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Influence of bluff-body shape on recirculation zone structure and mixing enhancement

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SUMMARY:
This study investigates the influence of the bluff body (BB) cross-sectional shape on the structure of the recirculation zone and mixing characteristics in a non-reacting turbulent flow. Particle Image velocimetry (PIV) was used to measure the velocity field for four BB geometries with identical surface area: circular, square, equilateral triangular, and hexagram-type star. The results show that the BB shape has a strong impact on the downstream recirculation zone. Tailoring the BB cross-sectional shape therefore provides an effective means of controlling recirculation zone topology and mixing properties. Non-circular geometries, particularly equilateral triangular and hexagram-type star, emerge as the most effective. They strongly influence the flow field by preserving their cross-sectional features over several BB diameters and enhancing the spatial uniformity of turbulence within the recirculation zone.

Keywords: bluff body, passive flow control, flame stabilization, mixing enhancement, PIV measurements

1. INTRODUCTION

The non-streamlined geometry of bluff bodies (BBs) induces flow separation and recirculation, which strongly influence entrainment, shear-layer evolution, and coherent structures (Bearman, 1996; Gnatowska et al., 2025). Therefore, BBs are widely used in urban and vehicle aerodynamics (Toparlar et al., 2017), as well as in thermal management and flow control (Oruc, 2017). In this context, recent research has focused on premixed and partially premixed combustion technologies (Cai et al., 2025; Nakamura et al., 2021). However, non-premixed systems remain widely used due to their high heat-release rates, flashback resistance, and operational robustness. In these systems, fuel and oxidiser mix downstream of injection, with combustion stabilized in highly turbulent regions using geometric or aerodynamic flame holders. A classical solution is the bluff body (BB), which induces flow separation and a recirculation zone containing hot products, thereby increasing residence time, enhancing mixing, and enabling stable flame anchoring. Previous studies (Esquiva-Dano and Escudié, 2005) focused on symmetric BB geometries, such as discs, cylinders, and cones, while multifaceted cross-sections like triangular, rectangular, or star-shaped profiles have been little studied. Recent research (Tyliszczak et al., 2022; Wawrzak et al., 2024) shows that sharp corners disrupt large-scale azimuthal structures and promote small-scale vortices, altering entrainment and mixing. This study examines how the cross-sectional shape of BB affects the mean and fluctuating velocity fields, the recirculation zone structure and mixing related properties of a non-reacting flow - relevant features for the combustion process.

2. METHODS

The experiments are conducted in a closed-loop wind tunnel with a square test section of 0.3×0.3 m^2 and a total length of 2.0 m. BB is mounted coaxially on a steel rod aligned with the wind tunnel axis. The incoming flow passes through a honeycomb and a fine-mesh screen to ensure a uniform velocity profile upstream of the BB. All measurements are performed at a free stream velocity of $U_\infty = 3$ m/s, corresponding to a Reynolds number of $Re = 5100$, based on the equivalent diameter $D = 0.025$. The turbulence intensity of the undisturbed flow, measured in front of the bluff-body is $I_v = 2\%$.

Four BB cross-sectional shapes were considered, shown in Fig. 1: circle (Crc), square (Sqr), equilateral triangle (Tri), and a six-armed star (Str). All geometries are aligned with the stream-wise direction (x). The axes of vertical alignment in cross-stream direction (y) are marked in red in Fig.1. Flow-field measurements are performed using a Particle Image Velocimetry (PIV) system.

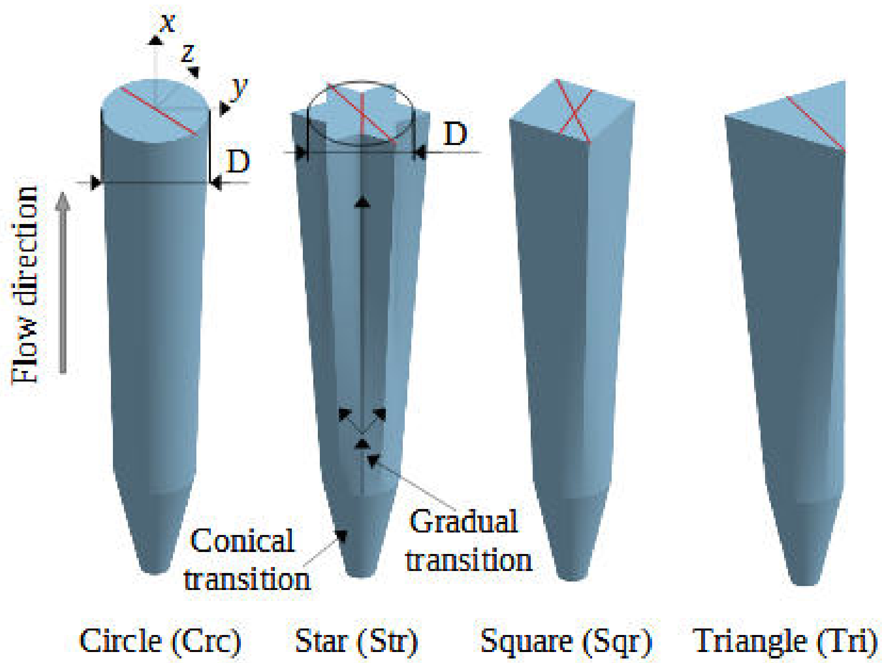

Figure 1. Geometrical characteristisc of BB models tested in wind tunnel

tem. Illumination is provided by a double-pulsed Nd:YLF laser (Litron) operating at 527 nm, while images are recorded using a SpeedSense VEO340 CCD camera. The measurement area was located in a vertical plane at the centerline, covering the wake behind the bluff-body. Oil-based droplets with a mean diameter of approximately 1 μm are used as seeding particles. PIV measurements are conducted over a total recording time of 10 s. The sampling frequency of 300 Hz results in 3000 image pairs, each with a resolution of 1644×1200 pixels. Final calculations are performed with an interrogation area of 16×16 pixels with a 50% overlap. The resulting velocity field typically consists of 207×149 velocity vectors.

3. RESULTS

Figure 2 presents contour maps of flow field - streamwise velocity (U_x/U_∞) and turbulent kinetic energy (TKE/U_∞^2) behind different BB models. Recirculation zone forms immediately downstream of the BB face. Its shape and extent depend on the geometry and, for non-axisymmetric cases, on the plane orientation. Generally, the BB cross-sectional shape is reflected at the beginning of the recirculation zone ($x/D < 1$), most clearly for Str and Tri. Farther downstream ($x/D = 1$), this effect weakens and the recirculation zones become nearly identical across all cases. This transition occurs in the region of the highest turbulence levels, which coincides with the location where fluid re-enters the recirculation zone and intense mixing takes place. The TKE/U_∞^2 profiles differ between the cases, with the Str case exhibiting the lowest turbulence levels, though with greater uniformity. To further asses the quantitative relations

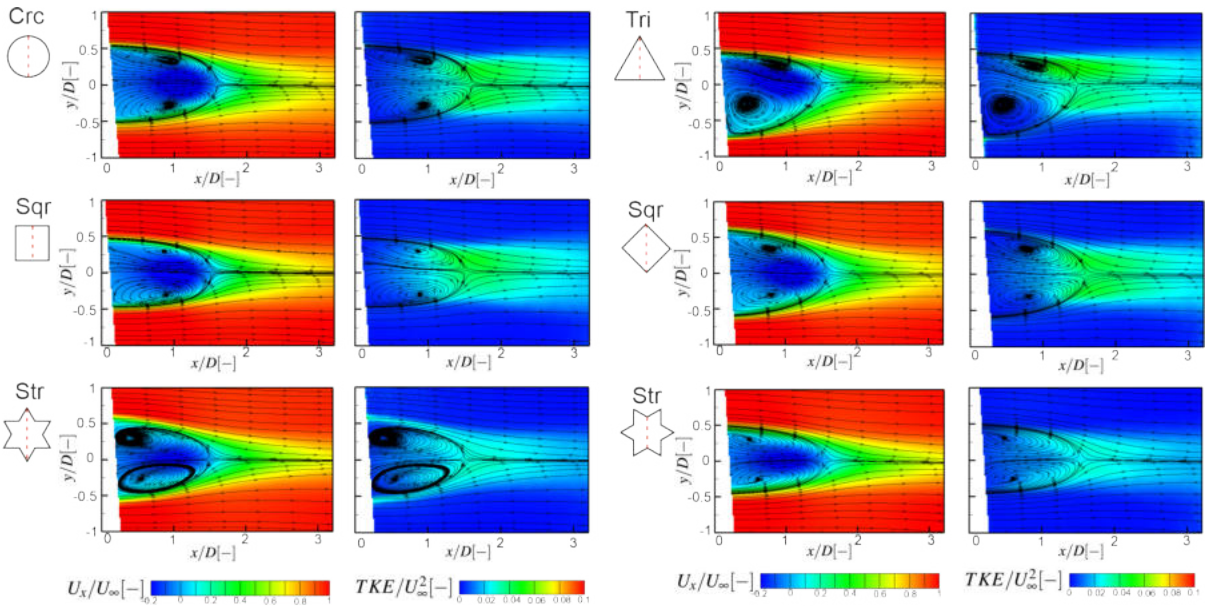

Figure 2. Contour maps of the normalized streamwise velocity component U_x/U_∞ (columns 1 and 3) and turbulent kinetic energy TKE/U_∞^2 (columns 3 and 4) for different BBs

between the configurations Figure 3 presents downstream profiles of U_x/U_∞ and TKE/U_∞^2 along BB cetreline. The profiles of U_x/U_∞ show that BB shape has a limited effect on the mean axial velocity, although the recirculation zone extends farther downstream for all shapes, compared to Crc, with Str producing the longest recirculation zone. As it was noticed above, TKE/U_∞^2 levels are the smallest for Str and are the highest for Crc and Sqr cases. Nevertheless, in practical applications such as bluff-body stabilized combustion, the region $x/D <= 2$ typically contains the flame core with highly unsteady reaction zone. In this region, a more uniform velocity field near the BB face is desirable in order to reduce strain-rate fluctuations and the risk of local flame extinction. Figure 4 presents cross-stream velocity component (U_y/U_∞) in two

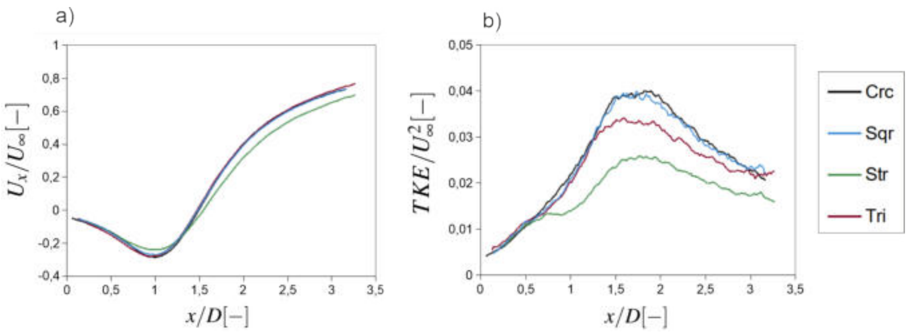

Figure 3. Downstream profiles of normalized streamwise velocity U_x/U_∞ (a), turbulent kinetic energy TKE/U_∞^2 (b) along the centerline

cross-sections, located at $1.5D$ and $2D$ downstream of the BBs. The profiles for non-circular BBs (Str, Sqrt) show more negative values than Crc for $y/D > 0$ and more positive values for $y/D < 0$ (Str, Sqrt, Tri), indicating that fluid is drawn inward toward the recirculation zone. This suggests enhanced mixing and larger volume flux toward the recirculation zone induced by non-circular BBs.

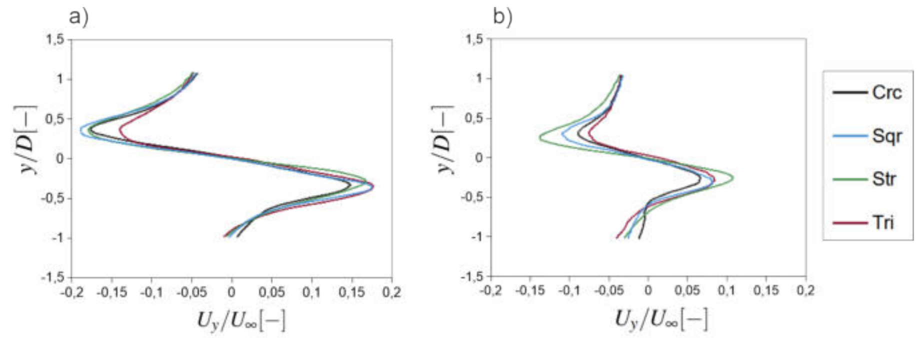

Figure 4. Downstream profiles of normalized cross-stream velocity U_y/U_∞ in the cross-sections located at $1.5D$ (a) and $2D$ (b)

4. CONCLUSIONS

The results indicate that the bluff-body (BB) shape has a strong influence on the downstream recirculation zone. In particular, the near wake initially retains a clear imprint of the BB cross-section, most pronounced for the Str and Tri cases, which feature sharp corners. Examination of the time-averaged velocity and fluctuations along the axis reveals that Str produces the largest streamwise recirculation region and maintains a lower mean axial velocity downstream than Crc. Moreover, Str and Tri BBs exhibit increased turbulence uniformity in the recirculation zone which is exptected to promote more homogeneous fuel–oxidiser mixture. A similar positive effect on the mixing process is observed for non-circular BBs when analyzing the cross-stream flow component, indicating a larger volumetric flux toward the recirculation zone. Overall, the results demonstrate that tailoring the BB cross-sectional shape provides a means to control wake topology and mixing properties. Two configurations emerge as the most effective candidates: Tri and Str. Future work should extend the present findings from non-reacting to reacting flows to test whether the observed changes in coherent structures, entrainment, and turbulence uniformity translate into more efficient combustion.

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