Figure 7. Reynolds shear stress contours in a vertical plane on the wake centerline ($y/D = 0$, the symmetry plane): (a) $AR = 9$; (b) $AR = 7$; (c) $AR = 5$; (d) $AR = 3$. Solid contour lines represent positive Reynolds shear stress, dashed contour lines represent negative Reynolds shear stress.

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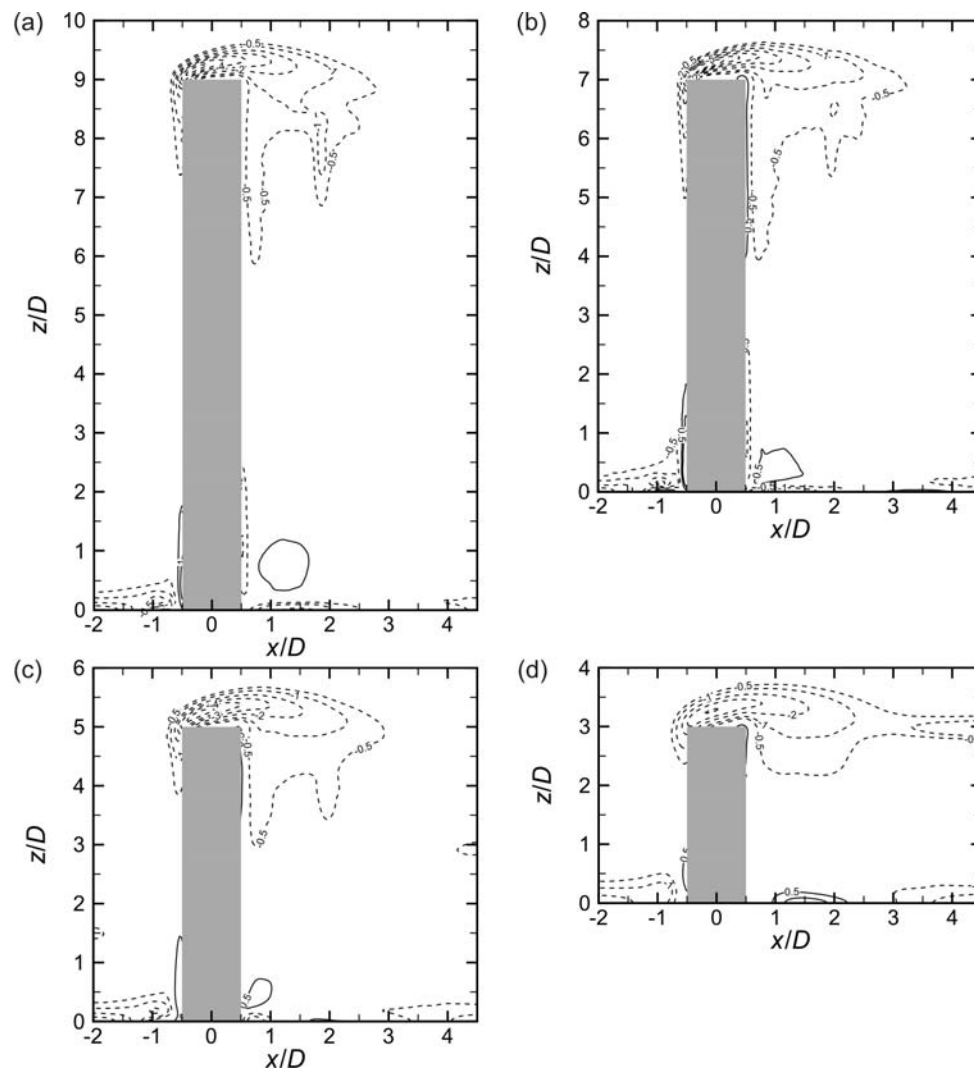


Figure 8. Mean in-plane dimensionless vorticity contours in a vertical plane on the wake centerline ($y/D = 0$, the symmetry plane): (a) $AR = 9$; (b) $AR = 7$; (c) $AR = 5$; (d) $AR = 3$. Solid contour lines represent positive (CCW) vorticity, dashed contour lines represent negative (CW) vorticity.