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Effect analysis on the macrostructure and static stability limits of oxy-methane flames in a premixed swirl combustor

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ABSTRACT

In this study, the changes in macrostructure and static stability limits of $CH_4/O_2/CO_2$ flames were recorded experimentally in a premixed swirl combustor over ranges of equivalence ratio (φ) and oxygen fraction (*OF*: volumetric percentage of O_2 in the O_2—CO_2 oxidizer mixture) and under fixed Reynolds (*Re*) operation to isolate its dynamic effect on flame stabilization. Two-dimensional stability maps are presented as function of φ and *OF.* The maps are presented on contours of inlet velocity (U_{in}), combustor power density (*PD*) and adiabatic flame temperature (T_{ad}) to correlate these parameters with the stability limits. Selected flames were imaged to analyze the effects of φ, *OF*, U_{in}, T_{ad} and Re on flame stability. The results showed that sustaining premixed oxy-flames is not possible for OF below 29% and above 70%. Reactions kinetic rate is a more relevant parameter than *Re* for determining flashback limit. *PD* has a leading role for controlling flame stability near the lean blow out limit. U_{in} is more relevant than Re for controlling flame transition from the inner shear layer to the outer recirculation zone. Increasing Re widens the operability window by shifting blow out limit to leaner conditions.

1. Introduction

The combustion of fossil fuels is the main source for producing power. However, it has hazardous effects on the environment in terms of NO_x, SO_x, and carbon emissions [1], with the latter being the chief cause of the greenhouse effect and hence the increasing fear of global warming. Many technologies have thus been invented to reduce those effects [2]. One of these technologies is oxy-fuel combustion, which can reduce CO_2 emissions up to 20% [3]. It utilizes oxygen instead of air and hence eliminates nitrogen from the oxidant gas stream. This reduces the volume and mass of the flue gas stream and, hence, the size of the flue gas treatment equipment [4]. The application of oxy-fuel combustion not only reduces volume and mass of the flue gas stream but also eliminates NOx formation. However, fuel combustion in pure oxygen makes the adiabatic flame temperature higher than that of burning hydrocarbon fuel in air [5]. The excessive rise in combustion temperature may not be suitable for applications like gas turbines [6]. Some of the exhaust CO_2 is thus recirculated back into the combustor to dilute the reactants and control the flame temperature. Premixing of combustion reactants prevents the creation of hot stoichiometric combustion zones.

Lean premixed (LPM) combustion is used in many combustion systems (such as largescale and aviation gas turbine systems and automotive internal combustion engines) primarily because of its benefits such as lower pollutant emissions and more efficient combustion when compared to non-premixed systems and configurations [7,8]. The LPM combustion technique results in less emission due to the reduction in flame temperature, which reduces the thermal nitric oxides emissions for air combustion [8]. However, a drawback of pre-mixed combustion is that the flame is more prone to thermo-acoustic instability and/or flashback [9]. Combustion instability has been one of the most critical phenomena encountered during the development of LPM combustor systems [10,11]. Moreover, if not anchored properly, LPM flames may blow off leading to what is referred to as lean flammability limit or static instability [12–14]. Combining oxy-combustion with LPM combustion can result in almost full control of emissions and flame temperature while capturing CO_2 efficiently. However, the replacement of N_2 by CO_2 may tighten the stable operation range of a given burner. The physical properties of N_2 and CO_2 are dissimilar and necessitate the modification of the burner design to adapt for such differences. Under the elevated combustion temperature conditions, CO_2 has a higher heat capacity than that of N_2 (about 1.6

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Nomenclature

2-D	Two dimensional
CH_4	Methane
CO_2	Carbon dioxide
O_2	Oxygen
D	Burner throat diameter (m)
DLE	Dry-low-emissions
H_2O	Water vapor
HV_{CH4}	Standard heating value of CH_4 (MJ/kg)
ISL	Inner shear layer
LPM	Lean premixed combustion
M_i	Molecular weight of species *i* (kg/kmol)
$\dot{m}_i$	Mass flow rate of species *i* (kg/s)
ORZ	Outer recirculation zone
OSL	Outer shear layer
OF	Oxygen fraction, volumetric percentage of O_2 in the O_2—CO_2 oxidizer mixture
p	Operating pressure (kPa)
PD	Combustor power density (MW/m^3/bar)
R_u	Universal gas constant (kJ/kmol/K)
Re	Reynolds number at the inlet throat
S_L	Flame speed (m/s)
T	Gas temperature (K)
T_{ad}	Adiabatic flame temperature (K)
U_{in}	Inlet bulk velocity (m/s)
Vc	Volume of the combustion chamber (m^3)
y_i	Mole fraction of species *i*

Greek symbols

φ	Equivalence ratio
ρ_{mix}	Mixture density (kg/m^3)
μ_{mix}	Mixture dynamic viscosity (kg/m/s)

times) [15]. Moreover, CO_2 is an active molecule in the infrared region, so the radiation heat transfer will be totally different than that in the case of air combustion. Also, under high-temperature operation, CO_2 becomes active and participates in the reactions and, accordingly, affects the rate of reaction kinetics within the combustor [16]. All such changes while adapting oxy-combustion technology should result in distinct behavior of the generated oxy-flame as compared to air-flame.

Premixed oxy-combustion has been examined in a number of relevant past studies. Kutne et al. [15] studied the stability of methane-oxygen swirl-stabilized partially-premixed flames in a model gas turbine combustor and compared the results with methane-air flames. The results showed that the oxygen fraction (*OF*) is a more relevant parameter than the equivalence ratio (φ) for controlling flame shape and stability. Increasing *OF* significantly improved the flame stability. They attributed this behavior to the associated changes in flame speed (S_L) and Reynolds number (*Re*). Rashwan et al. [17] investigated experimentally the impact of premixing level on the stability limits of methane-air flames stabilized over a perforated-plate burner and compared the results with those of methane-oxygen flames. The results showed wider flammability limits at lower premixing levels for the methane-air flames. In comparison with methane-air flames, methane-oxygen flames resulted in tighter flammability limits, about 20% reduction in operability. Watanabe et al. [18] compared the macro-structure of methane-air and methane-oxygen flames in a swirl-stabilized combustor at the same operating φ and adiabatic flame temperature (T_{ad}). The results showed the both flames behave similarly at higher φ. However, when φ drops down to a value of 0.6, the flame disappears from the outer shear layer (OSL) in the methane-air flames but exists within the OSL in the methane-oxygen flames, although the flame speed is lower in case of methane-oxygen flames. Their calculations showed higher extinction strain rate in the OSL for oxy-flames as compared to air-flames, which may justify the existence of the flame in the OSL for the oxy-flames at φ of 0.6. Baigmohammadi et al. [19] studied the effects of geometry, Re and φ on the dynamics of premixed oxy-methane flames in a backward-facing step reactor. The results demonstrated that the reactor geometry (in terms of length and diameter) significantly affect the speed and frequency of the flame. Also, increasing Re reduced the flame operability range. The effect of combustor design and flow configuration on flame stability are investigated in a series of numerical studies by Peng et al. [20,21] and Zuo et al. [22,23]. Peng et al. [20] performed a detailed numerical study considering premixed hydrogen/air flames in a micro combustor with and without front-cavity. The results showed that the front-cavity widens the flame operability range. Zuo et al. [22] studied numerically the effect of flow configuration on the distribution of the wall temperature in a micro combustor, and the results showed that the counter flow configuration resulted in more uniform wall temperature than the co-flow configuration.

Bollinger and Williams [24] studied the effect of Re (in the range from 3000 to 35,000) on the turbulent flame speed. The results showed that the turbulent flame speed is a function of the Re inside the burner tube. At constant Re operation (ranging from 6700 to 14200), high pressure turbulent burning velocity measurements were carried out by Liu et al. [25]. The results showed that, at constant *Re*, turbulent burning velocity reduces while increasing the pressure in a minus exponential manner. Also, the results showed that as the Re increases, the turbulent burning velocities increases at any pressure value. Jourdaine et al. [26] tested both N_2-diluted and CO_2-diluted CH_4—O_2 flames under fixed swirling conditions and concluded that similar flame shapes can be obtained for both flames provided that both the adiabatic flame temperature and the ratio of laminar burning velocity to bulk flow velocity are kept the same. They reported also reduced operability range of the CO_2-diluted flames. Yoon et al. [27] studied the effect of inlet mixture velocity on combustion instability of a model gas turbine combustor. The results showed a key role of the fluid dynamical vortex frequency and structure on generating unstable flames at lower inlet velocities. Very recently, we investigated experimentally the stability limits of premixed oxy-flame on the same swirl stabilized combustor utilized in the present study at fixed inlet bulk flow velocity [28]. The results revealed a leading role of T_{ad} in quantifying the combustor stability map.

Based on the above discussion, few research studies considered the coupling between LPM and oxy-combustion technologies for dry low emissions (DLE) gas turbine applications with carbon capture. It must be mentioned here that DLE combustors are based on LPM combustion. Moreover, no detailed stability maps exist that determine the operability ranges of such gas turbine combustors over considerable ranges of operating conditions. In this study, 2-D operability maps are presented over wide ranges of operating conditions, function of φ and *OF*, on a gas turbine model combustor of similar power density (*PD*) as commercial gas turbines. This means that the obtained stability maps can be extrapolated for controlling the operability ranges of industrial-scale *DLE* gas turbine combustors adapting premixed oxy-combustion technology.