

Flow above the free end of a surface-mounted square prism

N. Rostamy, J.F. McClean, D. Sumner, D.J. Bergstrom, J.D. Bugg

*Department of Mechanical Engineering, University of Saskatchewan
57 Campus Drive, Saskatoon, Saskatchewan, Canada*

ABSTRACT: The flow above the free end 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 above the free ends in three vertical planes parallel to the mean flow direction at cross-stream locations of $y/D = 0$ (the flow centreline), 0.25 , and 0.375 (where D is the side length of the square prism). The results show how the prism's aspect ratio influences the mean velocity field and the Reynolds stresses above the free end surface of the prism. A cross-stream vortex forms in the region of separated flow above the free end of the square prism, due to interaction between the separated flow from the leading edge of the prism and reverse flow over the free end. The centre of this vortex moves downstream and upwards as the aspect ratio is lowered. Another cross-stream vortex forms immediately behind the prism; the size and strength of this vortex increases as aspect ratio of the prism is lowered.

KEYWORDS: Bluff body, finite square prism, separated flow, vortex structures, particle image velocimetry

1. INTRODUCTION

The flow around surface-mounted circular cylinders and square prisms of finite height is more complex than the familiar case of a two-dimensional or “infinite” circular cylinder or prismatic body [1]. In engineering applications such as high-rise buildings, oil storage tanks, cooling towers, and chimneys, the flow fields of these prismatic structures are strongly three-dimensional due to the effect of the flow around the free end and the flow at the prism-wall junction.

A schematic of the flow past a surface-mounted finite-height square prism (of side length, D , and height, H), mounted normal to a ground plane and partially immersed in a flat-plate boundary layer (with thickness δ at the location of the prism), is shown in Figure 1. In this figure, x is the streamwise coordinate, y is the cross-stream coordinate, and z is the wall-normal coordinate. The flow field 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 or δ/H .

The flow field over and above the free end of the finite-height prism influences the flow pattern in the near-wake region, including the formation of a pair of mean streamwise trailing vortex structures in the upper wake and the downwash (downward-directed) flow associated with it. Few studies of finite circular cylinders and square prisms have examined, in detail, the flow separation on the free end and its potential for reattachment. Kawamura et al. [2] studied the flow pattern on the free ends of finite circular cylinders of $AR = 8, 4$ and 1 with $\delta/D = 1$ at $Re =$

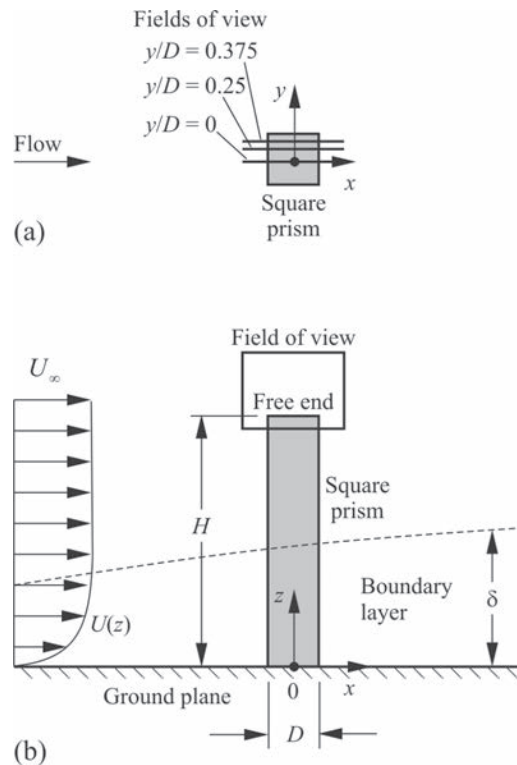


Figure 1. Schematic of the flow around a surface-mounted finite-height square prism partially immersed in a flat-plate boundary layer (with mean velocity profile, $U(z)$): (a) top view, showing the cross-stream positions of the fields of view for the particle image velocimetry (PIV) measurements; (b) side view, showing the field of view in the vicinity of the free end.

1.1×10^4 to 3.2×10^4 . According to their flow visualization results, reattachment of the separated flow on the free end was sensitive to both AR and δ/H : reattachment of the flow on the upper surface occurred for the most slender and the least slender cylinders (for $AR = 8$ and $\delta/H = 0.125$ and $AR = 1$ and $\delta/H = 1$) but not for the intermediate cylinder (for $AR = 4$ and $\delta/H = 0.25$). Leder [3] studied the flow past a finite circular cylinder of $AR = 2$ at $Re = 2 \times 10^5$ and with $\delta/D = 0.008$ using laser Doppler velocimetry (LDV). On the central vertical plane of the flow field, flow separated at the leading edge of the free end surface and reattached close to the trailing edge, at $x/D = 0.34$ (where x is measured from the centre of the cylinder). Weak recirculating flow was seen inside the time-mean separation bubble. Park and Lee [4] studied the flow around the free end of a finite circular cylinder of $AR = 6$ at $Re = 7,500$ using flow visualization, thermal anemometry, and particle image velocimetry (PIV). On the flow centreline, reattachment of the separated flow on the free-end surface was observed. Pattenden et al. [5] experimentally investigated the flow over a small-aspect-ratio surface-mounted finite circular cylinder of $AR = 1$ (well below a typical value for the critical aspect ratio), using PIV, surface flow visualization, and unsteady surface pressure measurements. Their results showed flow separation at the leading edge of the free end surface and, along the centreline, reattachment on the top of the circular cylinder at $x/D = 0.17$ (measured from the centre of the cylinder).

Recently, Krajnović [6] used large eddy simulation (LES) to study the flow around a finite circular cylinder with $AR = 6$, and reported that the flow on the top surface of the cylinder includes a large primary recirculation region and a secondary recirculation region. He showed

that the large recirculation region originates at the leading edge of the cylinder and reattaches at approximately $0.82D$ from the leading edge (i.e., at $x/D = 0.32$, as measured from the centre of the cylinder) in the streamwise direction and in the symmetry plane ($y = 0$). The results of his simulations disagree with the tip flow structure suggested by Roh and Park [7] but were in general agreement with the results of Pattenden et al. [5] and Kawamura et al. [2].

The above examples are all for the case of the finite circular cylinder. For the finite square prism, recent experimental studies have focused mostly on the wake dynamics [8–11], but without considering in depth the flow above the free end of the square prisms. In the present study, the flow field above the free-end surface of a surface-mounted, finite-height square prism was investigated in a low-speed wind tunnel using PIV. Of particular interest were the effects of prism aspect ratio on the flow field.

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, $D = 31.5 \text{ mm}$, 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 earlier experiments of [1,12]. 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 $U_\infty = 20 \text{ m/s}$, 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 $\delta = 54 \text{ mm}$ 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 -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 above the free end surfaces of the prisms in vertical (x - z) planes located on the centreline of the model ($y/D = 0$) and at two offset locations ($y/D = 0.25$ and 0.375); the locations of these fields of view are shown in Figure 1. 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. Each field of view was $61 \text{ mm} \times 61 \text{ mm}$ ($1.9D \times 1.9D$) yielding an image resolution of about $30 \mu\text{m}/\text{pixel}$. 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 [13] 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 [14] together with dynamic threshold outlier identification was used as a post-interrogation algorithm to detect spurious vectors in PIV measurements. The fields of view were analyzed with interrogation areas of 64×64 pixels. A two-level analysis technique was used that halved the size during the second pass. In addition, a 50% interrogation area overlap was used in all cases. The resulting velocity vector fields contained approximately 63×63 velocity vectors with a vector spacing (spatial resolution) of approximately $0.03D$. The uncertainty in the mean velocity measurements was estimated to be about 2%.

3. RESULTS AND DISCUSSION

Figure 2 shows the mean flow streamlines (obtained from the in-plane mean velocity components, $\bar{U}/U_\infty$, $\bar{W}/U_\infty$), on the wake centerline ($y/D = 0$) for each of the four prisms (of $AR = 9, 7, 5$, and 3). 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. 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 Fig. 2). In the near-wake region, a strong downwash flow is observed immediately downstream of the free end in the near wake of the prism. The downwash originates downstream of the free-end recirculation zone, persists in the streamwise direction and descends into the central portion of the wake.

The mean streamlines show that 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. 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. 2d). According to Figures 2a,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. 2d), flow moves upwards along the prism wall toward the free end, resulting in a larger vortex just below the free end.

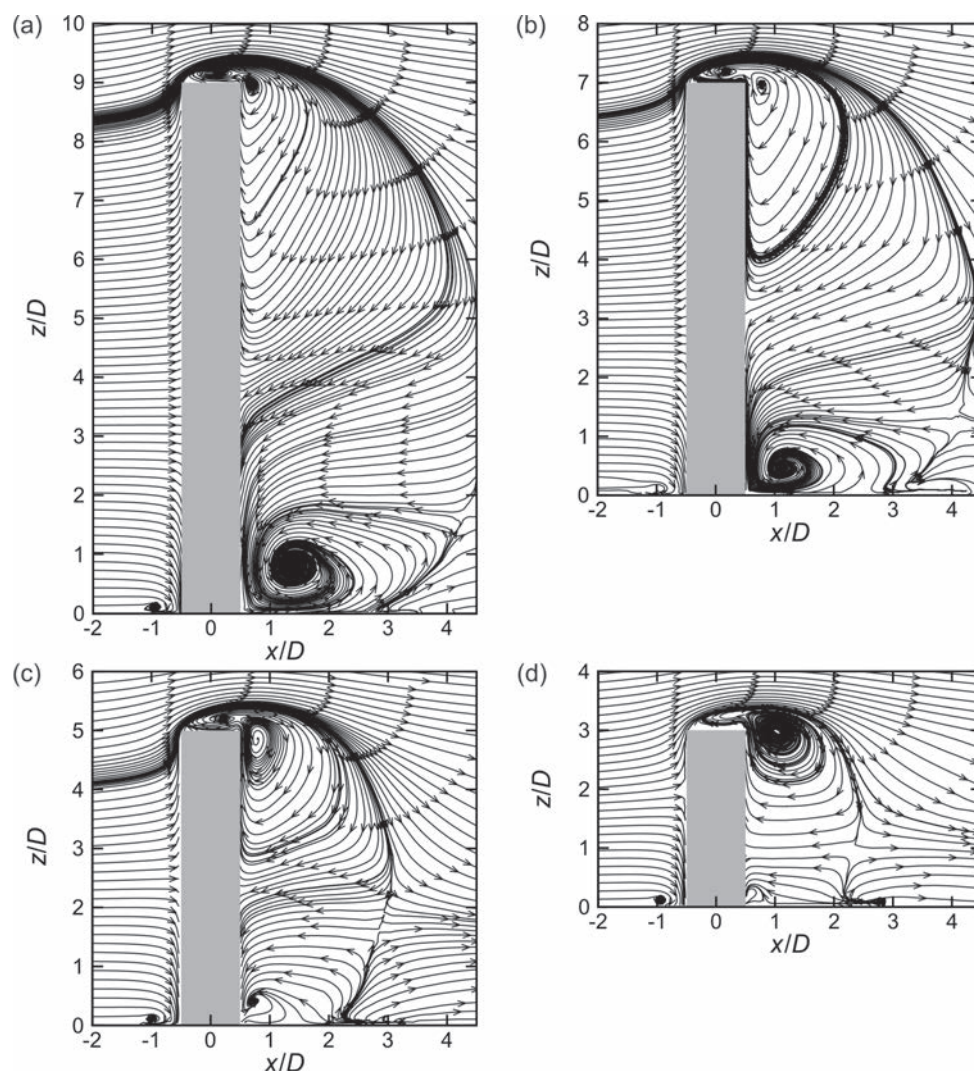


Figure 2. Mean streamlines in a vertical plane on the wake centerline ($y/D = 0$, the symmetry plane): (a) $AR = 9$; (b) $AR = 7$; (c) $AR = 5$; (d) $AR = 3$.

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. 2a,b). This vortex is much weaker and nearly absent for the prisms of $AR = 5$ and 3 (Fig. 2c,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 3 shows an enlarged view of mean streamlines (on the flow centreline) and the CW vortex behind the square prism close to the trailing edge of the prism's free end surface. The size of the vortex is a function of aspect ratio, such that the largest vortex occurs for the smallest aspect ratio ($AR = 3$, Fig. 3d). This vortex is related to the flow direction along the rear surface of the prism (seen in Fig. 2). The centre of the vortex moves downstream as the prism aspect ratio decreases.

The mean streamlines above the free ends (on the flow centreline) of the square prisms are shown in Figure 4. Flow separating from the leading edge does not reattach onto the upper surface but extends into the near-wake region. Another small region of locally separated flow

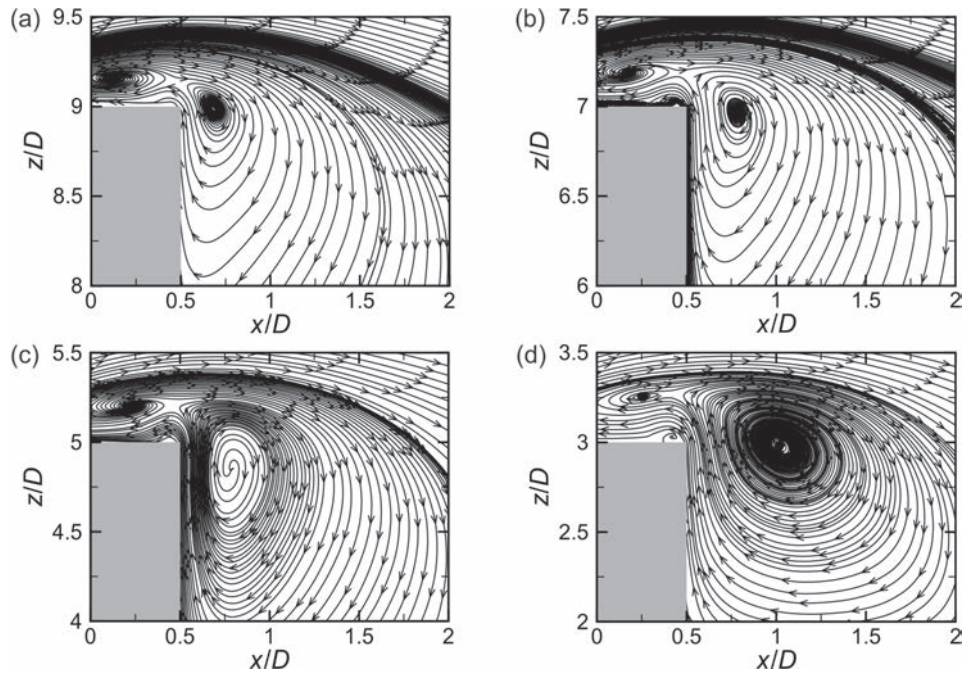


Figure 3. Mean streamlines immediately above and behind the prism, on the flow centreline (an enlargement of what is shown in Fig. 2): (a) AR = 9; (b) AR = 7; (c) AR = 5; (d) AR = 3.

may be seen on the upper surface just upstream of the trailing edge. A cross-stream vortex forms above the free end of the square prism, due to interaction between the separated flow from the leading edge of the prism and the reverse flow over the trailing edge. The role of the reverse flow coming up from the near wake of the prism and moving upstream over the free end surface is to form the vortices and saddle points in Figure 4. However, the behaviour of the reverse flow and its interaction with the separated flow changes with AR, and its overall behaviour is connected with the entire flow field around the prism. As seen in Figure 4, the centre of the cross-stream vortex moves downstream and upwards as the aspect ratio is lowered. Just behind this vortex, a saddle point is observed. As the aspect ratio is lowered, the locations of the vortex centre and saddle point are displaced farther away from the free end surface, moving from $z/D \approx 0.15$ above the surface for AR = 9 (Fig. 4a) to $z/D \approx 0.25$ for AR = 3 (Fig. 4d).

Contour plots of the streamwise turbulence intensity (u'/U_∞), above the free ends (on the flow centreline) of the finite square prisms are shown in Figure 5. This figure illustrates regions of elevated streamwise turbulence intensity above the free end surfaces that extend prominently downstream of the prisms. According to Figure 5, for all aspect ratios, the streamwise turbulence intensity level increases from its minimum value close to the free end surface to its highest level occurring along the shear-layer boundary between the outer flow and the mean recirculation zone. The maximum level of turbulence intensity for the prism of AR = 9 (Fig. 5a) is $u'/U_\infty \approx 0.43$, while for AR = 7, 5, and 3 (Fig. 5b,c,d) its value is $u'/U_\infty \approx 0.4$. For finite circular cylinders, however, the highest levels of u'/U_∞ are almost twice those for square prisms [15]. According to Figure 5, the region of highest level of u'/U_∞ is approximately located $0.2D$ to $0.3D$ above the free end surfaces of the square prisms and in the streamwise position range of $x/D = -0.3$ to -0.2 .

Figure 6 shows the contours of the in-plane Reynolds shear stress field ($-\overline{u'w'}/U_\infty^2$) above the free end surfaces of the finite square prisms. The flow above the free end is characterized by

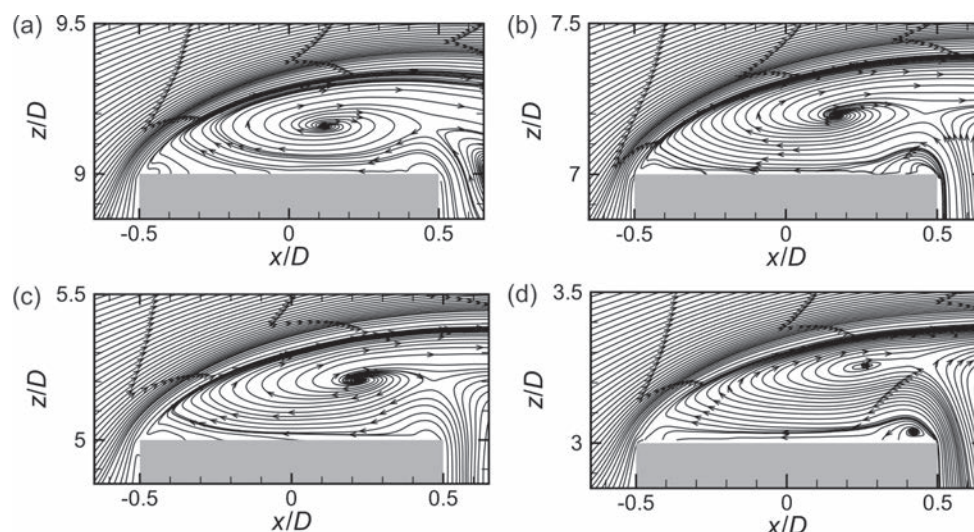


Figure 4. Mean streamlines above the free end on the flow centreline (an enlargement of what is shown in Figs. 2 and 3): (a) AR = 9; (b) AR = 7; (c) AR = 5; (d) AR = 3.

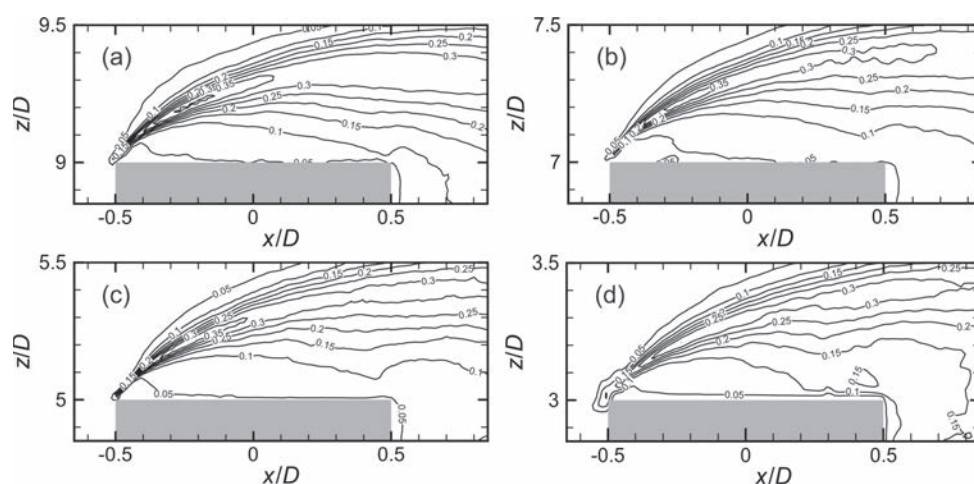


Figure 5. Streamwise turbulence intensity contours in a vertical plane on the wake centerline ($y/D = 0$, the symmetry plane): (a) AR = 9; (b) AR = 7; (c) AR = 5; (d) AR = 3.

two regions of elevated Reynolds shear stress: a region of negative shear stress above the free end that extends into the upper part of the near-wake region, and a region of positive shear stress originating from the leading edge and following the separated shear layer bounding the mean recirculation zone. The Reynolds shear stress behaviour does not change significantly as the aspect ratio of prism changes. However, as the prism aspect ratio increases, the region of negative Reynolds shear stress becomes wider so that for the prism of AR = 9 (Fig. 6a), the contour of negative Reynolds shear stress reaches the trailing edge of the free end surface.

Figure 7 shows the mean streamlines in three vertical (x - z) planes above the free ends of the square prisms; the three planes correspond to the three cross-stream positions of $y/D = 0$, 0.25, and 0.375 (illustrated in Fig. 1). According to Figure 7, the mean flow pattern above the free end of a square prism of a given aspect ratio changes considerably moving away from the

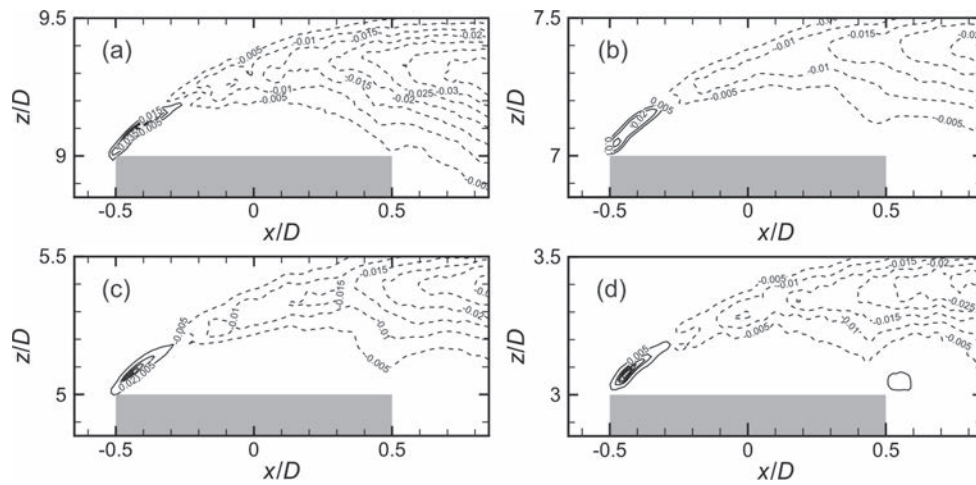


Figure 6. Reynolds shear stress contours in a vertical plane on the wake centerline ($y/D = 0$, the symmetry plane): (a) $AR = 9$; (b) $AR = 7$; (c) $AR = 5$; (d) $AR = 3$. Solid contour lines represent positive Reynolds shear stress, dashed contour lines represent negative Reynolds shear stress.

flow centreline. For the square prisms of $AR = 9, 7$, and 5 , the cross-stream vortex seen at $y/D = 0$ (Fig. 7a,d,g), is absent away from the symmetry plane, however, the cross-stream vortex is still present at all the y/D positions considered for the prism of $AR = 3$ (Fig. 7j,k,l)). In addition, the reverse flow and its local separation from the trailing edge is more dominant for the prism of $AR = 3$ at different y/D locations (Fig. 7j,k,l), while for the more slender prisms ($AR = 9, 7$, and 5), the effect of the shear layer separated from the leading edge is more dominant than the reverse flow as the distance from the symmetry plane increases (Fig. 7a-i).

4. CONCLUSIONS

In the present study, the flow field above the free end surface of a surface-mounted finite square prism was 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 vertical planes at the cross-stream locations of $y/D = 0, 0.25$, and 0.375 above the free end of the prism.

Flow separation occurs from the leading edge of the free end and the separated flow extends into the near-wake region. Unlike the circular cylinder case, there is no reattachment of the separated flow on the free end surface. A prominent CW vortex is found within the mean recirculation zone above the free end. A second CW vortex is found downstream in the upper part of the near wake. Elevated levels of turbulence intensity and Reynolds shear stress occur above the free end. The reverse flow and its local separation from the trailing edge of the free end surface was more dominant for the prism of $AR = 3$ at different cross-stream locations (y/D), while for prisms of $AR = 9, 7$, and 5 , the effect of the shear layer separated from the leading edge was more dominant than the reverse flow as the cross-stream distance (y/D) increases. The results suggest a distinct flow pattern and behaviour for the finite square prism of $AR = 3$, and place the critical aspect ratio between $AR = 3$ and $AR = 5$ for these experimental conditions.

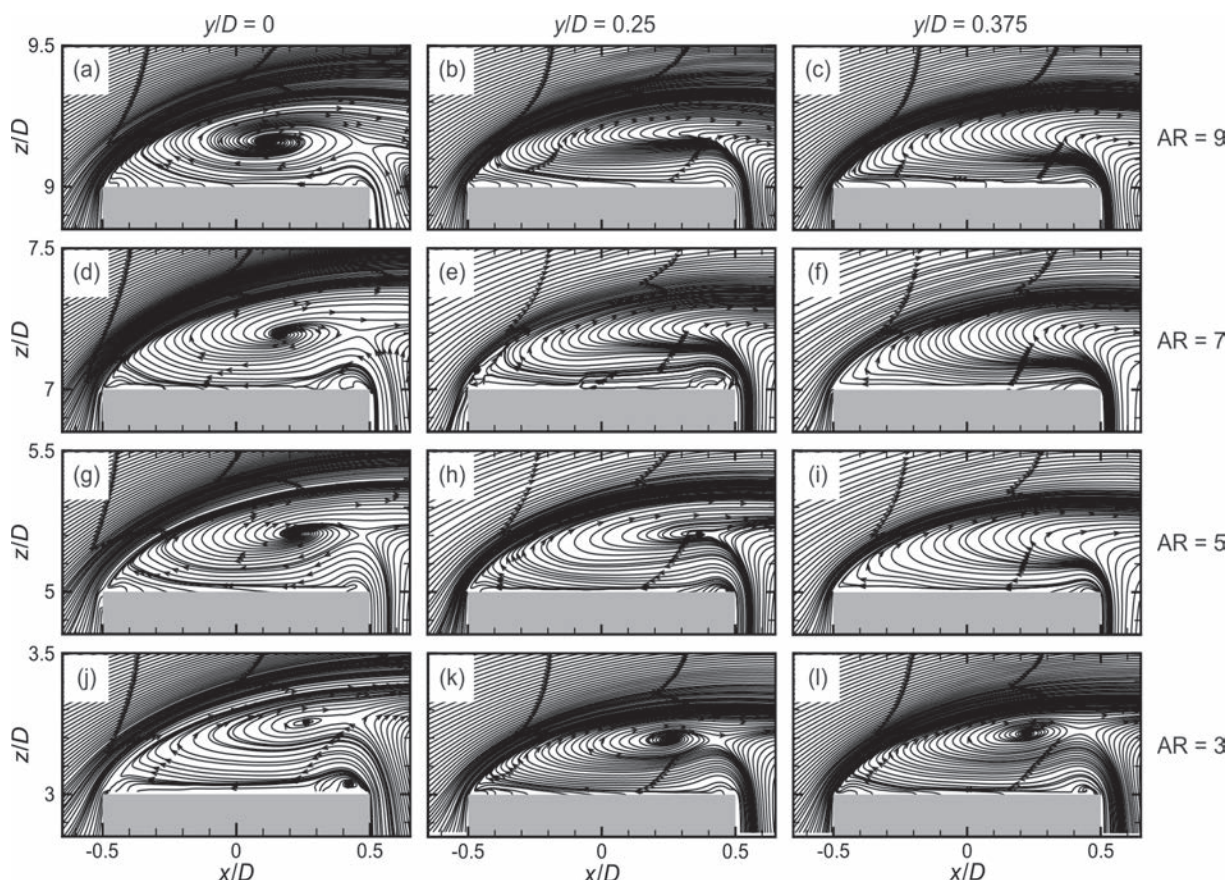


Figure 7. Mean streamlines for the flow over the free end of the finite square prism for aspect ratios of $AR = 9$ (first row, (a,b,c)), $AR = 7$ (second row, (d,e,f)), $AR = 5$ (third row, (g,h,i)), and $AR = 3$ (fourth row, (j,k,l)), for measurements made in vertical planes at $y/D = 0$ (left column, (a,d,g,j)), $y/D = 0.25$ (middle column, (b,e,h,k)), and $y/D = 0.375$ (right column, (c,f,i,l)).

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