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A comparative experimental study of turbulent non premixed flames stabilized by a bluff-body burner

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ABSTRACT

Turbulent non-premixed flames of natural gas and air stabilized in a semi-infinite bluff-body burner are assessed in this work. Different situations are investigated corresponding either to jet or to wake-dominated flow fields. Measurements of the OH radical fluorescence and of the velocity field are obtained by joint Planar Laser Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV) techniques. First, a study of two chemically inert cases is presented to base the flow field structure. Then, the instantaneous OH fluorescence and velocity fields analysis underscore the local extinctions and the interactions between combustion and turbulence. A comparison between the Reynolds stresses distribution reveals that the flame presence generates turbulence in intermittently lifted situations and suppresses part of the Reynolds stresses when fully lifted.

1. Introduction

This work presents a study of the flow field structure, i.e., of the OH fluorescence and velocity fields in different non-premixed natural-gas/air combustion regimes stabilized downstream of a semi-infinite bluff body burner. The aim is to identify the influence of the fuel jet and air coflow velocities on the measured results at the flame stabilization region in situations where intermittent flame liftoff and partial extinctions may occur.

The flow field structure and flame front analysis is achieved by performing combined velocity and OH radical fluorescence measurements and by applying Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF). This study involves the comparison of three different turbulent flames, i.e., a jet-like flame, a fully detached partially premixed flame and an intermittently stabilized flame. The instantaneous flame structures are analyzed aiming to identify the combustion regimes and to illustrate the flame front and turbulent flow field interaction processes. The combined velocity and flame front measurements allow turbulent flame characterization in terms of the velocity average and the Reynolds stress tensor components, as well as the OH fluorescence average and variance. To the best of the authors' knowledge, the comparison of such three regimes is absent from the literature. This introduction is followed by the experimental setup presentation, detailing the measurement apparatus and the corresponding uncertainty analysis. Then, two non-reactive measured flow fields representative of the studied flames are briefly discussed. The velocity average, Reynolds stress components and the flame front structure results are analyzed for three different flame regimes. Finally, the conclusions and recommendations for future works are presented.

1.1. Bluff body burner studies

In this section, works related to the investigation of the reactive flow field stabilized downstream to a semi-infinite bluff body burner are discussed. The term bluff body usually refers to the flow around an obstacle that is fully submerged in the flow, i.e., a flow that exhibits two stagnation points, upstream and downstream of the body. In this study a semi-infinite bluff body is considered, which has only a downstream stagnation point. In a sense, the resulting flow field resembles that of coaxial jets with very thick walls. Several studies have characterized the isothermal and reactive flow fields using similar burner configurations. Most of these works focus in the recirculation zone structure at the bluff body vicinity and in the interaction with the jet core. Additionally, the effect of combustion on the flow field and the turbulent properties have been quantified.

Several works have proposed overall flow field classifications based on the observed flame structure. In their pioneering work,

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Masri and Bilger [30] classified the turbulent flames of natural gas and liquefied petrol gas into the following types: (A) short, recirculation controlled; (B) transitional; and (C) long, fuel jet dominated. The investigated velocity ranges were (5, 80) m/s for the fuel jet and (10, 35) m/s for the air flow. Soot emission characteristics have also been evidenced. Subsequently, Huang and Lin [21] classified commercial propane bluff body flames into the following types: (I) recirculated region, (II) transition, (III) unsteady detached, (IV) laminar ring, (V) developing ring, (VI) split flashing and (VII) lifted. The air flow velocity range is (0, 6) m/s, whereas the fuel jet velocity spans (0, 120) m/s. More recently, Esquiva-Dano et al. [16] suggested yet another classification for natural gas flames in situations where the velocity ranges of fuel and air are (0, 14) and (0, 20) m/s, i.e., covering a velocity range that lies below that investigated by Masri and Bilger [30]. The obtained flames were categorized as (1) laminar, (2) laminar ring, (3) transition I, (4) transition II and (5) recirculating.

Longwell et al. [29] reviewed several works that analyzed flame stability in the entire range of flammable mixtures in the wake created in the flow field by the object (bluff body). Stability is defined as the range of the equivalence ratio which maintains the flame. A variety of existing empirical correlations were compared which are based on the flame stability in small scale bluff bodies. Flame stability was found to be associated with the residence time in the recirculation zone, defined as the ratio between the mass entrance rate and the volume of the zone. The stability range decreases as the residence time diminishes. Schefer et al. [42] presented a study of a non-premixed flame stabilized by a bluff body by applying the Laser Doppler Velocimetry (LDV) technique to measure the three velocity components and the associated statistical moments. Reactive and isothermal flow fields were characterized in situations for which the reverse flow at the vicinity of the bluff body predominates. In the isothermal case, two stagnation points along the center line were found, which are affected by the center jet and by the air coflow. In the reactive flow field, jet penetration occurs along the center line because of the low density of the gases at the recirculation zone. In this case, two vortexes were measured spinning in opposite directions, and a single stagnation point was observed along the center line. The velocity decrease along the longitudinal direction in the reactive case is higher than the isothermal case because of the shear associated with the average velocity gradient at the region between the center jet and recirculation zone. The resulting flames were categorized as dominated either by the jet or by the air coflow.

Correa and Gulati [6] presented an experimental and numerical study of the temperature and species concentration in a bluff body burner. This burner was employed to obtain higher turbulent strain rates than those achieved in jet flames. The interaction between turbulence and the chemical reaction of a mixture of the fuels CO e H_2 was analyzed at the recirculation zone applying a Raman technique. Regions of large dissipation rates are located far downstream, when compared with jet flames. Masri et al. [31] measured, by applying the Raman scattering technique, instantaneous mixing and reactive scalar fields in the recirculation zones of turbulent non-premixed flames stabilized by a bluff body. The recirculation zone of CH_4/CO and CH_4/H_2 flames were characterized in terms of means and RMS of mixture fraction, temperature, and mass fractions of stable species. In these flames, two regions were identified of almost homogenous mixture within the recirculation zone, i.e., (i) a large outer region, which is fuel lean, and (ii) an inner region, which is smaller and lies closer to the center jet. Combustion is more intense in the inner region, where the mean mixture fraction is stoichiometric and the peak values for temperature and mass fractions of combustion products are reached. Dally et al. [9] studied the mean structure of turbulent bluff body jets and flames by performing measurements of the flow and mixing fields. Comparisons of these results with predictions made using standard turbulence models were discussed. Two vortexes were observed in the recirculation zone, an outer one, close to the air coflow, and an inner vortex, situated between the outer vortex and the jet. The momentum flux ratio of the jet to the coflow is the only scaling parameter for the flow field structure. Additionally, three mixing layers were identified in the recirculation zone: (i) an external one located between the air coflow and the external vortex; (ii) an intermediate one, between both vortexes; and (iii) an internal one, placed between the internal vortex and the fuel jet.

Shanbhogue et al. [43] reviewed the dynamics of bluff body stabilized flames and described the phenomenology of the blow off process regarding the fluid mechanics of the non-reacting and reacting bluff body wake flow. Their study considered different flow characteristics, such as the boundary layer, separated shear layer, wake and flow instabilities. Additionally, the influences of these instabilities on the flames were verified. Large differences between the non-reacting wake and the reacting wake of flames were evidenced. Extinction was found to be random near a flame's blow-off, starting as holes in the flame that form and convect downstream. Blow-off occurred as a sequence of events: extinction along the flame sheet, large scale wake disruption and a final blow-off, which depends on wake cooling and shrinking. Huang e Lin 2010 analyzed the influence of the fuel jet and air coflow velocities, proposing a revision of the flame type classification. The proposed four flame types were dubbed pre-penetration, transition, penetration and shear flow fields. It was observed that the flame was lifted and difficult to stabilize. Their study revealed several characteristics of the flow field. Two stagnation points, one external vortex and also, one internal recirculation zone were found analyzing the streamlines. Additionally, it was noticed that a reduction in the Reynolds number due the viscosity increase induced by combustion hampers the formation of the internal vortex, which was found in the isothermal case. The internal region was dominated by fuel rich combustion and the external region was stoichiometric or lean. The lifted flame presented a stagnation point further downstream in the flow field structure, when compared with the recirculation flame. Furthermore, the recirculation zone length was increased. In the penetration regime it was found that the vortex size decreased when the flame lifts-off. No stagnation points were found along the axis of symmetry, and only one existed away from this center axis. In the shear regime, a part of the air coflow penetrated the recirculation zone due to the high velocity of the center jet. Dawson et al. [10] examined confined and unconfined turbulent methane-air lean premixed flames, stabilized by an axisymmetric bluff-body, close to the blow-off limit and during the extinction transition. Measurements of OH chemiluminescence, flame tomography and OH-PLIF allowed to quantify the duration of the blow-off event. During the blow-off event, fresh reactants entered the reaction zone from the forward stagnation region and a significant flame fragmentation occurred. Kariuki et al. [24] examined the structure of unconfined lean premixed methane–air flames stabilized by an axisymmetric bluff body for conditions increasingly closer to blow-off and during the blow-off event using a fast imaging technique of OH chemiluminescence, OH-PLIF and PIV. During blow-off an entrainment of fresh reactants from the downstream end of the recirculation zone and fragmentation of the downstream flame parts occurs in sequence. These results are useful for model validation and for exploring the changes in turbulent premixed flame structure as extinction is approached.

1.2. Laser diagnostics of turbulent flames

Interactions between turbulence, mixing and chemical reactions control turbulent flame stabilization processes [37]. Thus,