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Combustion behavior and stability map of hydrogen-enriched oxy-methane premixed flames in a model gas turbine combustor

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ABSTRACT

The article describes an experimental study and comparison of the combustion behavior and determines the stability map of turbulent premixed H_2-enriched oxy-methane flames in a model gas turbine combustor. Static stability limits, in terms of flashback and blow-out limits, are recorded over a range of hydrogen fraction (HF) at a fixed oxygen fraction (OF) of 30% and a particular inlet bulk velocity, and the results are compared with the non-enriched case (HF = 0%). The static stability limits are also recorded for different inlet bulk velocity (4.4, 5.2, and 6 m/s) and the results are compared to explore the effect of flow dynamics on operability limits of H_2-enriched flames. The stability maps are presented as a function of equivalence ratio (0.3–1.0) and HF (0%–75%) plotted on the contours of adiabatic flame temperature (AFT), power density (PD), inlet Reynolds number (Re) and reacting mixture mass flow rate ($\dot{m}$) to understand the physics behind flashback and blow-out phenomena. The results indicated that both the flashback and blow-out limits tend to move towards the leaner side with increasing HF due to the improved chemical kinetics. The stability limits are observed to follow the Reynolds number indicating its key role in controlling flame static stability limits. The results showed that H_2 enrichment is effective in the zone from HF = 20% up to HF = 50%, and O_2 enrichment is also effective in a similar zone from OF = 20% up to 50%, with wider stability boundaries for H_2 enrichment. Axial and radial temperature profiles are presented to explore the effect of HF on the progress of chemical reactions within the combustor and to serve as the basis for validation of numerical models. Flame shapes are recorded using a high-speed camera and compared for different inlet velocities to explore the effects of H_2-enrichment and equivalence ratio on flame stability. The equivalence ratio at which a transition of flame stabilization from the inner shear layer (ISL) to the outer recirculation zone (ORZ) occurs is determined for different inlet bulk velocities. The value of the transition equivalence ratio is found to decrease while increasing the inlet bulk velocity. Flame shapes near flashback limit, as well as near blow-out limit, are compared to explore the mechanisms of flame extinctions. Flame shapes are compared at fixed adiabatic flame temperature, fixed inlet velocity and fixed flow swirl to isolate their effects and investigate the effect of kinetic rates on flame stability. The results showed that the adiabatic flame temperature does not govern the flame static stability limits.

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Nomenclature

A_L	Laminar flame front area (m^2)
A_T	Turbulent flame front area (m^2)
AFT	Adiabatic flame temperature (K)
CIVB	Combustion induced vortex breakdown
CH_4	Methane
CO_2	Carbon dioxide
CV	Calorific value (kJ/kg)
H_2	Hydrogen
HF	Hydrogen fraction
ISL	Inner shear layer
$\dot{m}$	Mass flow rate (kg/s)
O_2	Oxygen
OF	Oxygen fraction
ORZ	Outer recirculation zone
PD	Power density ($MW/m^3/bar$)
Re	Reynolds number
S_L	Laminar flame speed (m/s)
S_T	Turbulent flame speed (m/s)
u'	Root mean square turbulent fluctuation magnitude (m/s)
ϕ	Equivalence ratio

Introduction

The insatiable demand for power is on rise worldwide to cope up with the emerging economies and technologies. In 2011, it has been reported that around 80% of the world's electricity production was based on the fossil fuels [1], indicating it as a major contributor to the greenhouse gases emissions. The Paris Agreement has reiterated the concerns of global warming and the implementation of carbon capture technologies to check the global average temperature rise [2]. In attempts to reduce the greenhouse gases emissions to the environment to curb the threats of global warming, several techniques to capture carbon dioxide resulting from burning hydrocarbon fossil fuels have been evolved. Oxy-combustion is a promising technology which can be easily retrofitted to an existing plant with slight modifications [3]. In contrast to the conventional air combustion, fuel is burnt with oxygen separated from air resulting in combustion products consisting mainly of carbon dioxide and water vapor. Carbon dioxide is, then, easily captured by condensing water vapor out of the flue gas stream. Combustion in pure oxygen environment is undesirable due to the excessive temperature rise in the flame zone, which can damage the combustor and the blades of the gas turbine. Hence, a part of carbon dioxide from the exhaust is recirculated back to the combustion chamber to control the flame temperature. Non-premixed flames have been used in gas turbines for power generation thanks to their strong stability behavior over wide ranges of loading conditions. However, non-premixed flames results in stoichiometric combustion zones within the combustor and, consequently, elevated temperature spots are created within the combustor, which can exceed the limit for gas turbine blades. The case may even get worse when oxy-combustion is adapted in non-premixed flames, as the temperature is expected to be excessively raised. Converting the combustion mode from non-premixed to premixed prevents the creation of stoichiometric combustion zones within the combustor as the reactants are premixed upstream of the combustor resulting in effective control of combustion temperature. Pre-mixed combustion is a promising approach for many industrial applications (such as large-scale gas turbine systems, automotive and aero-engines) primarily because of its benefits such as lower pollutant emissions and more efficient combustion when compared to non-premixed systems and configurations.

Due to higher specific heat of carbon dioxide, as compared to nitrogen, lower volumetric flow rates are required for similar flame characteristics [4–9], resulting in reduced reactor size. Moreover, oxy-combustion technology has an innate advantage of elimination of NOx formation as the combustion takes place in absence of nitrogen. However, the application of oxy-combustion technology for gas turbine is associated with a set of constraints. The main constraint for wider application of oxy-combustion technology is the separation of combustion oxygen from air, which adds additional cost to the process. However, the continuous advances in the air separation and hydrogen production technologies make the future look promising for this integration. Since the technology requires pure oxygen, which is obtained at the expense of extra energy, it is preferred based on economics to keep the operating equivalence ratio near unity i.e. stoichiometric combustion. Also, replacement of N_2 by CO_2 as a diluent within the combustor affects significantly the behavior and operability ranges of the generated flames because of the differences in chemical kinetics and thermo-physical and radiative properties [7,10–12]. This may result in tight operability limits of the generated premixed oxy-flames when compared to air flames due to the slower kinetics and generated flame instabilities [10]. Fuel flexibility approach, mainly through hydrogen enrichment, is considered as an effective technique to control combustion instabilities within gas turbine combustors to avoid flashback, auto ignition and combustion dynamics [13–15]. Also, hydrogen is becoming a paramount topic for storage of energy resources. Hydrogen-enriched premixed oxy-flame stability and its characteristics are vital for proper application of this technology in new or existing power plants, which is the subject of the present study.

There have been in the literature a set of studies on determining the flame characteristics under oxy-combustion conditions [16–21]. Also, a number of studies on hydrogen-enriched flames have been carried out; however, they are mainly focusing on the formation of NOx in the presence of hydrogen under air combustion conditions [22–24]. The characteristics of premixed oxy-combustion flames have also been examined extensively as per the open literature. A brief analysis of the most relevant ones is discussed in the present investigation. Abdelhafez et al. [25] conducted stability mapping of premixed oxy-methane combustion at various oxygen fraction and equivalence ratios. Their main finding was the dependence of stability limits on the adiabatic flame temperature. Mazas et al. [26] investigated the characteristics of oxygen-enriched methane flames under atmospheric