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Experimental study on dynamics of a confined low swirl partially premixed methane-hydrogen-air flame

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ABSTRACT

The addition of hydrogen to swirl stabilized methane-air flame in gas turbine has gained more and more attentions in recent years. In the current study, flame structures, flame dynamics and lean blowout limits of partially premixed hydrogen-methane-air flames were investigated. The swirling flow, which was generated from the tangential flow injection, was utilized to stabilize the flame. The flow swirl number was kept low varying from $S \approx 0.28$ to $S \approx 0.34$ while the thermal power of the burner ranged from 10.8 kW to 13.8 kW. Two different fuel injection strategies were investigated and compared with each other. Long exposure CH* chemiluminescence from the flame was captured to visualize the time averaged flame shapes. In addition, an intensified high speed camera was adopted to study the flame dynamics. A high speed PIV system was utilized to investigate the interaction of flame dynamics and flow fields oscillations. Based on the experimental results, it can be concluded that: in the current experimental cases, fuel injection strategy plays an important role in determining the flame macro-structures and thus strongly affects the flame dynamics and lean blowout limits. Flame with fuel injected through the axial flow has lower lean blowout limits. The flashback and vortex breakdown were observed when fuel was injected in the tangential flow near lean blowout. High frequency flame oscillations ($f \approx 170$ Hz) were observed when the global equivalence ratio $\Phi_g > 0.72$ while lower frequency oscillations ($f \approx 50$ Hz and $f \approx 20$ Hz) were found near lean blowout limits, $\Phi_g < 0.55$. Combustion dynamic and its interaction with the pressure oscillation, flow fields alternation and mass flow rate oscillation are proposed. The differences on fuel concentration at the burner exit are proposed as the main reason for different flame instabilities and flame structures.

Introduction

Modern premixed gas turbine combustors are usually operated near the lean blowout limits due to the emissions requirements [1]. It is a practical method to reduce thermal NO_x formation due to the lower flame temperature operated in lean conditions [2]. In order to have a better flame stabilization in lean conditions, hydrogen addition to the natural gas-air

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Nomenclature

d_c	optical confinement inner diameter [mm]
d_m	mixing tube inner diameter [mm]
d_p	pilot tube inner diameter [mm]
d_{probe}	emission probe inner diameter [mm]
f	oscillation frequency [Hz]
h	axial position [mm]
H_{COHR}	Position of flame's corner of heat release [mm]
h_t	tangential inlet height [mm]
l_c	optical confinement length [mm]
L_F	characteristic flame length [mm]
l_m	mixing tube length [mm]
m_a	axial air mass flow rate [SLPM]
m_{CH4}	methane mass flow rate [SLPM]
m_{H2}	hydrogen mass flow rate [SLPM]
m_t	tangential air mass flow rate [SLPM]
m_{total}	total air mass flow rate [SLPM]
$m_{t\text{-}N2}$	tangential mass flow rate of N_2 [SLPM]
Re	Reynolds number at the burner exit [–]
S	Swirl number [–]
T	oscillation cycle time [s]
U_b	bulk velocity at the burner exit [m/s]
w_t	tangential inlet width [mm]
Δt	time delay between two laser pulses [μs]
Φ_{LBO}	lean blowout equivalence ratio [–]
Φ_g	global equivalence ratio [–]

Abbreviations

COHR	corner of heat release
FFT	Fast Fourier Transform
fps	frames per second
FWHM	full width at half maximum
LBO	lean blowout
LDA	Laser Doppler Anemometry
PIV	Particle Image Velocimetry
PVC	processing vortex core
SLPM	standard litter per minute

premixed flame is a practical strategy. The use of hydrogen addition to extend the lean blowout limits of premixed natural gas-air flames in gas turbine combustors has been investigated by various researchers. Hydrogen addition to the premixed methane-air flame increases the global reaction rate leading to a higher turbulent burning velocity which in turn have the possibility to promote the flame stabilization especially under lean conditions [3–6].

However, with the addition of hydrogen to premixed natural gas-air or premixed methane-air flames, several challenges will show up as well, i.e. flame flashback and even auto-ignition upstream in the premixing tube due to the high combustion chemistry of hydrogen [7] [8]. In addition, the flame oscillation caused by hydrogen addition might cause gas turbines to shut down or even lead to hardware damage. Therefore, the composition of the fuel impacts the turbine life and thus characterizations of the flame behaviors with hydrogen addition are important issues [9]. Tuncer et al. [7] pointed out that under atmospheric conditions the flame speed of a stoichiometric hydrogen-air mixture was about five times faster than that of a premixed methane-air flame. They studied the dynamics of premixed flames with different hydrogen contents and found the 40–47 Hz flame oscillation accompanied with flame flashback when the hydrogen composition was 40–50%. Cheng et al. [8] concluded that the flame shape changing with the enrichment of hydrogen was strongly affected by the increase in turbulent flame speed and the reactants burning in the outer recirculation zone. The increasing of hydrogen concentration in the fuel forced the flame getting closer or even attaching to the burner exit where the local turbulence intensity was high. Strakey et al. [10] found the flame anchoring in the outer recirculation zone prior to lean blowout in the swirl stabilized premixed hydrogen-methane-air flame. Sayad et al. [11] experimentally studied the flashback and lean blowout limits of premixed syngas flames. They found that with the increasing of hydrogen content in the syngas reactants, both the lean blowout limits and flashback equivalence ratio decreased significantly. The change of the flame stabilization limits was caused by the faster reactivity of mixtures with higher hydrogen content, which increased the flame speeds and thus the residence times that was required for the reactions to be completed was shorter.

On the other hand, in order to better stabilize the flame, swirling flows were commonly employed in gas turbine combustors. The typical swirling flow fields with a vortex breakdown inside a confinement is shown in Fig. 1 [12]. As described in Ref. [13], with strong swirling effects, the central vortex breakdown and thus an inner recirculation zone (or central recirculation zone) are formed. While due to the effects from the confinement, an outer recirculation zone (or corner recirculation zone) is generated as well. Between the inner recirculation zone and the main flow is the inner shear layer, while the outer shear layer locates between the main flow and the outer recirculation zone. The flame behaviors are strongly interacted with the swirling flow fields [14]. In addition, there are two common ways to generate swirling flows: the guiding vane and the tangential entry swirler. Compared with a guiding vane swirler, the tangential entry

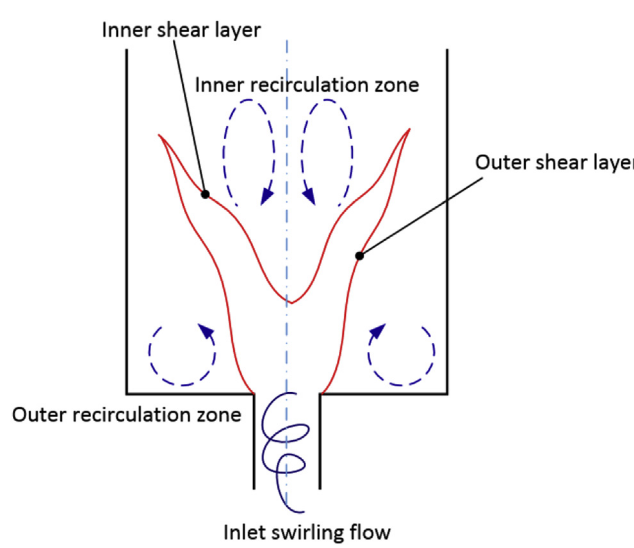

Fig. 1 – Schematic of swirling flow fields with vortex breakdown inside a confinement.