An Experimental Study of the Near-Wake Region of Low-Aspect-Ratio Surface-Mounted Flat Plates

K. Baron and D. Sumner

Abstract A surface-mounted flat plate is an important fundamental shape in fluid dynamics, due to the interaction of the plate with the boundary layer on the surface (or ground plane), and the vortex structures produced in the wake. The plate acts as a bluff body when oriented normal to the flow. When angled with respect to the flow, a low-aspect-ratio flat plate may be used as a vortex generator. In the present study, the flow over a surface-mounted flat plate is examined experimentally in a low-speed wind tunnel using a seven-hole pressure probe and particle image velocimetry, with the aim of better understanding the behaviour of the flow in the near wake. This study investigates the wake region for four low-aspect-ratio rectangular flat plates with aspect (height-to-width) ratios of AR = 0.2, 0.35, 0.5, and 1. In each test, the plate was oriented normal to the flow, with a boundary layer thickness to plate width ratio of $\delta/D = 0.6$ and a Reynolds number of Re = 7.5×10^4. For the three lowest aspect ratios, there were two streamwise vortex pairs within the wake, leading to upwards flow at the centerline and one region of downwash on either side. Additionally, in the vertical symmetry plane, these three aspect ratios had a saddle point near the downstream edge of the recirculation zone that defines the flow field and leads to regions of upward and downward directed flow at the edge of the mean recirculation zone. In contrast, for the plate with AR = 1, there is only downwash on the wake centerline, a single pair of streamwise vorticity concentrations, and the saddle point is absent in the vertical symmetry plane.

Keywords Bluff body · Flat plate · Near wake

1 Introduction

Flow around a simple surface-mounted rectangular flat plate (Fig. 1) is an important fundamental shape in fluid dynamics, whether as a bluff body when the plate is oriented normal to the flow [1, 2], or as a vortex generator [3–5] when the plate is

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placed at an angle to the flow. For both examples, of specific interest are the interaction of the plate with the boundary layer on the surface (or ground plane) as well as the behaviour of the vortex structures that are produced in the wake. As a bluff body, surface-mounted flat plates resemble various structures, such as signs, fences, and windbreaks. As a vortex generator, the surface-mounted flat plate generates a strong streamwise vortex close to the surface that increases momentum transport towards the wall, re-energises the boundary layer, and delays flow separation. The flow around the plate is influenced by its shape (e.g., rectangular, trapezoidal), aspect ratio (AR $= H/D$, where H and D refer to the plate's height and width, respectively), and angle with respect to the flow (β, where $\beta = 90°$ refers to the plate oriented normal to the flow, as in Fig. 1). The relative thickness of the boundary layer on the ground plane, δ/D or δ/H, will also influence the flow. In the present study, the flow around surface-mounted rectangular flat plates is studied for the typical bluff-body configuration ($\beta = 90°$) for different aspect ratios. An experimental approach is adopted using a low-speed wind tunnel, seven-hole probe measurements, and particle image velocimetry (PIV). The novelty of this study of flat plates compared to others in the literature is its focus on near-wake recirculation zone and the streamwise vortex structures, which have not been extensively reported.

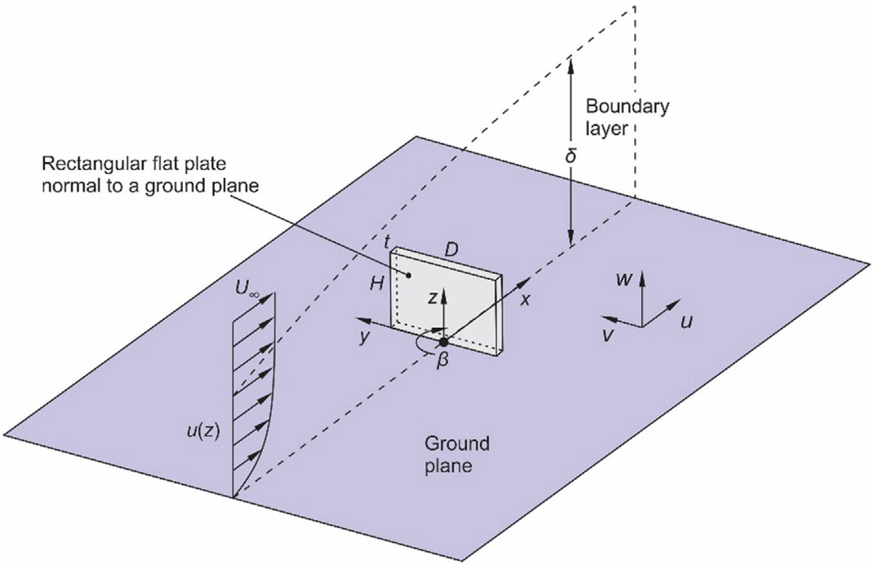

Fig. 1 Schematic of the flow over a surface-mounted rectangular flat plate (of width D, height H, and thickness t) at $\beta = 90°$ and freestream velocity U_∞. Note the coordinate system (x, y, z) and the velocity components (u, v, w). The plate is immersed in a flat-plate boundary layer on the ground plane, with streamwise mean velocity profile $u(z)$ and thickness δ

2 Experimental Approach

The wind tunnel experiments used a seven-hole pressure probe and two-dimensional particle PIV to obtain the mean velocity fields. The setup and instrumentation were similar to that of da Silva et al. [6] and Montes Gomes and Sumner [1]. Four rectangular flat plates of AR = 0.2, 0.35, 0.5, and 1 were tested at $\beta = 90°$ (the plate was oriented normal to the incoming flow). The steel plates all had the same width of $D =$ 60 mm and a thickness of $t = 1.5$ mm. The Reynolds number based on the freestream velocity U_∞ and the width of the plate was Re $= 7.5 \times 10^4$ and the relative thickness of the boundary layer on the ground plane was $\delta/D = 0.6$.

Time-averaged wake velocity measurements were made with the seven-hole probe in several vertical transverse (y–z) measurement planes at various streamwise locations (x/D) downstream of the plate. A grid spacing of 0.1 D was used, with a 10 s sampling time and 1 kHz sampling frequency. The pressures from the probe were measured with a Scanivalve ZOC-17IP/8Px pressure scanner.

PIV measurements were made in the vertical symmetry (x–z) plane. Image pairs were acquired at 15 Hz, and the time step between laser pulses was 15 µs. A TSI PIV system and Insight 3G software were used to acquire and process the image pairs. Several fields of view were combined to construct an overall picture of the flow upstream, around, and behind the plate. Each field of view was approximately $0.11D \times 0.075D$, and for each field of view, an ensemble average of 2100 velocity vector fields was used to obtain the mean velocity field.

3 Results and Discussion

Only a subset of the seven-hole probe and PIV results and analysis is reported here, due to space constraints. Some results from the seven-hole probe measurements are shown in Fig. 2. At the streamwise location of $x/D = 4$, the wake (as measured by the seven-hole probe) is characterised by either one or two pairs of streamwise vortex structures. For AR = 0.2 (Fig. 2d) and AR = 0.35 (Fig. 2c), there are two pairs of streamwise vortex structures: the larger and outermost pair is adjacent to the ground plane while the smaller and innermost pair is in the upper part of the wake on either side of the centerline. Farther downstream of the plate, the inner pair of streamwise vortices either disappears or merges with the outermost pair of vortices. This inner pair of streamwise vortices has been seen for other low-aspect ratio bluff bodies, such as low-aspect-ratio square prisms in thick boundary layers [6]. For AR = 0.5 (Fig. 2b) and AR = 1 (Fig. 2a), the inner pair of vortices is absent at $x/D = 4$ and the mean wake is dominated by the two large streamwise vortices adjacent to the ground plane. These vortices expand and disperse as the streamwise distance from the flat plate increases. Downwash is seen on the wake centreline for the plates of AR = 1 and 0.5, but with the presence of the inner pair of streamwise vortices for AR = 0.35 and 0.2, there are instead two regions of downwash and the flow on the wake centreline is either stagnant or directed upwards. The maximum streamwise vorticity for each AR occurs in the center of each inner vortex pair at *x/D* positions nearest to the plate.

Some results from the PIV experiments are shown in Fig. 3. The mean streamlines in the vertical symmetry plane (Fig. 3) show the near-wake recirculation zone and the horseshoe vortex upstream. Both the size of the horseshoe vortex and the streamwise extent of the recirculation zone increase with AR, but the horseshoe vortex moves further from the plate with increasing AR. Additionally, the size of the wake region (shown by the location of the focus with respect to the plate and ground plane) increases in both height and width with AR. The growth of the recirculation zone with increasing AR for the low-aspect-ratio plates is consistent with what is reported in [1] for plates of higher aspect ratio. The focus is located above the plate near the center of the recirculation zone and moves closer to the plate for smaller aspect ratios. The focus is important for identifying large scale recirculation, and seems to identify the familiar "arch vortex", which is the dominant structure in this near-wake region.

The recirculation zone also contains a lower intensity and opposite rotation structure on the ground plane immediately behind the plate, where the reversing flow along the ground plane locally separates as it approaches the back of the plate. This structure's size increases with AR.

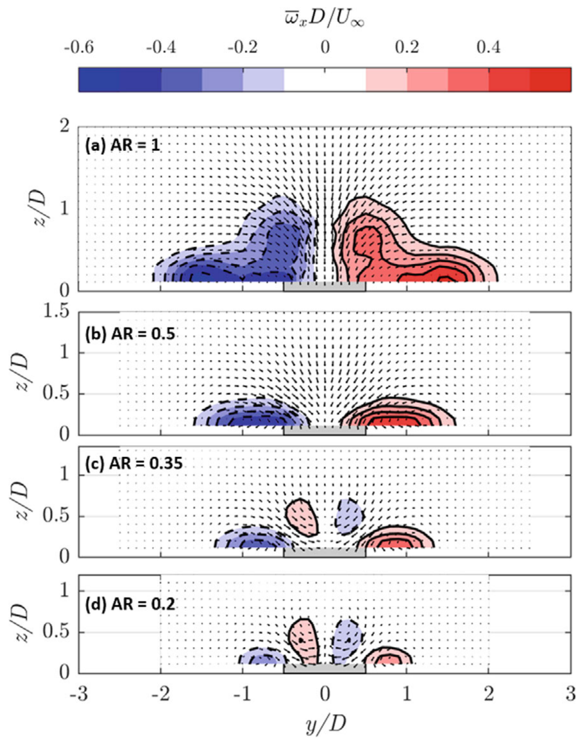

Fig. 2 Mean in-plane velocity vectors (v, w) and mean streamwise vorticity (ω_x) contour lines in the vertical transverse (y–z) plane at $x/D = 4$ in the wakes of four rectangular flat plates. Dashed contour lines show clockwise (negative) vorticity; solid contour lines show counterclockwise (positive) vorticity

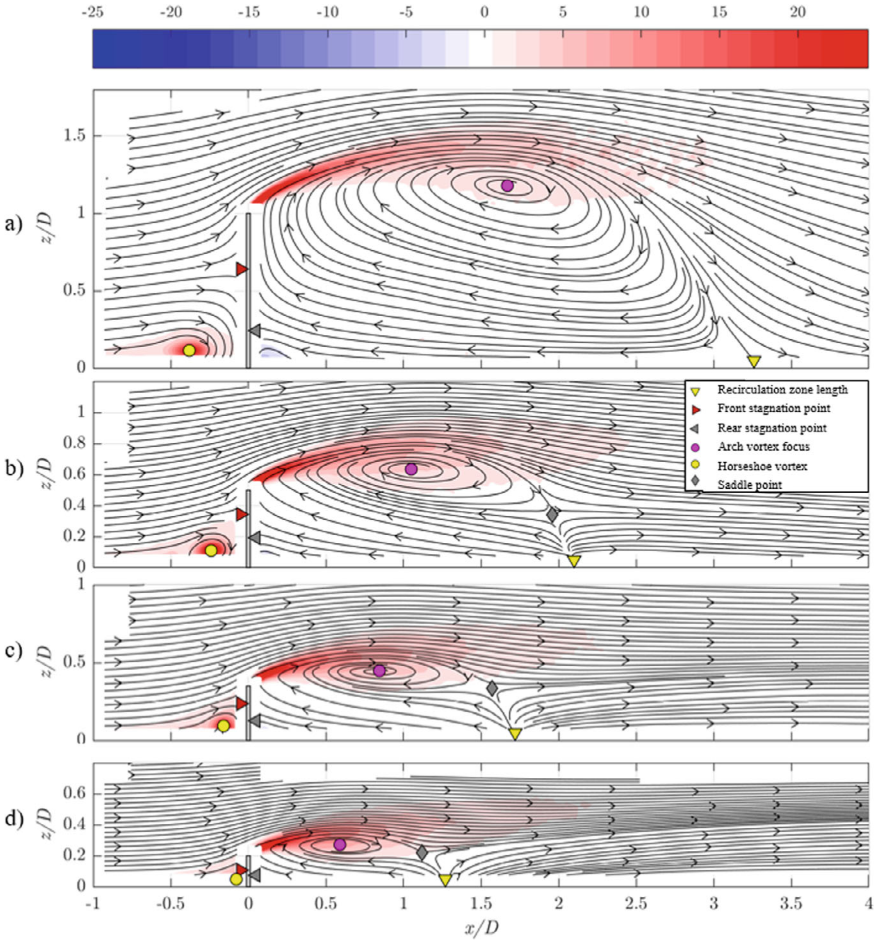

Fig. 3 Mean streamlines in the vertical (*x*–*z*) symmetry plane for the flow over the four rectangular flat plates, obtained from the PIV measurements. Flow is from left to right. The mean transverse vorticity (ω_y) contours are overlaid

Figure 3 also contains time-averaged and filtered transverse vorticity contours. Both the streamlines and contours show the flow separation from the upper edge of the plate, and a prominent shear layer forms downstream of this edge. The maximum transverse vorticity in this plane occurs in this shear layer. The angle of this flow separation is largest for AR = 1 and smallest for AR = 0.2.

The mean streamline pattern is distinct for AR = 1 (Fig. 3a) with no saddle point at the edge of the recirculation zone. A single dividing streamline encompasses the entire recirculation zone. For the smaller plates of AR = 0.5, 0.35 and 0.2, a saddle point is a prominent feature of the mean streamline pattern in the near wake of the plate, and its appearance is associated with some upwash in the flow; this upwash can be seen in the vertical transverse plane results (Fig. 2) on the wake centreline, for the smallest two plates. As such, the presence or absence of this saddle point indicates the average vertical direction of flow along the wake centerline. This saddle point exists at approximately 90% of the recirculation zone length.

There is a stagnation point located on the front and rear sides of the plate. The front stagnation point is always higher than the one on the back of the plate and its distance from the ground plane increases linearly with AR. The position of the rear stagnation point increases linearly with AR, for low aspect ratio plates especially.

4 Conclusions

In the present study, the flow over surface-mounted rectangular flat plates was studied in a low—speed wind tunnel at Re $= 7.5 \times 10^4$ and for $\delta/D = 0.6$ and $\beta = 90°$ (the plate was oriented normal to the incoming flow). The flow over the plates of AR = 0.5, 0.35, and 0.2 was found to behave differently than the plate of AR = 1. For the three lowest aspect ratios, there are typically two streamwise vortex pairs within the wake at $x/D = 4$ (with the exception of AR = 0.5, in which the inner pair has dispersed at this streamwise location). These two pairs cause upwards flow at the centerline, with one region of downwash on either side. Additionally, in the vertical symmetry plane, these three aspect ratios have a saddle point near the downstream edge of the recirculation zone that defines the flow field and leads to regions of upward and downward directed flow at the edge of the mean recirculation zone. In contrast, for the plate with AR = 1, there is only downwash on the wake centerline and a single pair of streamwise vorticity concentrations at $x/D = 4$. The saddle point is absent in the vertical symmetry plane and flow that passes over the plate and recirculation zone reaches the ground plane.

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