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On the characteristic flow and flame times for scaling oxy and air flame stabilization modes in premixed swirl combustion

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Abstract

We compare the conditions leading to the stabilization of turbulent methane air and oxy-flames in the outer recirculation zone (ORZ) of a lean premixed acoustically decoupled swirl combustor. The appearance of a flame in the ORZ is an important flame macrostructure transition that was previously shown to be associated with the onset of thermo-acoustic instability under acoustically coupled conditions. We find that, when similar bulk flow conditions are imposed in the ORZ, the transition is governed by the extinction strain rate and can occur at different adiabatic flame temperature and unstretched laminar burning velocity. First, we show that an important non-dimensional parameter characterizing the flow in the ORZ, that is the Strouhal number associated with the azimuthal ORZ spinning frequency, is independent of the Reynolds number and has the same constant value in air and oxy-combustion ($St = \frac{f_{ORZ}.D_{in}}{U_{in,bulk}} \approx 0.12$). This has the important implication that the inlet velocity is a more relevant parameter choice than the inlet Reynolds number in order to maintain similar flow conditions in the ORZ. Next, by comparing the extinction strain rates – computed at the measured ORZ temperature – we show the existence of a single correlation between the inverse of the ORZ spinning frequency (taken as a characteristic ORZ flow time) and the inverse of the extinction strain rate (taken as a characteristic flame time) valid for both air and oxy flames and delimiting the regions of existence of different flame macrostructures.

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1. Introduction

The world relies heavily on fossil fuels (86.7% in 1973, 81.7% in 2012[1]) and this trend is likely to continue for several decades (potentially 75% in 2040[2]). Meanwhile climate change concerns associated with the accumulation of carbon dioxide (CO_2) in the atmosphere continues to be a pressing issue that needs to be addressed. While it is important to continue the deployment of renewable energy technologies, it is also crucial to develop cleaner and more efficient fossil fuel-based energy conversion systems.

Among the promising technologies for cleaner power generation using fossil fuels is oxy-combustion with carbon capture. In premixed oxy-combustion, CO_2 can be used as diluent to control the flame and turbine inlet temperatures.

1.1. From air to oxy flame combustion

Changing the diluent from nitrogen (N_2) to CO_2 impacts the combustion process because of the differences in thermo-physical properties, chemical kinetics and radiative properties [1–5]. N_2 and CO_2 have sizable differences in density, specific heat capacity and diffusivities. CO_2 dilution impacts the chemical kinetics by affecting the radical pool mainly through the reaction $CO_2 + H \rightleftarrows CO + OH$ [6]. Moreover, the CO_2 dominated combustion products lead to more radiative heat exchange with the surroundings, compared to air-flames.

There have been a number of studies on premixed methane (CH_4) oxy-flames in swirl-stabilized combustion systems [3–5,7,8]. We will briefly review the most relevant ones to our current investigation. Shroll et al. [4] investigated thermo-acoustic stability of premixed $CH_4/O_2/CO_2$ and $CH_4/O_2/N_2$ mixtures in a swirl combustor. Oxy-flames were kept at stoichiometric conditions, which is the practical operating condition owing to the relatively large O_2-production cost; variable CO_2 dilution levels were used to keep the same adiabatic flame temperature (T_{ad}) as the air-flame. They found that the transition between thermo-acoustic modes is mainly a function of T_{ad}.

Watanabe et al. [5] compared lean air-flames and oxy-flames in a premixed swirl combustor identical to the one considered in this paper. When comparing oxy and air flames with the same inlet Reynolds (Re) and swirl (Sw) numbers, T_{ad} and equivalence ratio (ϕ), they found differences in flame shape.

The effects of Sw and T_{ad} on the lean stability and shapes of premixed air and oxy-flames were analyzed by Jourdaine et al. [7]. Air and oxy-flame shapes matched when Sw and T_{ad} were the same for both, at Re less than 20,000.

Amato et al. [3] focused on the lean blowoff limit and showed that the operability boundaries of a CO_2 diluted system reduces significantly compared to methane-air mixtures in a premixed swirl combustor; this was attributed to the slower kinetics of $CH_4/O_2/CO_2$. The CO_2 diluted mixture was found to blowoff at T_{ad} around 300 K higher than the air mixture for a given nozzle exit velocity, showing that the T_{ad} does not govern the flame static stability.

Work on oxy-combustion has been also carried-out in a swirl combustor by Kutne et al. [8] at atmospheric conditions. The O_2 mole fraction in the oxidizer mixture, as well as the equivalence ratio and thermal power were varied to also study the flame macrostructure and static stability at lean conditions. Here, an enhanced stability was found as the O_2 fraction in the oxidizer was raised; they attributed this observation to the change in laminar burning velocity (S_L^0) and Re.

When comparing air and oxy combustion, some parameters need to be held constant in order to isolate the desired effects, often thermo-chemical effects. Some studies kept the inlet Re constant to satisfy dynamic similarity. Others kept the thermal input constant, driven by a more practical need for testing the retrofit of existing air combustor. Other studies compared oxy and air flames at the same T_{ad} to keep similar combustor and turbine inlet temperatures, a major constraint in gas turbine combustion. The choice of the inlet parameter to be controlled is crucial and will be an important part of the current study.

1.2. Flame macrostructure transition in swirl combustion: importance and modeling

Several researchers reported the existence of different flame shapes or macrostructures in swirl-stabilized combustion with air as oxidizer. These have been previously documented as function of different parameters such as the fuel composition, ϕ, Re, Sw, confinement as well as centerbody geometry [10–14]. Similar swirling flame macrostructures have also been reported for oxy-flames under stoichiometric conditions [4,15]. Most of these studies reported the following flame macrostructures: columnar tubular flames (I); bubble-columnar flames (II); single conical flames stabilized along the inner shear layer ISL (flame III); and a double conical flame with an additional flame front stabilized in the outer recirculation zone (ORZ) and along the outer shear layer OSL (flame IV). We previously documented and analyzed the change in flow field between these different flames [16].

Recently, we demonstrated [12,16] the strong correlation between these flame macrostructures, the transitions among them and the different

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[1] Percent of total primary energy. Source: IEA Key World Energy Statistics 2014.

[2] Percent of total primary energy. Source: IEA energy outlook 2014

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