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Stability maps of non-premixed methane flames in different oxidizing environments of a gas turbine model combustor

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HIGHLIGHTS

- Recording stability maps for non-premixed methane flames in gas turbine combustor.
- Recording stability limits of oxy-combustion and O_2-enriched air-combustion flames.
- Effects of oxygen fraction and Reynolds number on flammability limits are investigated.
- Comparison of stability maps of oxy-combustion and O_2-enriched air-combustion flames.
- Flames visualizations in terms of length, appearance and color are reported.

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ABSTRACT

Oxy-fuel combustion provides a promising solution to the problem of excessive NOx emissions generated by air-based combustion systems; NOx is potentially eliminated in the absence of air-based nitrogen. However, severe temperatures are reached if fuel is burned in pure oxygen. Dilution by CO_2 is thus implemented to control the flame temperature. The addition of CO_2, however, was found to retard chemical-kinetics rates and negatively affect the laminar burning velocity and combustion efficiency. This study thus set out to examine oxy-fuel combustion and compare it to oxygen-enriched air-fuel combustion based on flame stability and appearance. Experiments were conducted on a swirl-stabilized model gas-turbine combustor to determine the ranges of stable operation of methane flames in different oxidizer environments, including CO_2-diluted oxy-combustion and oxygen-enriched air-combustion. Based on that, two sets of experiments were conducted over ranges of oxidizer Reynolds number, equivalence ratio, and oxygen fraction in the oxidizer mixture. The first set of experiments considered CO_2-diluted oxy-combustion, while the second set considered oxygen-enriched air-combustion. For both sets, the results showed that the stability map widens as the oxygen fraction is increased in the oxidizer mixture. This can be attributed to higher flame speeds, which assist flame stabilization under lean operation. For the same oxygen fraction and Reynolds number, the oxy-combustion flames were found to stabilize at higher equivalence ratios and fuel flow rates when compared to the oxygen-enriched air flames. This difference in flame stability magnifies at smaller oxygen fractions and gradually diminishes as the oxygen fraction is increased.

1. Introduction

The most dangerous pollutants as a result of burning natural gas are nitrogen oxides (NOx), which result from the reaction of air-based oxygen and nitrogen. Other hazardous exhaust emissions that should be taken into consideration are CO and CO_2. Interestingly, there are different methods for eliminating NOx, including process modifications, pre-treatment, combustion modification, and post-combustion. An approach to completely eliminate NOx emissions is through the application of oxy-fuel combustion technology [1,2]. N_2 is removed from air using an air-separation unit. The remaining gas (mainly O_2) is used as oxidizer. However, the combustion of fuel using pure oxygen results in excessively high flame temperature [3]. For the sake of preventing this, some of

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Nomenclature

CH_4 methane
O_2 oxygen
N_2 nitrogen
CO_2 carbon dioxide
CO carbon monoxide
HC hydrocarbons
OF oxygen fraction, volumetric percentage of oxygen in the oxidizer mixture
Re Reynolds number of oxidizer mixture
$\dot{m}$ mass flow rate of oxidizer mixture
U velocity of oxidizer mixture
D_h hydraulic diameter of the annular inlet section of oxidizer mixture
SLPM standard liters per minute

Greek symbols
μ dynamic viscosity of oxidizer mixture
ν kinematic viscosity of oxidizer mixture

the CO_2 in the exhaust stream is captured and recirculated to be mixed with the incoming oxygen [4]; a technology that is termed exhaust-gas recirculation (EGR). This new technology makes the exhaust gases mainly consist of CO_2 and H_2O, hence, facilitates the capture and sequestration of CO_2 to eliminate its release into the atmosphere. This technology also reduces the mass and volume of the exhaust gases significantly with further benefits of reducing the amount of heat losses and reducing the size of the treatment equipment of the flue gases [5].

Oxy-fuel and air-fuel combustion technologies have different degrees of freedom that confine the operational space. Oxy-fuel flames are more likely to be operated close to stoichiometry, in order to effectively utilize both fuel and O_2 with controlled EGR (i.e., controlled ratio of O_2/CO_2) to maintain the combustion temperature within desired limits. Fuel-rich combustion increases fuel consumption, results in incomplete combustion, and generates excessive CO emissions, while fuel-lean operation is associated with unutilized O_2 in the exhaust stream. The characteristics of oxy-fuel combustion also differ from those of air-fuel combustion. This may be attributed to significant differences in the physical properties of CO_2 and N_2 [6–8]. The replacement of N_2 by CO_2 in the oxidizer mixture affects the flame from different aspects, namely changes in oxidizer-mixture density, volumetric heat capacity, and transport properties, including thermal conductivity, mass diffusivity, and dynamic viscosity. Table 1 compares select properties of air to those of O_2/CO_2 mixtures (25% and 50% oxygen fraction by volume) at 298 K.

The increased concentration of CO_2 in the oxidizer mixture also results in reduced rates of chemical kinetics, which, in turn, decrease the laminar burning velocity and combustion efficiency [10,11]. Consequently, combustion in a CO_2-diluted atmosphere needs higher minimum oxygen threshold, i.e., more than 21% by volume, in order to obtain stable flame at the same level of operating equivalence ratio [12,13]. Rashwan et al. [14–16] illustrated the effect of carbon-dioxide addition. CO_2 has higher density than N_2, which affects gas density, jet velocity, flame shape, and pressure drop. The higher density of CO_2 also leads to higher heat capacity of the O_2/CO_2 mixtures as compared to air (see Table 1), which directly reduces the flame temperature level and results in lower flame speeds and reduced flame stability. Flame speed is also affected by gas-transport properties [17].

Recently, an experimental investigation have been performed to study the effect of partial premixing on oxy-fuel combustion characteristics [14]. The results showed that, in order to get a stable flame, the range of oxygen fraction should be higher than 21% by volume (normal oxygen concentration in air). The study revealed that air-fuel flames have wider stability range than oxy-fuel flames. Also, it was reported that oxy-fuel combustion with an oxygen fraction of 40% by volume results in similar combustion characteristics to air-fuel combustion under premixed conditions. Ditaranto et al. [18,19] reported that the process of oxy-combustion needs at least 30% of oxygen fraction by volume in the oxidizer mixture to perform stably as compared to air-fuel combustion. This 9% increase in oxygen fraction to get a stable flame is compensating for the higher heat capacity of carbon dioxide. Liu et al. [20] numerically studied the oxy-combustion characteristics in a gas-turbine combustor. They concluded that the higher the oxygen fraction in oxidizer mixture, the higher the flammability limits and the wider the stability map. Nemitallah and Habib [21] experimentally and numerically studied the oxy-fuel combustion characteristics of a diffusion flame in a co-axial gas-turbine combustor. They reported that the stability of oxy-fuel combustion is adversely affected when the controlled oxygen fraction is reduced below 25% by volume. Hudak et al. [22] studied the extinction mechanisms under premixed combustion conditions. They showed that using CO_2 as a diluent reduces the operability limits, due to the slower chemical reactions of this system, as compared to the case of burning in air. A recent study conducted by Jerzak and Kunia [23] investigated the upper and lower flammability limits of natural-gas combustion utilizing different oxidizers including air, oxygen-enriched air, and oxy-mixture of O_2 and CO_2. The experiments were conducted under two different swirl numbers of 0.69 and 1.35. The study revealed that CO_2 dilution improved the flashback limits, as compared to the cases of combustion in air and oxygen-enriched air. However, in comparison of the total stability limits, oxy-fuel combustion recorded the lowest flammability limits for both considered swirl numbers. The most favorable stable combustion range was recorded for oxygen-enriched air with 25% of oxygen by volume at swirl number of 1.35. Shi et al. [24] experimentally studied the oxy-combustion of methane under different oxygen fractions. The effect of varying the oxygen fraction from 21% to 86% by volume was analyzed and reported. They reported tight flame stabilization

Table 1
Select properties of air and different O_2/CO_2 mixtures at 298 K [9].

	Air	O_2/CO_2 mixture 25% OF	O_2/CO_2 mixture 50% OF	% Change 25% → 50% OF
Density [kg/m^3]	1.17	1.65	1.53	−7%
Dynamic viscosity [$\times10^{-6}$ Pa s]	18.6	16.2	17.5	8%
Kinematic viscosity [$\times10^{-6}$ m^2/s]	15.9	9.82	11.4	16%
Vol. heat capacity [kJ/m^3/K]	1.18	1.44	1.35	−6%