Flow, Mixing and Combustion Characteristics of a Stratified Bluff Body Burner, Interacting With a Co-annular Swirl Induced Recirculation

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Introduction

To meet the increasing energy demand on fossil fuels for the next two decades (IEA 2016) without further affecting the environment, the development and implementation of clean power generation concepts is urgently required. The gas turbine represents one of the best available technologies, in a diverse market, for addressing efficiency and emissions issues. Sustainable gas turbine combustion would encompass fuel flexibility, higher efficiencies and drastically reduced emissions of CO, CO_2, NOx, soot and UHC (Dunn-Rankin 2008). Several low emission combustor technologies have been proposed and are currently under development through laboratory investigations and test bed evaluations.

The present work investigates an axisymmetric bluff body stabilized, primary flame zone, fuelled by a stratified inlet mixture, interacting with a co-annular swirling gas stream that can supply pure or vitiated 'overfire' air. This annular swirl disposition establishes an axial sequence of two, aerodynamically interacting, recirculations. An upstream bluff body primary zone and a downstream secondary, central toroidal recirculation zone (CTRZ), induced by the peripheral swirl, which promotes mixing of the main combustion products. A similar burner has been studied experimentally and computationally by [1.2], under unconfined conditions and different annular inlet flow settings. In those works, attention was paid to the effect of the premixing section and the inlet stratification on the near wake velocity fields, under moderate swirl interactions with the bluff body zone.

The combination of the two consecutive recirculation regions with primary zone inlet stratification and swirl imposition on the combustion gases instead of the flame anchoring region, represents a set up [3-5] that is different from traditional bluff-body, quarl expansions or in-tandem swirl arrangements and has not been fully investigated. Here the impact of the interactions of the central fuel supply, the variable inlet swirl, and the external air co-flow settings, with the variable two-recirculation wake zone, on fuel-air mixing fields and emissions levels, under inert and reacting conditions, is investigated. Measurements of fuel-air concentrations, temperatures and chemiluminescence images of OH* and CH* assisted in this preliminary assessment of the relative variations in flame structure, mixing topology and burner performance [6]. PIV measurements in flow field and supporting isothermal mixing computations provided insight into the complex flow patterns and delineated optimum configurations.

Experimental Methodology

The burner geometry was used for the present study (Figures 1a, b and c) are similar to those reported in [2,6]. The premixer/burner assembly was composed of two cavities formed between

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three disks, connected along their axis with a vertical, fuel supply, hollow tube. Propane was injected into the primary fuel-air mixing cavity, Figure 1c. The secondary cavity promoted partial-premixing with the central air and prevented flashback by balancing mixing and autoignition times [2]. This upstream section supplied the afterbody primary stabilization region with a radial equivalence ratio gradient (Figure 1d) regulated via the central air, the injected fuel and the secondary cavity. The bluff body flame zone was surrounded by a co-annular swirl flow (Figures 1a, b), introduced through four tangential inlets upstream of the cavities. An external surrounding annular air-flow (Figure 1a), impinging obliquely onto the divergent swirl motion, was employed to adjust the swirl penetration along the primary zone and provide extra control of the interaction between the primary zone with the swirl induced CTRZ. The multi-annular system was here enclosed within a 300mm square cross-section confining duct.

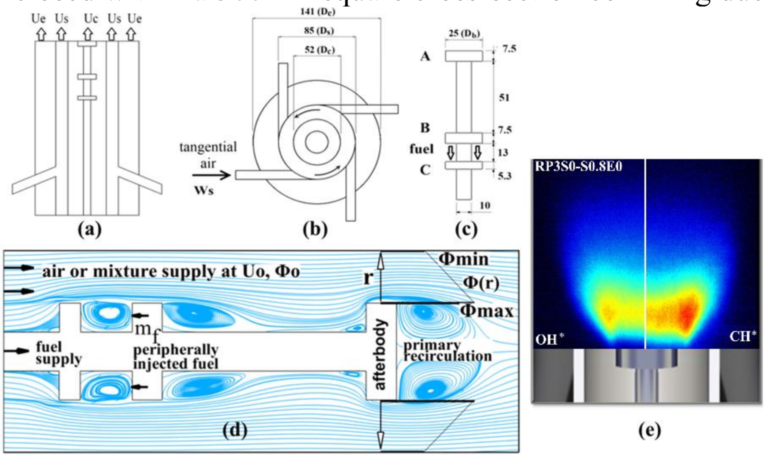

Figure 1: Experimental rig

The selected Swirl levels were 0 and 0.8 and were calculated as the ratio of the angular to axial momentum, obtained by integration of, measured and computed, axial and tangential velocity profiles at the swirl exit plane. Fuel-air mixture strength comparisons are based on the proximity to flame lean blow out (LBO), through the parameter, $\delta = (m_{fuel} - m_{fuel,\,LBO})/m_{fuel,\,LBO}$ (%), where $m_{fuel,\,LBO}$ is the primary fuel injection at lean blow-off. The nomenclature used for the comparisons of the inert or reacting topologies is given as an acronym. The first letter refers to (I)sothermal, (M)ixing or (R)eacting conditions, i.e. (I/M/R), the second unit refers to the placement and level of fuel injection, in the (P)rimary cavity (i.e. P3 or P25, based on δ), the third refers to the swirl intensity and the fourth is the ratio of the axial momentum of the external air stream to that of the sum of the swirl and central streams, i.e. (E0/2.7). Therefore, a mixing configuration with primary fuel injection at δ=3%, no swirl stream injection, swirl 0.8 and external stream with momentum ratio 2.7 is expressed as MP3S0-S0.8E2.7.

Results and Discussion

Isothermal Flow

The isothermal and inert, fuel injected, wake topologies will be presented first, to depict the variety of fuel-air mixing configurations that can be sustained by the multi-annular system.
The cold flow patterns that can be achieved by parametrically varying the swirl intensity and the external co-annular air are displayed in Figure 2 in the form of time-averaged velocity contours. Without swirl (a) the primary afterbody recirculation controls the development of the wake; vortex breakdown occurs at about 0.7 in the computations and 0.74 in the experiments, and at a swirl of 0.8 (b), (c), (d) a secondary central toroidal recirculation zone (CTRZ) is formed sequentially to the bluff body recirculation. This behavior was first noted by Xiouris and

Koutmos (2011), who discussed the mean velocity variations along the center-line, under unconfined conditions, without regulation from the external co-flow.

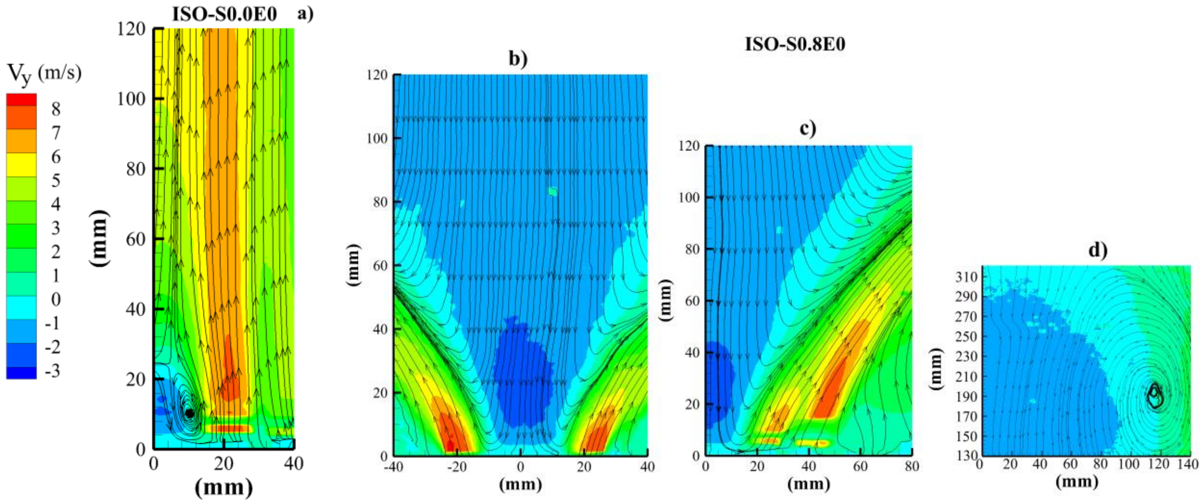

Figure 2: Isothermal velocity field of axial component for three investigated regions focused either (a), (b) on the primary recirculation region at exit of the bluff-body, or (c), (d) on the secondary recirculation zone with variable swirl intensity (i.e. 0/08).

Mixing Flow

The variations in the isothermal fuel-air mixing fields due to swirl effects and co-annular stream settings are important in determining the resulting wake development under reacting conditions. An effort has been made to measure the fuel distributions resulting from different annular flow settings and fuel injections, maintaining the primary zone inlet stratification. This will be a first assessment of the rate and efficiency of admixing of secondary gases introduced e.g. through the swirl, as well as of the capacity of regulating this process through the external air stream. Measured and computed distributions of the cold flow equivalence ratio are displayed in Figure 3 in terms of contour plots. Standard fuel injection was first placed within the primary cavity at δ = 3 and 25%, similar to the counterpart reacting cases and for swirl levels of 0 and 0.8. At the limiting ultra-lean, 3% fuel level, swirl promotes accumulation of a richer mixture closer to the disk, contracts the spread of the mixing field and strengthens the near rim region, which is also a low velocity zone, favorable for fame front anchoring. At the richer, δ =25% case, the impact of swirl addition seems more pronounced at the downstream developing wake. A suitable combination of these settings could well be exploited for a controlled burn out of the primary zone gases possibly through swirl stream vitiation. By properly adjusting this consecutive vortex placement one can regulate its interactive mixing effectiveness.

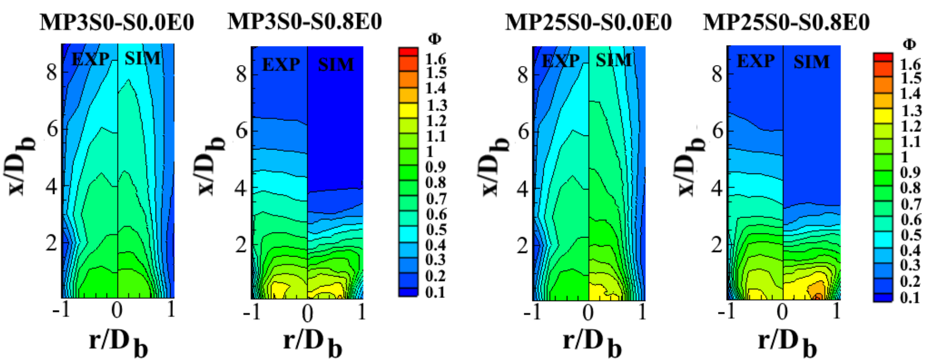

Figure 3: Measured and simulated time-mean equivalence ratio distributions for the range of the investigated cases

Reacting Flow

The flame topology variations obtained with the different inlet mixture conditions for the studied swirl intensities at lean and closer to LBO settings are displayed in Figure 4 in terms of time-mean CH* and OH* chemiluminescence distributions that portray the overall high temperature near wake formations. The images reveal improved flame anchoring near the disk rims as swirl retracts and expands the toroidal reacting front at both lean and limiting mixtures (e.g. compare RP3S0-S0.8E0 and RP25S0-S0.8E0). Increased fuel injection and external co-flow regulation at a momentum ratio of 2.7, elongates the flame front disposition (e.g. RP3S0-S0.8E2.7 or RP25S0-S0.8E2.7), an alteration that was more visible in the temperature fields discussed below.

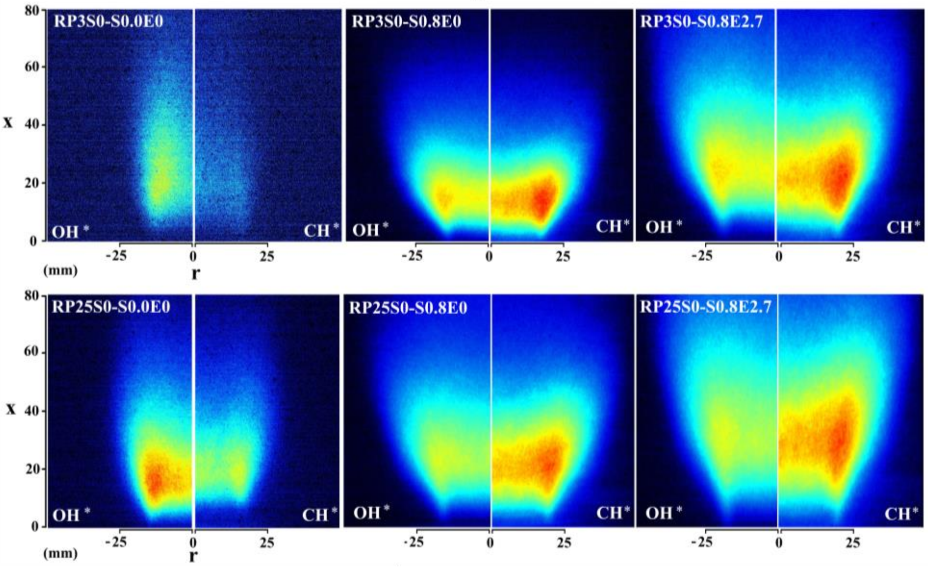

Figure 4: CH and OH* Flame Chemiluminescence Images (without Abel transform)*

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