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Influence of bluff bodies on lean premixed combustion and pollutant emissions: A numerical approach

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ABSTRACT

The flame holder configuration can significantly affect the performance of a combustion system. In this study, the influence of fuel composition and bluff body geometry on the lean premixed combustion system performance indicators, including temperature, stability, NO_x production, and unburned hydrocarbons, are numerically investigated. The premixed combustion of five pure hydrocarbon fuels, namely H₂, CH₄, C₂H₂, C₂H₄, and C₂H₆, is simulated using a three-dimensional coupled stoichiometric-CFD model. The holder bluff body cross-section shape is varied to assess the impact of the flow patterns on the combustion parameters. The numerical model provided satisfactory agreement with experimental data for propane-air combustion. Results indicate that lighter fuels sustain higher combustion completion and higher flame stability. The bluff body shape significantly impacted temperature distribution and flame shape compared to the plate flame holder design, which produced a broad flame along the burner. The findings establish a relationship between bluff body geometry, enhanced flame stability, and the conditions that influence pollutant formation, providing a basis for designs that mitigate NO_x emissions during stable operation at leaner equivalence ratios.

1. Introduction

Premixed combustion burners are essential components in industrial applications such as boilers, steam generators, ramjets, and turbojet burners [1]. Recently, there has been a significant interest in using bluff bodies to enhance flame characteristics in turbulent premixed combustion [2–4]. Burners used with premixed, or diffusion flames, can include a bluff body to stabilize the flame by creating a recirculation region. The swirling jets and sudden expansion downstream of the bluff body entrain combustion gases in shear layers and carry them upstream to ensure a complete ignition of reactants [5]. The burner performance is affected by the bluff body shape, the fuel type, and the flammability range of the fuel [6–15]. Chen et al. [16] investigated the influence of cooling air jets on the flame

structure and lean blowout limits in a rectangular premixed combustor, demonstrating that flow entrainment and velocities are critical to flame stability and blowoff limits. Esquivia-Dano et al. [17] experimentally studied the effect of the bluff body shape on flame stabilization for non-premixed flames. Two bluff body geometries were investigated: the disk and tulip geometries. Their results showed that the tulip geometry increased the expansion rate in the stabilization domain. Tong et al. [18] investigated the impact of the central air jet for a conical bluff body combustor over the flame characteristics and blowoff limits, showing a significant improvement in the heat load. Ibrahim et al. [19] examined the impact of the bluff body shape on the stabilization and combustion characteristics of LPG with blockage ratios of 0.25, 0.35, 0.45, and 0.55. Results showed that increasing the blockage ratio leads to a higher flame temperature, a larger flame diameter, and a shorter flame for all shapes. On the other hand, the bluff body shape had a significant impact on flame stability. Chen et al. [20] investigated the effect of flame velocity on the

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stabilization and lift-off limits. Their results showed that the air co-flow rate had a greater impact on flame stabilization than the fuel jet velocity at low fuel velocity. In contrast, annular airflows have less influence on the lift-off limits at high fuel velocities. For a simple disk bluff body placed at the center of the burner, Chaudhuri and Cetegen [21] experimentally studied the impact of equivalence ratio on blow-off for lean premixed conical flames of a propane-air mixture at different mixture velocities. The flame blow-off was preceded by cumulative narrowing of the flame cone for higher inner jet equivalence ratios, suggesting that the inner stream fuel enrichment reduces the overall blow-off equivalence ratio. On the other hand, the blow-off was not associated with fuel enrichment in the outer flames. Likewise, the stability of flames on a bluff body swirl burner for premixed propane fuel was studied by Karagiannaki et al. [22] for mixtures formed along three concentric disks. Results indicated that the flame is stable at a range of co-flow swirl intensities. Xiouris and Koutmos [23] investigated the interaction of swirl flow with partially premixed disk-stabilized propane flames, indicating that as the swirl increases, two successive vortices emerge. Æsøy et al. investigated experimentally [24] the effects of hydrogen addition to the fuel mixture on the premixed flame stability with single-flame and three-flame burners. As hydrogen content increases, the burning speed increases, resulting in a shorter flame. Moreover, the flame adheres to the combustor wall with compact flames, leading to the growth of the cut-off frequency and self-excited modes.

Due to the limitations of experimental methods, RANS-based computational fluid dynamics models have seen wider use in the literature [25–29]. Numerical models can provide insights into the underlying structure of the flame, the impact of a large space of parameters on specific observables, and correlations among different quantities of interest, including temperature, species profiles, Schmidt numbers, and turbulent Prandtl numbers [30]. Sun et al. [31] used the Reynolds-averaged Navier-Stokes equations to model the effect of a triangular bluff body blockage ratio on the rich-lean blended combustion of semicoke fuels. They showed that low NO_x formation occurs due to a local homogeneous regime on the fuel-rich side. Chaparro and Cetegen [32] studied the blowoff characteristics of conical premixed flames for three different flame holder geometries: rod, disk, and cone with propane–air mixtures. They observed that the blowoff equivalence ratio depends on the flow modulation frequency. Chen et al. [33] used Large Eddy Simulation to study the self-excited acoustic modes in a cylindrical plenum combustor with a central bluff body to investigate the thermoacoustic azimuthal instability. Using a similar numerical approach, Shaaban et al. [34] showed a significant effect of the combustor geometry on the frequency and intensity of these modes. Kedia and Ghoniem [35] used a two-dimensional model to identify the flame stabilization mechanism and the blowoff conditions of a laminar premixed flame with a perforated plate burner, showing a significant effect of the inlet velocity on flame stability and blowoff. Michaels and Ghoniem [36] experimentally and numerically investigated the impact of swirl flow and bluff body combinations on flame stability. The results obtained experimentally, using high-speed PIV, showed quite good

agreement with the numerical model, indicating that the position of the outer recirculation zone depends on the size of the bluff body and the swirl strength. In addition, the shape of the bluff body sharp edge can have a significant effect on the flow structure [37]. For a larger bluff body, the air-driven recirculation zone occurs upstream, closer to the burner exit, increasing the flame stability and strengthening the swirl flow. When the swirl is sufficiently strong, the flame propagates into the upstream region without a bluff body or, in some cases, with a small bluff body [5]. Zohra et al. [38] numerically examined the impact of increasing hydrogen concentration on the methane-air mixture of a non-premixed turbulent flame, providing temperature profiles for concentrations up to 50%. Zhang et al. [39] numerically examined the combustion characteristics of methane in a cube micro-combustor with a hollow hemispherical bluff body. They illustrated that a hollow hemispherical body increases the blow-off limit by a factor of 2.5. On the other hand, the methane conversion rate has a higher dependency on the equivalence ratio and inlet velocity. Meraner et al. [40] conducted a numerical study of a novel partial premixed bluff body burner using hydrogen and methane-hydrogen blends, testing the performance of five different turbulence models. The simulations were validated against particle image velocimetry measurements. The results show that the turbulent model has little influence on the recirculation zone length. More recently, Huang et al. [41] investigated the effect of bluff bodies on the performance of micro-combustors, showing that the insertion of a bluff body significantly influences the flow field, alters the distribution of temperature and OH radical, and enhances the preheating effect and gas-solid heat transfer.

Earlier research on bluff body flame stability has considered premixed or non-premixed conditions. However, there is no comparison between different fuel types of the bluff body to show the effect on combustion and emissions for the same flame holder. While individual parameters have been reported in experimental and numerical studies, a systematic comparison of how fuel composition interacts with bluff body geometry under identical lean-premixed conditions is absent from the literature. In this work, the impact of fuel type and bluff body shape on flame characteristics was numerically investigated. A three-dimensional computational fluid dynamics model, along with a premixed combustion model of species propagation, is used to examine the effect of bluff body shape on stabilization of turbulent premixed combustion using different fuels H_2 , CH_4 , C_2H_2 , C_2H_4 , and C_2H_6 . Additionally, various candidate geometric configurations for the bluff body are modeled to investigate their impact on flame stability, temperature, and NO_x profiles. The primary objective of this investigation is to demonstrate that optimizing the bluff body geometry for flame stability enables a wider operational envelope, which allows for combustion at leaner conditions to lower the peak flame temperatures and mitigates the formation of thermal NO_x through the Zeldovich mechanism.

2. Numerical model

2.1. Governing equations

The model assumes that chemical reactions occur only at the dissipative scales of turbulence and is used for premixed flame simulation. To model the problem using CFD to simulate the flow, heat transfer, and combustion of a premixed mixture numerically, the set of governing equations using finite volume methods, including mass conservation equation, momentum equation, combustion equations, and energy equations, is solved simultaneously. The mass conservation equation for reactive flows can be represented by equation (1).

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

where ρ represents the density, and u represents the velocity.

The equation of the momentum conservation, or the Navier-Stokes equations, is represented by equations (2-4):

$$\frac{\partial(\rho u_j)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i} + F_i \quad (2)$$

$$\tau_{il} = \mu S_{ij} - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij} \quad (3)$$

$$S_{il} = \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \quad (4)$$

where, τ is the viscous stress tensor, P is the pressure, F represents the body force, and μ is the dynamic viscosity.

The premixed combustion process is modeled using the ANSYS FLUENT software library. The laminar finite-rate model, which computes the chemical source terms using Arrhenius expressions and ignores the effects of turbulent fluctuations, is a reasonable approach for combustion with relatively slow chemistry and small turbulence-chemistry interaction. The net source of chemical species due to reaction is computed as the sum of the Arrhenius reaction sources over the reactions that the species participate in. The prediction of the turbulent flame speed normal to the mean surface of the flame is influenced by the laminar flame speed determined by the fuel concentration, temperature, molecular diffusion, and the detailed chemical kinetics. The flame front wrinkling and stretching by large eddies and flame thickening by small eddies are taken into account. The laminar flame speed is based on the correlation proposed by Metghalchi and Keck [42].

The energy equation for a fluid region can be written as equations (5-8):

$$\frac{\partial \rho h_t}{\partial t} + \frac{\partial(\rho u_j h_t)}{\partial x_j} = \frac{\partial p}{\partial t} - \frac{\partial Q_j}{\partial x_j} - \frac{\partial u_i \tau_{ij}}{\partial x_j} + u_j F_j + S_r + S_e \quad (5)$$

$$Q_j = -k \rho \frac{\partial h_t}{\partial x_j} \quad (6)$$

$$h_t = \frac{1}{2} u_i u_i + \sum_{a=1}^N Y_a h_a \quad (7)$$

$$h_a = H_a + \int_{T_{ref}}^T s_{p,a} dT \quad (8)$$

Where, Q_j is the heat flux vector, H_a is the heat of species formation a , S_e is the heat release rate, and S_r represents the radiative heat loss. For the current case, $S_r = 0$. The equation for species conservation is expressed in equations 9 and 10 as:

$$\frac{\partial(\rho Y_a)}{\partial t} + \frac{\partial(\rho u_j Y_a)}{\partial x_j} = \frac{\partial \left(D_{L,a} \rho \frac{\partial Y_a}{\partial x_j} \right)}{\partial x_j} + \omega_a \quad (9)$$

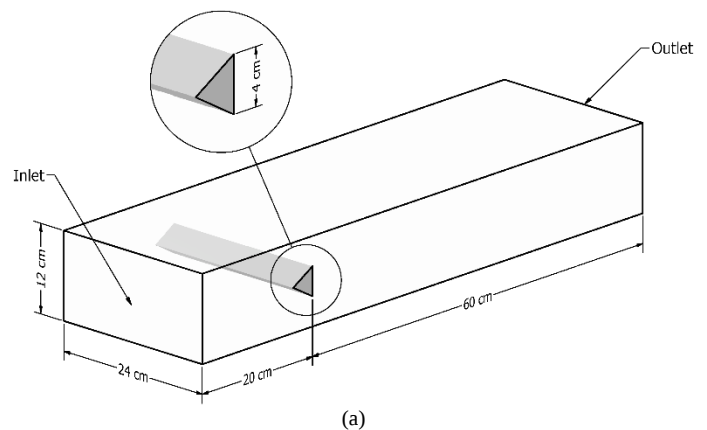
$$Y = \frac{Y_F}{Y_{F,u}} \quad (10)$$

Where, Y_a represents the mass fraction of species a ($\forall a = 1, 2, \dots, N$). ω_a is the mass burning rate. Y_F is the fuel mass fraction. $Y_{F,u}$ represents the fuel mass fraction in the unburnt mixture. For this turbulent premixed combustion model, the mean pressure is assumed to be constant, and the Lewis number (Le) is assumed to be 1.

2.2. Model Geometry

The model dimensions are selected to represent the experimental case described by Sjunnesson et al. [43]. Several bluff body configurations are considered. The bluff body and burner dimensions are shown in Figure 1. The burner consists of a straight channel with a length of 80 cm and a rectangular cross-section with side lengths of 12 cm and 24 cm. For the validation case, the bluff body has an equilateral triangular cross-section with a side length of 4 cm, located 10 cm upstream of the exit of the air-fuel mixture.

The shape of the bluff body was varied to investigate the influence of geometry on the combustion parameters. The shapes considered included a triangular cross-section, a square with a side length of 4 cm, a cylindrical geometry with a diameter of 4 cm, and a semi-cylinder with a diameter of 4 cm. All shapes were selected to have the same blockage ratio. Figure 2 illustrates the utilized shapes of the bluff body studied in the present study.



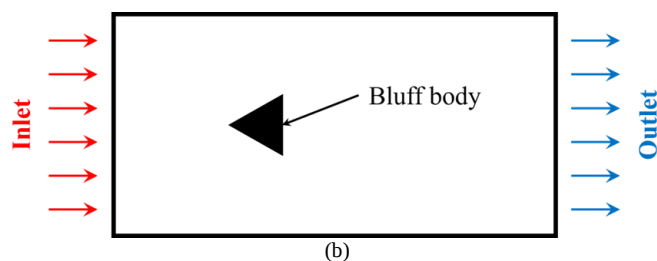


Figure 1: The geometry of the bluff body combustor. The geometry of the bluff body combustor: a) 3D view showing the dimensions, b) sectional elevation view showing the boundaries.

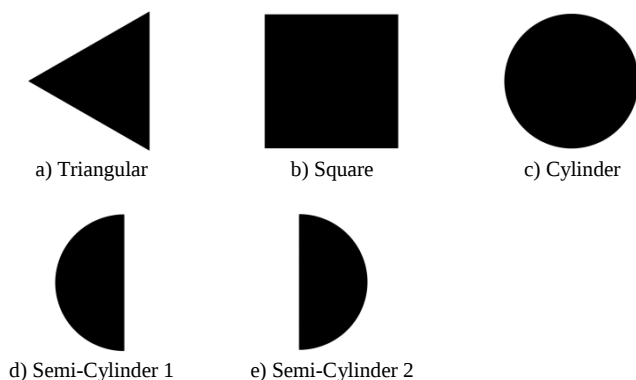


Figure 2: The cross-sectional views of bluff bodies studied.

Figure 3 shows the grid of the bluff body burner. The computational grid employed in the present study consists of high-quality structured hexahedral elements. The adequacy of the spatial grid resolution was validated using the method proposed by Roache [44] and recommended by many others [45–47]. The Grid Convergence Index (GCI) was determined using a grid refinement error estimator based on the generalized Richardson extrapolation theory, providing a quantifiable measure of the uncertainty associated with grid convergence. The GCI indicates the percentage deviation between the calculated and asymptotic numerical values. Three configurations of hexahedral elements with a refinement ratio of 1.8, referred to as M1, M2, and M3, are detailed in Table 1, were used to compute the GCI. Based on the GCI analysis, the grid configuration M2 yielded sufficiently accurate results, exhibiting an error of less than 0.05%.

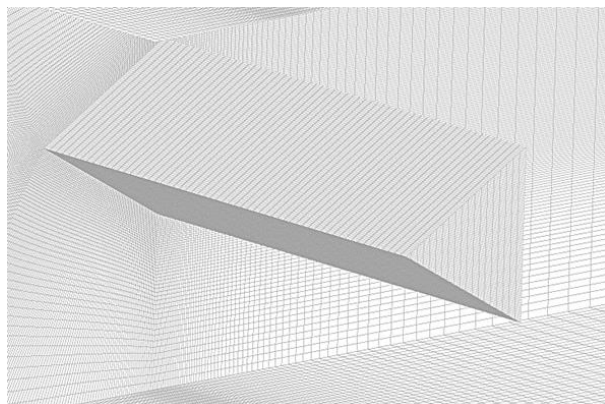


Figure 3: Mesh of the triangular bluff body burner.

Table 1: Mesh convergence study.

Mesh	Number of elements	Average mesh size	T at $X = 15$ cm	GCI
M1	717,926	0.65 cm	1903.4 K	0.130%
M2	1,292,266	0.36 cm	1899.6 K	0.044%
M3	2,326,078	0.20 cm	1898.3 K	

2.3. Boundary conditions

The gas mixture temperature, species concentrations, and gas flow velocity are specified at the burner inlet as uniform field values. The vanishing axial gradient condition for gas temperature, species concentrations, and gas flow velocity is implemented at the burner outlet. The inlet velocity and equivalence ratio were kept constant in this study at $U = 17$ m/s and $\phi = 0.65$, respectively. The boundary walls of the exit burner are assigned as wall boundary conditions with a steady surface temperature of 300 K. On the other hand, the other walls, such as the bluff body walls, are considered boundary conditions with zero heat flux. With these configurations, the model was built to study the combustion of a premixed methane-air mixture with a bluff body. The model was then meshed, and computational meshing details are presented in Table 2. For the second stage, the model was used to investigate the combustion of other fuels, including H_2 , CH_4 , C_2H_2 , C_2H_4 , and C_2H_6 . These investigations were performed with the same flame holder. Finally, the model was used to evaluate the impact of other shapes of the bluff body (e.g., square, cylinder, and semi-cylinder) with the same blockage ratio on the combustion of a premixed methane-air mixture.

Table 2: Model and boundary conditions configurations.

Turbulence model	Standard k- ϵ turbulence model with non-equilibrium wall function. $C_{mu}=0.09$, $C_{1-\epsilon}=1.44$, $C_2=1.29$, $T_{KE}=1$	
Fuel	Hydrocarbon fuel air mixture	
Numerical scheme	Second-order accuracy and SIMPLE pressure-velocity coupling were used.	
Convergence criteria	Convergence criteria should be less than 10^{-6}	
Species model	Reaction Type: Volumetric reaction.	
Boundary conditions	Inlet Velocity inlet: 17 m/s Turbulence intensity: 3% Temperature: 288 K	Outlet Turbulence intensity: 3% Temperature: 288 K

3. Results and discussions

3.1. Model validation against experimental data

To validate the predictions of the model, results were compared with the EDC flame measurements for a bluff body burner configuration previously studied by Sjunnesson et al. [43] as depicted in Figure 4. The comparison reveals good agreement between the velocity and temperature profiles at the given locations. The flow is characterized by a recirculation zone downstream of the bluff body, anchoring the flame and symmetric vortex shedding. These findings support the reasonable consistency and accuracy of the numerical model used in this study.

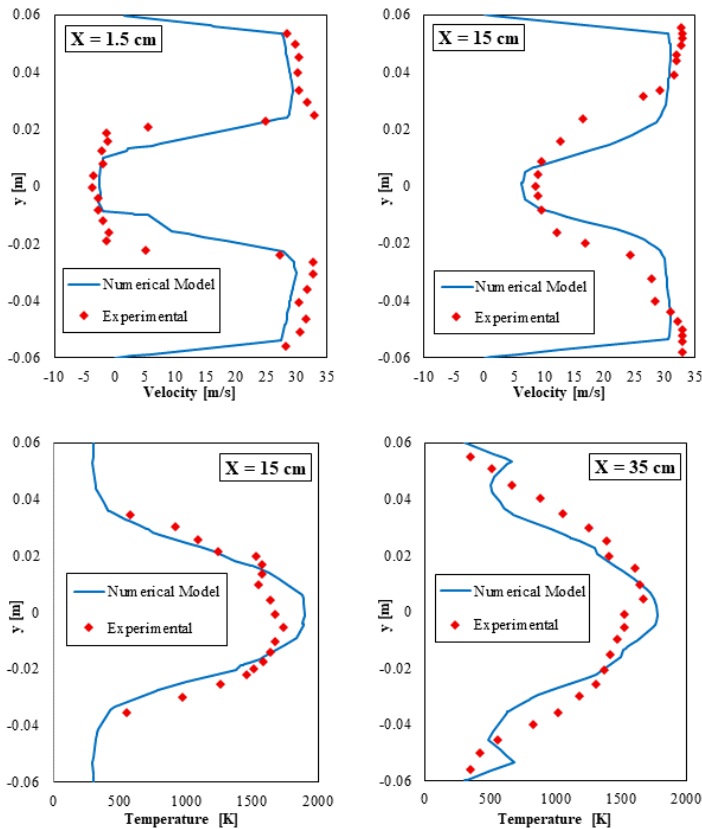


Figure 4: Comparison between the numerical results obtained from the present 3D-CFD model with the experimental data provided by Sjunnesson et al. [43].

3.2. Effect of fuel composition

Five different types of fuels, including H_2 , CH_4 , C_2H_2 , C_2H_4 , and C_2H_6 , were tested to study their impact on combustion performance. The combustion performance was evaluated by measuring the velocity, temperature, and NO_x concentration. Four locations along the bluff were selected, namely $X = 1.5$, 6.5 , 15 , and 35 cm (near the outlet), to measure the distribution of the three performance metrics, i.e., velocity, temperature, and NO_x concentration. Figure 5 illustrates the velocity distribution for the four typical locations. The results show that the velocity distribution remains unchanged for fuel H_2 at the location $X = 1.5$ cm. However, there is a slight variation in the velocity direction at $X = 6.5$ cm and $X = 15$ cm. At $X = 35$ cm, the velocity distribution changes significantly among different fuels. Notably, the maximum velocity is achieved when hydrogen is used as fuel.

Figure 6 displays the mean static temperature contours for various fuel types, each at an inlet velocity of 17 m/s and an equivalence ratio of 0.65 . The four locations ($X = 1.5$, 6.5 , 15 , and 35 cm) have been examined. The results indicate that the fuel type plays a crucial role in shaping the temperature distribution and flame structure. A high-temperature region is visible downstream of the bluff body, extending further downstream. Additionally, hydrogen fuel produces the highest temperatures and the widest flame.

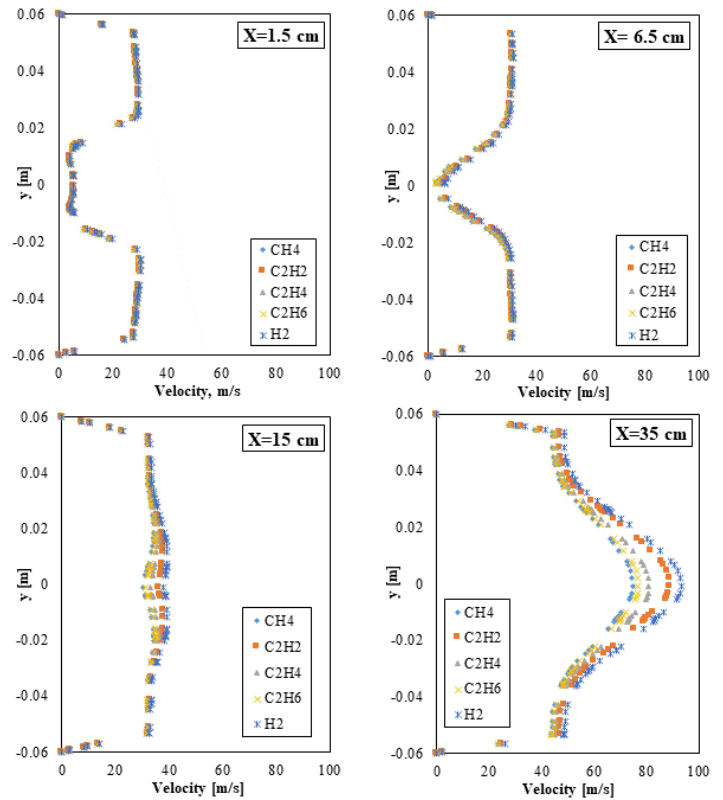


Figure 5: Comparison of stream-wise velocity profiles at inlet velocity 17 m/s and equivalence ratio 0.65 at a distance from the bluff body.

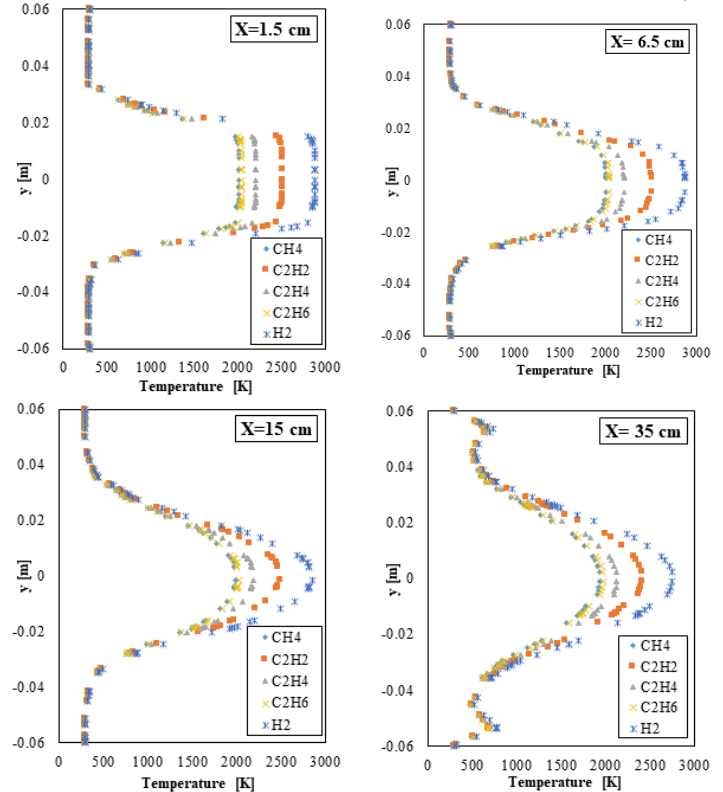


Figure 6: Comparison of stream-wise temperature profiles at inlet velocity 17 m/s and equivalence ratio 0.65 at different distances from the bluff body.

Figure 7 displays the concentration of NO_x at four distinct locations ($X = 1.5, 6.5, 15,$ and 35 cm). The fuel type plays a crucial role in altering the temperature profile, thereby affecting the concentration of NO_x . Notably, the concentration of NO_x is higher when hydrogen fuel is used, except at $X = 1.5 \text{ cm}$, where C_2H_2 fuel records a high concentration.

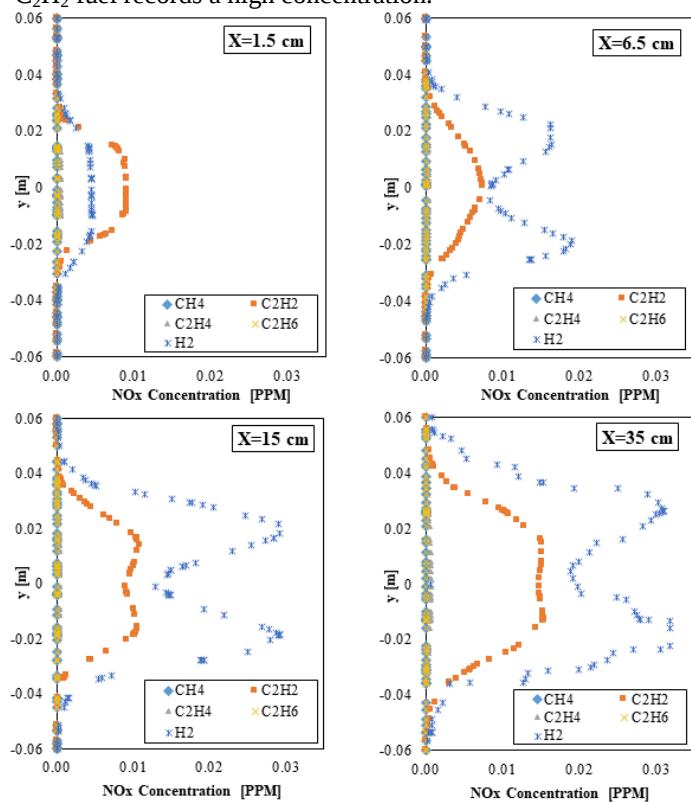


Figure 7: Comparison of NO_x concentration at inlet velocity 17 m/s and equivalence ratio 0.65 at different distances from the bluff body.

The underlying chemical kinetics of pollutant formation can account for the strong correlation between the peak in NO_x concentrations (Figure 7) and the high temperatures seen with hydrogen combustion (Figure 6). At the high temperatures characteristic of these flames, the main source for NO_x production is the thermal mechanism [48], also known as the Zeldovich mechanism [49,50]. This mechanism directly oxidizes atmospheric nitrogen (N_2) through a series of high-activation-energy reactions, primarily $\text{N}_2 + \text{O} \rightarrow \text{NO} + \text{N}$ and $\text{N} + \text{O}_2 \rightarrow \text{NO} + \text{O}$ [51]. Only at temperatures above roughly 1800 K does it become a significant source of NO_x , and it is temperature-dependent [52–54]. The peak flame temperatures for hydrogen combustion in our simulations surpass this critical threshold, leading to a rapid acceleration of the Zeldovich reactions and consequently higher NO_x formation compared to the cooler-burning hydrocarbon fuels.

3.3. Effect of bluff body geometry

The effect of the geometry of the bluff body on the three metrics of combustion performance was investigated. The contours of the longitudinal velocity component for different shapes of the bluff body at the same inlet velocity = 17 m/s and

equivalence ratio = 0.65 are shown in Figure 8. It can be seen that the area of the recirculation zone is correlated to the change in the bluff body shape, while the blockage ratio is the same for all cases. It can be observed that the plate flame holder shape provides a large recirculation zone, leading to greater flame stability compared to other shapes.

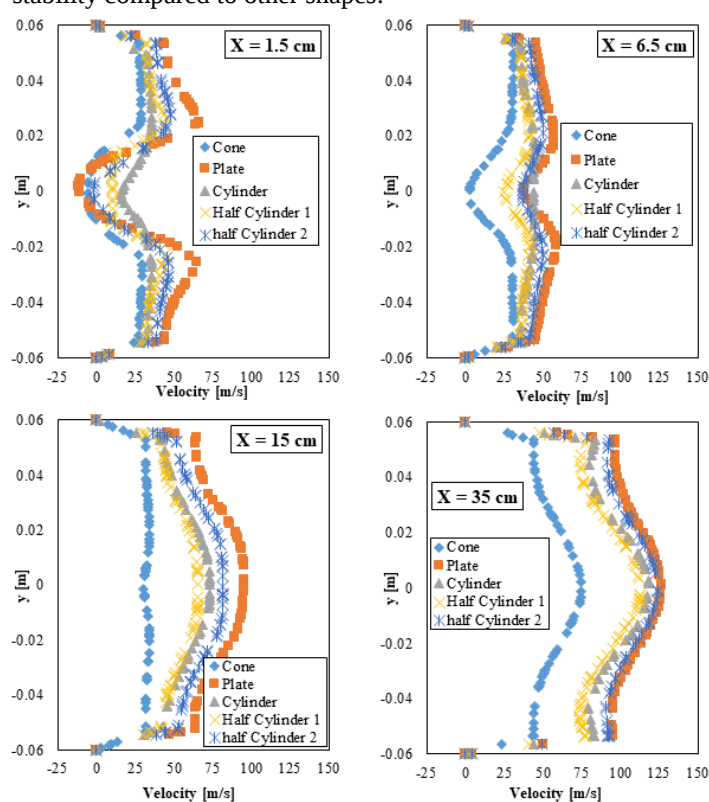


Figure 8: Comparison of stream-wise velocity profiles at inlet velocity 17 m/s and equivalence ratio 0.65 at different distances from the bluff body.

The effect of bluff body shape on the mean static temperature contours for the investigated fuel types at the same inlet velocity of 17 m/s and equivalence ratio of 0.65 is shown in Figure 9. One can notice that at all locations, as the bluff body shape changes, the temperature profile changes, the maximum temperature changes slightly, and the flame width also changes. The wider curve indicates that the reaction area is larger due to the turbulence and flow pulsation enhancement, which makes the combustion more efficient. Moreover, it was found that the plate flame holder shape produced a wide flame at all locations along the burner, indicating that the bluff body shape significantly affected the temperature distribution and flame shape. The plate-shaped flame holder produces a large recirculation zone and a more stable flame. It is expected that the sharp, ninety-degree separation angles of the plate create a more extensive, lower-pressure wake region compared to the more streamlined triangular or cylindrical shapes. This larger wake entrains more hot products and provides a lower-velocity region, increasing the residence time for the fuel-air mixture and thereby promoting a more stable ignition source.

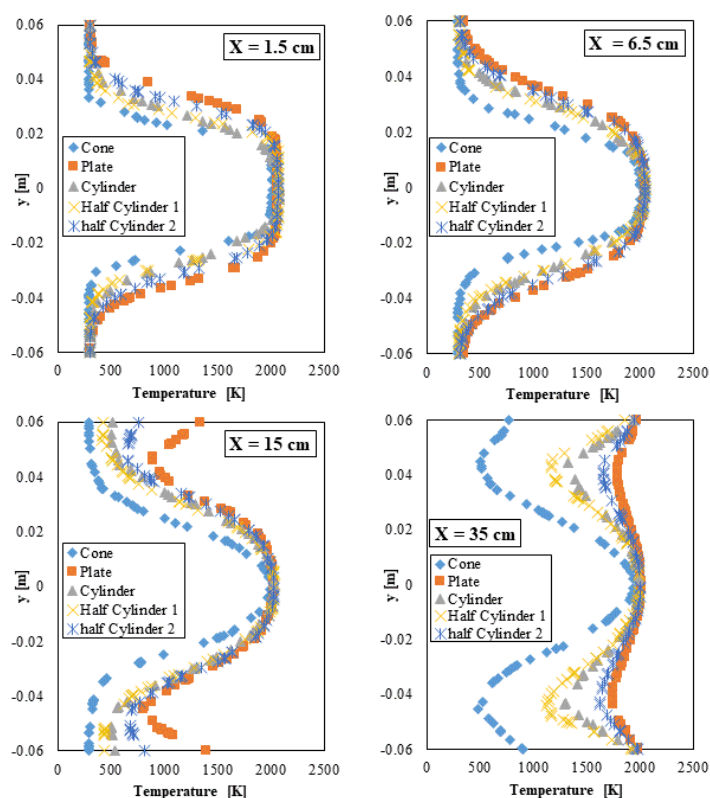


Figure 9: Comparison of stream-wise temperature profiles at inlet velocity 17 m/s and equivalence ratio 0.65 at a distance from the bluff body.

4. Conclusions

The paper presents a comprehensive study on combustion performance for a lean premixed mixture behind a bluff body. A numerical model incorporating a bluff body stabilized combustor was developed to analyze the improvement of confined premixed flame stabilization. A three-dimensional computational domain was developed to investigate the effects of bluff body shape and fuel type on temperature and velocity variations during premixed mixture combustion. The experimental results were compared to the proposed model, which showed acceptable agreement. The model results indicate that the bluff body provided the most flame stabilization when using hydrogen fuel. Starting with the same velocity profile immediately after the bluff body, irrespective of the fuel type, a significant effect on the velocity profile was observed as the flow moved downstream from the bluff body. Notably, hydrogen fuel achieved the maximum flow velocity, suggesting a tendency towards complete combustion conditions. The highest concentration of NO_x was observed with hydrogen fuel, likely due to the higher flame temperatures, which trigger the thermal Zeldovich mechanism.

The findings of this study offer direct implications for the design of industrial combustion systems, such as turbines and low-emission boilers. The demonstrated sensitivity of the flame structure to the bluff body geometry, particularly the wide, stable flame anchored by the plate flame holder, is a critical design parameter. A more stable flame provides a broader operational envelope, such that combustion can be maintained at more lean

equivalence ratios. Burners operating under these leaner regimes lower the peak flame temperature, the primary means through which the formation of thermal NO_x through the temperature-dependent Zeldovich mechanism is reduced. In turn, through optimization of the bluff body geometry for more stable flames, designers can both expand operational reliability and reduce harmful pollutant emission, an overriding goal of modern combustor development.

Higher-fidelity numerical techniques, like Large Eddy Simulations (LES), could be used in future studies to resolve the turbulence-chemistry interactions and transient flame dynamics that the current RANS-based model is unable to adequately capture. Additionally, future research examining the effectiveness of integrated active or passive pollutant reduction strategies can use the validated framework developed in this study as a baseline.

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