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Transitions and blowoff of unconfined non-premixed swirling flame

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The present experimental work reports the first observations of primary and secondary transitions in the time-averaged flame topology in a non-premixed swirling flame as the geometric swirl number S_G (a non-dimensional number used to quantify the intensity of imparted swirl) is varied from a magnitude of zero till flame blowout. First observations of two transition types viz. primary and secondary transitions are reported. The primary transition represents a transformation from yellow *straight jet flame* (at $S_G = 0$) to *lifted flame with blue base* and finally to *swirling seated (burner attached) yellow flame*. Time-averaged streamline plot obtained from 2D PIV in mid-longitudinal plane shows a recirculation zone (RZ) at the immediate vicinity of burner exit. The lifted flame is stabilized along the vortex core of this RZ. Further, when $S_G \sim 1.4$–3, the first occurrence of vortex breakdown (VB) induced internal recirculation zone (IRZ) is witnessed. The flame now stabilizes at the upstream stagnation point of the VB-IRZ, which is attached to the burner lip. The secondary transition represents a transformation from a swirling *seated flame* to *swirling flame with a conical tailpiece* and finally to a *highly-swirled near blowout oxidizer-rich flame*. This transition is understood to be the result of transition in vortex breakdown modes of the swirling flow field from dual-ring VB bubble to central toroidal recirculation zone (CTRZ). The physics of transition is described on the basis of modified Rossby number (Ro_m). Finally, when the swirl intensity is very high i.e. $S_G \sim 10$, the flame blows out due to excessive straining and due to entrainment of large amount of oxidizer due to partial premixing. The present investigation involving changes in flame topology is immensely important because any change in global flame structure causes oscillatory heat release that can couple with dynamic pressure and velocity fluctuations leading to unsteady combustion. In this light, understanding mechanisms of flame stabilization is essential to tackle the problem of thermo-acoustic instability.

1. Introduction

Non-premixed swirling flames are used in several industrial applications such as gas turbine combustors, ramjets, rocket motors, industrial furnaces, petrochemical flares etc. The multiple benefits of utilizing swirl are: (a) effective flame stabilization (b) enhanced efficiency (c) improved mixing (d) compact or shorter flame. In particular, the significance of employing swirl as flame stabilization mechanism is due to its ability to form a toroidal vortex-type recirculation zone. This toroidal vortex structure is characterized by a central region of negative axial velocity (reverse flow) which facilitates the intense mixing of radical species, hot combustion products and the incoming reactants [1–4]. Other methods used to establish recirculation zone includes employing a bluff body, backward facing step, trapped vortex concept and a combination of these methods [3].

Swirl stabilized flames are susceptible to thermo-acoustic instability or combustion instability. This instability is characterized by dynamic feedback between heat release rate, pressure fluctuations and equivalence ratio at natural acoustic modes of the combustor. The large amplitude pressure fluctuations resulting from combustion instability can cause premature deterioration of combustor lining [4–6]. In some cases, the damage can be catastrophic [6–8]. The unsteady flame behavior due to swirl is possibly due to two dominant instability mechanisms [9]. First, the low-frequency oscillations of the precessing vortex core (PVC) and the vortex shedding due to Kelvin–Helmholtz instability in convectively unstable shear layers may lock-on to the natural acoustic modes of the combustion chamber. Second, swirl may inflict changes in global flame topology which causes oscillatory heat release that can couple with dynamic pressure and velocity fluctuations leading to unstable combustion. The latter underlines the importance of studying the effect of swirl intensity on the flame stabilization location which has strong influence on flame shape, which in turn determines heat flux to combustor walls, dome plate and other hardware [10]. Also, combustor operability, durability and emissions are influenced by flame location/spatial distribution. In addition, stabilization locations play an important role in determining the blowoff limits. Lastly, the flame stabilization mode determines the key physical processes that control the transient

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Nomenclature

A	line-of-sight flame area
A_a	cross-sectional area of co-flow burner annulus
A_t	total area across all swirl inducing ports.
d_i	diameter of the central fuel pipe
d_0 or D_0 or d_a	diameter of the co-flow pipe
d_θ	area averaged diameter
d_t	diameter of swirl inducing ports
dt	laser pulse separation time
h	flame lift-off height
H	flame height
m	normalized recirculation mass flow
m_A	mass flow rates of axial air inlet (fuel+co-flow)
m_a	mass flow rates of oxidizer, air in the present study (co-flow+swirl)
m_{in}	inlet total mass flow rate
m_f	mass flow rate of fuel
m_θ	mass flow rate of tangential air inlet
$OH^{*\prime}$	transient fluctuation of OH* chemiluminescence signal
$\overline{OH^*}$	time-mean of OH* chemiluminescence signal over acquisition time period
Q_a	volumetric flow rate of the co-flow air
Q_f	volumetric flow rate of the fuel flow
r_0	transverse distance between burner axis and tangential inlet
r_{vcc}	radius of vortex core center
r_s	radius of swirl ports
R	radial distance from centerline to the outer shear layer
R_i	radius of inner pipe
R_0	radius of co-annular pipe
R_s	radial distance from central axis to the edge of the vortex core
Re_a	Reynolds number of the co-annular jet
Re_f	Reynolds number of the fuel jet
Re_θ	Reynolds number calculated based on U_θ
Ro_m	modified Rossby number
$Re_{a,S_G=0}$	pure-coflow no-swirl blow-off limit
S_G	geometric swirl number
St	Stokes number
S_L	laminar flame speed
$S_{G,Re_a=0}$	pure-swirl no co-flow blow-out limit
U	local centerline velocity
U_a	velocity of co-flow annulus based on Q_a
U_f	velocity of fuel jet based on Q_f
U_θ	angular velocity at co-annular jet exit
Δu_y	velocity deficit between co-flow streams
u_y	local axial velocity
$u_{\theta,avg}$	spatio-temporal averaged tangential velocity at the nozzle exit

Greek symbols

α	thermal diffusivity
ϵ	time-averaged strain rate
ν_a	kinematic viscosity of air
ν_f	kinematic viscosity of fuel (Methane)
ρ	fluid density
ξ	strain-rate distribution factor
κ	flame stretch rate
κ_s	flame stretch rate due to hydrodynamic strain
κ_{curv}	flame stretch rate due to flame curvature
$\kappa_{s,shear}$	flame stretch due to shear (anti-symmetric) flow strain
$\kappa_{s,normal}$	flame stretch due to normal (symmetric) flow strain
$Ka_{s,shear}$	shear contribution to Karlovitz number Ka
ϕ_0	fuel-air ratio based on inlet mass flow rates

dynamics. In the present work, a systematic characterization of the transformations in time-averaged flame topology due to stepwise increase in swirl intensity is documented. The underling physics for such transformations is also probed in detail.

In the following, we present a review of studies concerning flame stabilization modes. Different flame shapes were observed in a step swirl combustor (SSC) depending on the intensity of inner and/or outer swirled air streams [11]. The fuel was introduced (without swirl) in between the inner and outer air jets. Zero inner swirl and strong outer swirl produced a flame attached to both fuel and air injection tubes. The flame shifted to single attachment mode (flame attached to fuel injection tube only) when the strength of inner swirl was increased with concurrent decrease in outer swirl. At strong inner swirl, the flame lifted-off with premixing of fuel and air occurring at the base of the flame.

Different flame configurations in annular swirling jet with bluff centerbody were reported by Lieuwen and co-workers [10,12–14] as shown in Fig. 1.

The annular swirling jet consisted of two shear layers: (a) inner shear layer (ISL) – between inner recirculation zone-IRZ (caused by vortex breakdown –VB phenomenon) and annular jet (b) outer shear layer (OSL) – between annular jet and corner recirculation zone-CRZ (caused by sudden expansion of nozzle into the combustor) [15,16]. Fig. 1d depicts a flame configuration stabilized in OSL. It bifurcated to 1c (stabilized in ISL) if the flame failed to anchor in OSL. If the flame failed to anchor in ISL then it then bifurcated to either configuration 1a or 1b which were stabilized by the vortex breakdown bubble (VBB). The reason behind the transitions was explained as follows. The flame stabilized in the low velocity zone of the shear layers created by the centerbody. However, shear induced aerodynamic stretching on the flame. When the stretch rate was too high, the flame quenched locally and blew-out or stabilized at another location. Flame configurations stabilized in ISL and/or OSL were strongly dependent upon the flow velocities and fuel/air ratios.

The flame configurations in annular swirling jet were observed to also depend on the diameter of centerbody and intensity of swirl. For instance, lifted flame was observed for small diameter centerbody [17,18]. The flow field consisted of two unmerged separate IRZs, one due to centerbody wake and the other due to VB. The lifted flame was also observed at low swirl numbers without VB feature [19,20]. For larger centerbody diameters, the flame was stabilized in the stagnation region which preceded VB bubble (the flame was attached to the burner lip).

Flame configurations in swirling non-premixed flames were investigated by Tummers et al [21]. Two different flame types were studied. First type was a long sooty flame stabilized around the IRZ of bluff-body type. Second type consisted of a short lifted blue flame stabilized by VB IRZ of much larger size when compared to IRZ of bluff body type. It was shown that in the major portion of the upstream region of yellow flame, the reaction took place only in edge shear layer exterior to IRZ. Downstream, the reaction covered the whole flame cross-section. In contrast, VB IRZ stabilized blue flame displayed significantly higher turbulence intensity within IRZ resulting in enhanced mixing and reaction in the entire flame region. The lifted and attached flames in swirling non-premixed type setup were investigated recently by Saediamiri et al [22] for biogas flames.

We next review key concepts from past works on stability limits and blowoff of swirling and non-swirling flames. Few of the early