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Full Length Article

A comparison between the stabilization of premixed swirling CO_2-diluted methane oxy-flames and methane/air flames

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HIGHLIGHTS

- Stabilization of premixed swirling $CH_4/O_2/CO_2$ flames is deduced from CH_4/air flames.
- The flame leading edge position depends on three parameters.
- Adiabatic flame temperature needs to be matched.
- Swirl number needs to be matched.
- The ratio of injection velocity to laminar burning velocity needs to be matched.

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ABSTRACT

Revamp of air powered industrial boilers to oxy-combustion operation raises several issues. In this study, the stabilization of CO_2-diluted premixed swirling CH_4/O_2 flames is compared to operation with CH_4/air flames by a set of experiments in a generic labscale combustor equipped with an axial-plus-tangential swirler. The investigated flames are stabilized aerodynamically within the swirling flow without help of any solid anchoring device. The structure of the turbulent swirling flames is examined by recording their OH^* chemiluminescence. Laser induced OH fluorescence measurements are carried out to delineate the location of the flame front and burnt gases and infer the shape taken by the flame. Particle imaging velocimetry measurements reveal the corresponding velocity field. The temperature is also recorded with thermocouples in the internal and the external recirculation zones of the flow and inside the combustion chamber walls. These diagnostics reveal similarities between the topology of CH_4/air and $CH_4/O_2/CO_2$ flames near their stabilization point. For a fixed swirl number, it is found that N_2- and CO_2-diluted CH_4/O_2 flames at the same equivalence ratio feature very similar shapes provided the adiabatic flame temperature and the ratio of bulk velocity to laminar burning velocity are kept the same although the absolute value of bulk velocity and the general velocity level inside the combustor are different. This result was found for injection Reynolds numbers varying from $Re = 8500–28\,000$ and for swirl numbers ranging from $S_0 = 0.5$ to 1.2. The operability range of well stabilized CO_2-diluted flames is however reduced. It is also found that the temperature of the burnt gases in the outer recirculation zone differs between the CO_2- and N_2 diluted combustible mixtures sharing the same adiabatic temperature, but this does not affect the stabilization of the flames near the burner outlet, the temperature in the burnt gases and inside the combustor sidewalls. The flame leading edge is stabilized on average off-axis due to the structure of the W axial velocity profile produced by the axial-plus-tangential swirler at the burner outlet. This study indicates that CO_2-diluted CH_4/O_2 premixed swirling flames can be stabilized with similar shapes as CH_4/air flames without design modification provided the suggested similarity is obeyed.

1. Introduction

Oxy-combustion is a way to reduce CO_2 emission levels from industrial plants. Combined with carbon capture and storage technologies it eases separation of CO_2 from the other flue gases [1,2]. One difficulty is to revamp existing air powered combustors with

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Nomenclature

IRZ	inner recirculation zone
ISL	internal shear layer
ORZ	outer recirculation zone
OSL	outer shear layer
PIV	particle imaging velocimetry
ϕ	equivalence ratio
$\dot{m}_z, \dot{m}_\theta$	mass flow rate injected axially and tangentially [kg/s]
P	thermal power [kW]
Re	injection Reynolds number $Re = U_b 2r_0/\nu$
r_0	radius of the injector [mm]
r_1	radius of the diffuser outlet [mm]
S_0	geometrical swirl number
S_L	laminar burning velocity [cm/s]
T_{ad}	adiabatic flame temperature [K]
U_b	bulk injection velocity [m/s]
u_z, u_θ	axial and tangential velocities [m/s]
X_d	molar fraction of diluent d in the oxidizer stream
x_f	radial distance between the flame leading edge and the burner axis [mm]
z_f	axial distance between the flame leading edge and the burner outlet [mm]
z_{st}	axial distance between the stagnation point and the burner outlet [mm]

oxy-burners with a limited number of modifications and without impairing performances and emissions. Since oxygen separation from air represents the largest share of electricity consumption in oxy-fuel powered plants [3], oxy-burners are generally operated near stoichiometry, typically with a global equivalence ratio $\phi = 0.95$ and recirculation of exhaust gases is used to lower the temperature of the burnt products [4]. These new operation regimes modify the combustor performances, its operability and its stability with respect to dynamical phenomena [5]. The main features of oxy-flames diluted by exhaust gases need to be documented in order to reproduce similar conditions as in air powered combustors. Otherwise, the furnace could eventually be damaged.

The objective of this study is to document the stabilization of premixed CO_2-diluted methane oxy-flames for its use in industrial boilers. This problem has already been considered for gas turbines [6,7] and for boilers powered by oxy-coal combustion [8]. In the targeted industrial boilers, the fuel is natural gas, the combustor operates near atmospheric conditions, the dump ratio is bigger than in gas turbines, the oxydizer stream is not necessarily preheated, and flames provide thermal power to heat a load (non-adiabatic combustion).

2. Stabilization of swirling oxy-flames

It is first worth starting by examining differences in the fundamental properties between CO_2- and N_2-diluted CH_4/O_2 flames. CO_2 is chemically active [9]. It is found that dilution by CO_2 decreases faster the laminar burning velocity than N_2 dilution [10,11] and these flames are less resistant to aerodynamic strain [12,13]. Thermodynamic and detailed chemical kinetics calculations of $CH_4/O_2/CO_2/H_2O$ flames under high pressure conditions relevant to gas turbine operations indicate that a good oxygen/diluent ratio needs to be selected otherwise the flame is blown off or is too hot for its industrial use [14].

Comparisons between CH_4/O_2 N_2- and CO_2-diluted premixed swirling flames have been reported in a few studies. It was found that the operability boundaries of a combustor contract when powered by CH_4/O_2 CO_2-diluted mixtures compared to operation with air due to the slower kinetics of the CO_2-diluted mixtures relative to air [5]. For the same power and adiabatic flame temperature, N_2-diluted flames are found stable at a lower equivalence ratio than CO_2-diluted flames. Kutne et al. [15] concluded that operation with $CH_4/O_2/CO_2$ mixtures in gas turbine like conditions are difficult without modifications of the combustor. In their study CO_2-diluted oxy-flames could only be stabilized near stoichiometry impairing pollutant emissions with too high temperatures for the turbine. These issues can however be circumvented by water addition or by small changes in the turbine design as demonstrated in several pilot scale gas turbines [1].

Oxy-flames in boilers are generally stabilized by swirl and as a consequence the structure of the swirling flame largely depends on the structure of the swirling jet exhausting the injector [16–18]. In combustors equipped with premixed swirling injectors, flames generally take a V-shape or an M-shape [19,20]. In a V-shaped flame, the combustion reaction only takes place at the boundaries of the internal shear layer (ISL) of the swirling jet of fresh gases, which is in contact with an internal recirculation zone (IRZ) filled with hot burnt gases above the burner outlet. An M-shaped flame features also a reaction layer between the outer shear layer (OSL) of the reactant jet and the external recirculation zone (ORZ) of burnt gases located in the corners of the combustor dump plane.

The swirl number [21,16,18], the heat losses to the chamber walls and the injector geometry are known to alter the swirling flame topology [22–24]. It is known that above a critical threshold value of about $S_c \sim 0.6$ a stable internal recirculation zone (IRZ) appears along the burner axis allowing to aerodynamically anchor swirling flames without direct contact with the solid pieces of the injector. The critical value for S_c is however not absolute and is very sensitive to geometrical details of the injector and the combustion chamber. It also depends on the peculiar structure of the flow field inside the injector and inside the injection slits [25,26]. A series of studies have already been carried out to test the potential of CO_2 diluted oxy-combustion for gas turbine applications with emphasis on pollutant emissions, combustor operability and determination of critical conditions [6,7,27]. The main findings are that the CO_2 chemical activity needs to be taken into account for the simulation of pollutant emissions, CO_2-diluted flames cannot sustain as large dilution rates as N_2-diluted flames and as a consequence the operability of the gas turbine narrows.

This brief review indicates that the stabilization of CO_2-diluted CH_4/O_2 flames is more difficult than CH_4/air flames because their fundamental properties like their laminar burning velocity and their resistance to aerodynamic strain differ. The thermo-physical properties of CO_2 differ also from N_2. The stabilization of swirling flames also largely depends on the injector and combustor geometries. Observations are reported in this article on the effects of laminar burning velocity, adiabatic flame temperature and swirl number on the shape taken by aerodynamically stabilized premixed swirling oxy-flames diluted with N_2 and CO_2 away from critical conditions, *i.e.* away from lean blow-off, flashback and thermo-acoustic oscillations.

The test-rig and the optical diagnostics are presented in the next section. Effects of laminar burning velocity and adiabatic flame temperature are then investigated in Section 4. Effects of the swirl number are examined in Section 5. The differences between the temperature distributions of the N_2- and the CO_2-diluted flames are presented in Section 6. The structure of the velocity field of these flames is finally examined in Section 7 in