

Experimental investigation of turbulent flow over bluff-body geometries using high-speed PIV

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ABSTRACT

Bluff-body-induced turbulent flows are widely used in engineering, most notably for stabilizing flames in combustion systems. This study focuses on the aerodynamic behavior of such flows under non-reactive conditions, forming a critical baseline for future investigations involving ammonia–hydrogen combustion. Three bluff body geometries, namely flat, convex, and concave geometries were investigated using high-speed Particle Image Velocimetry (PIV) under identical operating conditions with a mean annular velocity of 18.28 ms^{-1} and a corresponding Reynolds number of approximately 18240. From the PIV-derived axial velocity fields, three key parameters were extracted: recirculation zone length (RZL), peak annular axial velocity, and peak axial velocity fluctuations. In general, the investigated geometries exhibited similar flow characteristics. However, the concave bluff body produced the longest and most coherent recirculation zone, whereas the convex configuration resulted in the shortest. These cold-flow measurements provide a detailed aerodynamic baseline for interpreting flame stabilization, mixing behavior, and wake characteristics in future reactive flow studies with ammonia–hydrogen blends.

1. Introduction

Turbulent flow over bluff bodies plays a critical role in a wide range of engineering applications, spanning the aerodynamics of buildings and bridges, the performance of ground and air vehicles (Forouzi Feshalami et al., 2022), the operation of industrial reactors (Suksam & Charoen-suk, 2019), and the stabilization of flames in combustion systems (Williams et al., 1948; Filippi & Fabbrovich-Mazza, 1961; Longwell et al., 1953; Winterfeld, 1965). Canonical bluff body geometries such as circular cylinders, disks, and rectangular prisms provide a controlled platform for examining the interplay between turbulence intensity, boundary layer development, shear layer roll up, and wake dynamics. These insights are essential for developing predictive models of separated flows and for designing structures and devices that must operate reliably under unsteady aerodynamic conditions.

In combustion systems, bluff bodies are extensively employed as flame holding elements because the recirculation zone formed downstream of the obstruction provides a robust source of hot products that anchor the flame (Filippi & Fabbroovich-Mazza, 1961). The turbulent wake behind the bluff body strongly influences mixing, flame stabilization limits, ignition behavior, and pollutant formation pathways. Understanding how geometric parameters, confinement, and upstream turbulence shape the wake structure is therefore critical for advancing low emission, high efficiency combustion technologies (Williams et al., 1948; Filippi & Fabbroovich-Mazza, 1961; Longwell et al., 1953; Winterfeld, 1965). Moreover, the presence of heat release introduces additional complexities such as dilatation, density gradients, and altered turbulence production mechanisms that fundamentally modify the canonical cold flow behavior (Fujii & Eguchi, 1981). These effects must be characterized carefully to enable accurate modeling of turbulent reacting flows.

In our work, we aim to investigate bluff body based burner configurations with a particular focus on ammonia-hydrogen combustion, a promising pathway towards carbon free energy systems. As a preliminary step, we conduct detailed cold flow studies to isolate the influence of bluff body geometry on wake development, shear layer behavior, and flow separation in the absence of heat release. These measurements establish a baseline for interpreting the substantial modifications introduced by combustion. Building on this foundation, we leverage additive manufacturing to rapidly prototype high temperature resistant burner components tailored to the thermochemical and mechanical demands of ammonia-hydrogen flames. This integrated approach, combining canonical flow studies, advanced diagnostics, and modern fabrication techniques, supports the development of next generation bluff body burners optimized for clean, efficient, and stable operation under challenging conditions.

This study employs high-speed 2D particle image velocimetry (PIV) to investigate turbulence characteristics in cold flow over a range of bluff body geometries. Particular attention is given to how geometric variations influence the length of the recirculation zone and the associated velocity fluctuations within the wake. The resulting measurements provide new insight into the dependence of turbulent flow behaviour on bluff body shape and establish a foundation for interpreting more complex reacting flow configurations. In addition to characterizing the flow field, a central objective of this work is to generate high quality experimental datasets that will support and validate future high fidelity numerical simulations and guide the optimization of bluff body geometries for subsequent reactive flow experiments. To this end, section 2 details the experimental apparatus and measurement procedures. Section 3 introduces the bluff body geometries considered in this study. Section 4 presents the flow field results, followed by conclusions and perspectives for future work.

2. Experiment methodology

For the present experimental campaign, a modular cylindrical burner was employed, incorporating an interchangeable bluff-body mount to enable systematic variation of stabilizer geometries. The burner includes a dedicated inlet for cold-flow air supplied through a flow distributor and an optional coflow arrangement. A schematic of the burner is provided in Figure 1, illustrating the throat diameter of 22.7 mm and the bluff-body head diameter of 15 mm, resulting in an annular passage of 7.7 mm. A flat-head bluff body was selected as the reference configuration, and two additional geometries with modified crown profiles were fabricated, as shown in Figure 1. The designs are denoted as “Flat,” “Convex,” and “Concave”. The geometries are inspired from literature (Caban et al., 2024) and represent simple crown shapes suitable for future numerical validation studies.

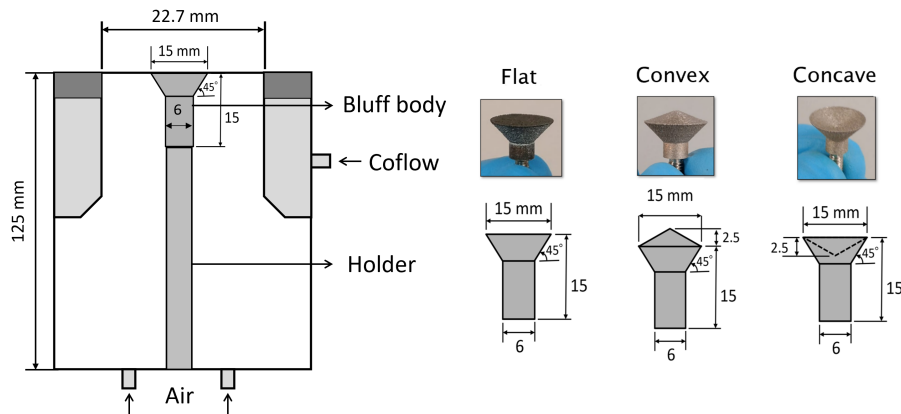


Figure 1. Bluff-body placement in the burner and various geometrical designs investigated in the study

Figure 2 illustrates the experimental apparatus, which comprises three primary subsystems: a laser unit equipped with sheet-forming optics and control electronics, a bluff-body-based burner with air-supply and flow-regulation components, and an imaging system incorporating a high-speed camera with associated optics and control hardware. The burner operates in an open-to-atmosphere configuration and includes a mounting arrangement that enables rapid interchange of bluff-body geometries.

Flow-field measurements during the cold flow studies were obtained using high-speed PIV at 2 kHz. A double-pulse green laser (532 nm) was used as light source. A laser sheet of approximately 60 mm in height and 0.8 mm in thickness was formed using lenses and aligned with the burner axis. Titanium dioxide (TiO_2) particles served as the seeding medium, and images were recorded at a spatial resolution of 0.125 mm/pixel.

PIV acquisition and image post-processing were carried out using Davis 8.4 software. Background signal and optical reflections were suppressed by subtracting a moving-average reference image, and instantaneous velocity fields were obtained through adaptive multipass cross-correlation. The

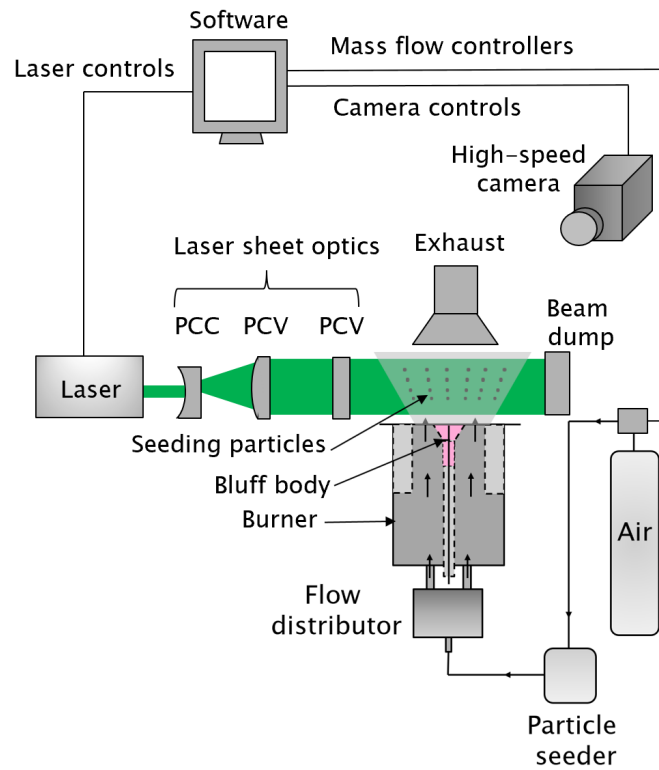


Figure 2. Schematic of experimental apparatus, consisting of a 532 nm laser with light sheet optics, the burner with changeable bluff bodies and gas supply, a high-speed camera for imaging seeded tracer particles and a PC for central control and data acquisition.

interrogation window was successively refined from 64×64 pixels (two passes, 75% overlap) to 16×16 pixels (four passes, 50% overlap). Spurious vectors were identified and corrected using a standard median-filtering procedure. The uncertainties associated with the velocity and its fluctuations were approximately 2%.

3. Bluff body manufacturing

Although the present work focuses on cold-flow characterization, a high-temperature alloy was selected to ensure compatibility with future reactive-flow experiments. Bluff bodies were additively manufactured using Laser Powder Bed Fusion (L-PBF) with an IN718 nickel-based superalloy feedstock, and powder morphology was characterized via dynamic image analysis (Camsizer XT, Microtac MRT GmbH) prior to fabrication. Components were utilized in the as-built condition without post-processing, preserving the intrinsic L-PBF dimensional accuracy and surface roughness. The resulting microstructure exhibited columnar grains with a fine dendritic substructure and interdendritic Laves phases. To refine the microstructure and mechanical response, specimen were subsequently subjected to a standard IN718 heat-treatment protocol (Huang et al., 2019).

4. Results

In the present cold-flow experiments, an air flow of 250 L min^{-1} was supplied to the burner, yielding a mean annular velocity of 18.28 m s^{-1} . This corresponds to a Reynolds number of approximately 18240, placing the flow well within the turbulent regime. Under these operating conditions, the bluff body generates pronounced flow separation at its leading edges, which in turn establishes a well-defined recirculation zone immediately downstream. This region exhibits reversed or significantly reduced axial velocities along the centerline, while elevated velocities develop along the surrounding shear layers, producing a strong radial velocity gradient.

The recirculation zone is a key aerodynamic feature of bluff-body-stabilized flows, as it enhances entrainment and mixing by continuously transporting fluid between the wake and the incoming stream. In non-reactive operation, the resulting flow topology provides a clear representation of the intrinsic aerodynamic response of the bluff body, independent of heat-release effects. These cold-flow measurements therefore serve as a baseline for interpreting flame anchoring, stabilization mechanisms, and wake dynamics under subsequent reactive-flow conditions.

Figure 3(a) and Figure 3(b) show the mean axial velocity field and the corresponding axial velocity fluctuations for the flat bluff-body configuration. Shear layers originate at the burner throat, where strong velocity gradients near the burner lips lead to turbulence production. A slight asymmetry develops in the flow field, as observed in Figure 3(b), and is likely due to the open configuration of the burner in combination with minor non-uniformities in the annular gap introduced by mechanical tolerances. These factors are unavoidable within the present experimental setup and do not affect the overall flow characteristics reported.

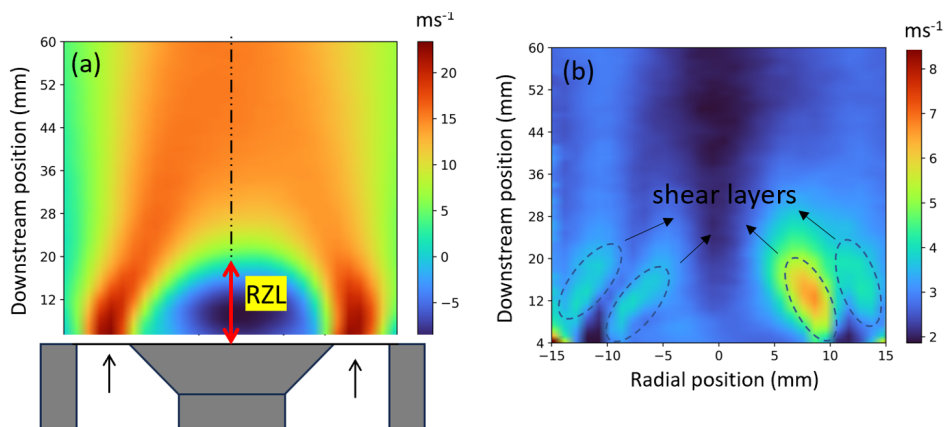


Figure 3. Cold-flow characteristics over a flat bluff body: (a) mean axial velocity field with recirculation zone length (RZL), and (b) fluctuating axial velocity field.

From these PIV-derived axial velocity fields, three key parameters are extracted. The first parameter is the recirculation zone length (RZL), defined along the centerline from the bluff-body surface

to the axial location where the velocity becomes zero and subsequently reverses direction. This recirculation region entrains incoming fluid and enhances turbulence mixing; in reactive flows, it plays a central role in flame anchoring and overall flame stability. A stable and sufficiently large recirculation volume is therefore indicative of favorable mixing in non-reacting flows and robust flame stabilization under reacting conditions. The second parameter is the mean axial velocity $\bar{u}_y$ which is governed by the annular gap and influences the turbulence generated as the flow passes over the bluff body. The third parameter is the axial velocity fluctuation, u'_y , within the measurement domain, representing turbulence production induced by the bluff-body surface. Both the peak axial velocity and the peak fluctuations occur near the burner throat within the shear-layer region as shown in Figures 3(a) and 3(b).

4.1. Geometry effects

As described earlier, three bluff-body geometries were examined in this study. All PIV measurements were conducted under identical operating conditions for each geometry. A total of 2000 image pairs were recorded at a sampling frequency of 2 kHz, and the corresponding velocity fields were obtained using the PIV processing workflow, as given in section 2. Mean and fluctuating axial velocity fields were then computed from this dataset. For each bluff-body shape, three characteristic parameters were extracted from the axial velocity fields: the recirculation zone length (RZL), the peak annular axial velocity, and the peak axial velocity fluctuations.

Figure 4 presents the mean axial velocity distribution along the downstream direction at the radial location $x = 0$ mm as indicated in Fig 3(a) for all three geometries. Both the axial velocity and the downstream coordinate are normalized using the annular bulk velocity (18.28 ms^{-1}) and the bluff-body head diameter (15 mm), respectively. The profiles clearly delineate the extent of the recirculation zone and the magnitude of flow reversal (i.e., negative axial velocities) associated with each shape. The point at which the mean velocity crosses zero marks the onset of flow reversal and is used to determine the RZL.

From Figure 4, the geometries exhibit notable differences in RZL: the concave bluff body produces the longest recirculation zone, whereas the convex geometry yields the shortest. Since the head diameter and annular gap are fixed for these three shapes, the reduced recirculation volume in the convex case arises from the outward curvature, while the inward curvature of the concave design promotes an enlarged recirculation region. Apart from the observed variation in RZL, the mean and fluctuating axial velocity fields exhibit only minor differences across the investigated geometries. The corresponding mean axial velocity profiles are shown in Figure 5.

A consolidated overview of geometric effects on the turbulence characteristics is provided in Table 1. These results indicate that the primary influence of the simplified bluff-body shapes is the modification of the recirculation zone, which in turn can alter mixing behaviour and turbulent fluc-

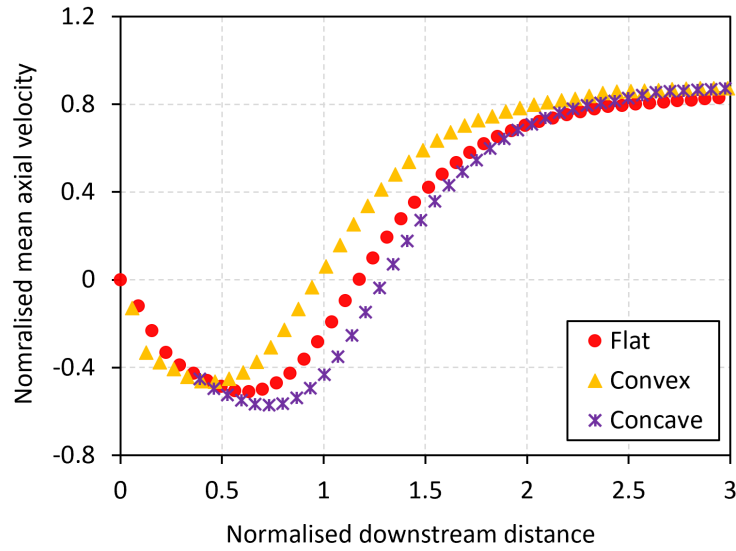


Figure 4. Mean axial velocity component with downstream position at a radial position $x = 0$.

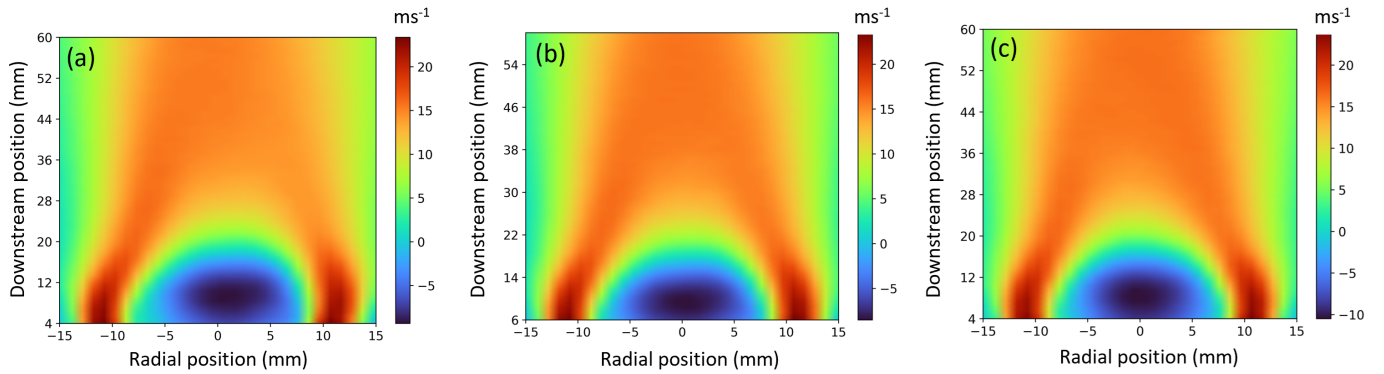


Figure 5. Mean axial velocity field of (a) Flat (b) Convex (c) Concave shaped bluff body

tuations. Among all configurations assessed, the concave bluff body yields the most favourable performance, exhibiting the largest recirculation zone.

5. Conclusions

Cold-flow PIV measurements demonstrated a clear geometric influence on the wake characteristics of bluff-body-stabilized flows. Although all geometries produced a downstream recirculation zone, its size and coherence varied markedly with shape. The crown-modified flat, convex, and concave configurations retained the typical bluff-body flow structure, differing mainly in recirculation zone length (RZL). Among them, the concave bluff body generated the longest and most coherent recirculation region, indicating stronger entrainment and mixing, whereas the convex design produced the shortest RZL due to its reduced recirculation volume. The concave bluff body

Table 1. Comparison of shape effects on flow parameters. Here U and D_B represent the mean annular velocity (18.28 ms^{-1}) and bluff body diameter (15 mm), respectively. $\bar{u}_y$ and u'_y represent the mean and fluctuating axial velocities.

Bluff body shape	RZL	Peak $\bar{u}_y$	Peak u'_y
Flat	1.18 D_B	1.23 U	0.19 U
Convex	1.00 D_B	1.27 U	0.22 U
Concave	1.30 D_B	1.25 U	0.23 U

emerged as the most effective design, offering the strongest mixing characteristics and the most robust recirculation behavior among them. By isolating geometric effects from thermochemical influences, the results will support future analyses of heat-release-driven modifications in ammonia–hydrogen combustion experiments.

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Nomenclature

D_B	Bluff-body diameter [mm]
D_t	Burner throat diameter [mm]
U	Mean annular velocity [m s^{-1}]
$\bar{u}_y$	Mean axial velocity [m s^{-1}]
u'_y	Fluctuating axial velocity [m s^{-1}]
RZL	Recirculation zone length [mm]

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