Transitions and blowoff of unconfined non-premixed swirling flame

R. Santhosh and Saptarshi Basu a)
Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

The present experimental work reports the first observations of primary and secondary transitions in the time-averaged flame topology in a non-premixed co-airflow 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. The aim is to systematically study the parametric dependence of flame stabilization modes on swirl intensity, which in turn determines the flame shape. The fuel (99.5% pure research grade Methane) is injected through the central pipe. Three fuel flow rates (Reynolds number-$Re_f$ range: 107.52-537.64) are studied in the present work. For each of the fuel flow cases, six different co-airflow settings are considered ($Re_a$ range: 2647-5029). For a particular $Re_f$ and $Re_a$, $S_G$ is varied to build a regime map ($S_G$ vs $Re_a$) that depicts various regions of flame stabilization modes and study the transition from one mode to another.

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. For all the fuel flow cases considered, the primary transition is observed at critical $Re_a$ and beyond it (super critical $Re_a$). Within the $Re_f$ range tested, it is observed that as the swirl number is increased from $S_G = 0$ to $S_G \sim$0.8-1.4, the straight jet flame lifts-off from the burner exit to stabilize at a lift-off distance $h \sim 0.4R_0$ ($R_0$ is the radius of the co-annular pipe). The lifted flame is significantly blue in color. Time-averaged streamline plot obtained from 2D PIV in mid-longitudinal plane showed a wake-like 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.

a) Author to whom correspondence should be addressed. E-mail: sbasu@mecheng.iisc.ernet.in
As a result the flame is burner tip anchored and stabilized around the shear layer separating VB-IRZ and co-annular stream.

The secondary transition is observed at critical and super-critical $Re_a$ after the primary transitions as well as at sub-critical $Re_a$ (at which primary transitions are absent). It represents a transformation from swirling seated flame to swirling flame with a conical tailpiece and finally to highly-swirled near blowout ultra-lean flame. This transition is understood to be 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 which renders the flame ultra-lean (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, diesel engines, 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 (e) low NOx (due to lean combustion). 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].

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. In some cases, the damage can be catastrophic as well. The unsteady flame behavior due to swirl is possibly due to two dominant instability mechanisms [5]. 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 [6]. Also, combustor operability, durability and emissions are influenced by flame location/spatial distribution. In addition, stabilization locations play an important in determining the blowoff limits. Lastly, the flame stabilization mode determines the key physical processes that control the transient 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.
Next, 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 [7]. 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 shifts to single attachment (flame was now only attached to fuel injection tube) mode when the strength of inner swirl was increased with a simultaneous 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 were studied by Lieuwen and co-workers [6, 8-10]. The annular swirling jet consists of two shear layers: (a) inner shear layer (ISL) - between inner recirculation zone-IRZ (caused due to vortex breakdown -VB phenomenon) and annular jet (b) Outer shear layer (OSL) - between annular jet and corner recirculation zone-CRZ (caused due to sudden expansion of nozzle into the combustor) [11-12]. Flame configurations stabilized in ISL and/or OSL were strongly dependent upon the flow velocities and fuel/air ratios. The flame configuration also depended on the diameter of centerbody and intensity of swirl. For instance, lifted flame was observed for small diameter centerbody [13-14]. The flow field consisted of two unmerged separate IRZs, one due to centerbody wake and other due to VB. The lifted flame was also observed at low swirl numbers without VB feature [15-16]. For larger centerbody diameters, the flame is stabilized in the stagnation region which precedes VB bubble (the flame was attached to the burner lip).

Flame configurations in swirling non-premixed flames were investigated by Tummers et al [17]. Two different flame types were studied. First type is a long sooty flame stabilized around the IRZ of bluff-body (smaller in size as compared to VB induced IRZ). Second type is a short lifted blue flame stabilized by VB IRZ of much larger size. The lifted and attached flames in swirling non-premixed type setup were also investigated recently by Saediamiri et al [18] for biogas flames. It is clear from the above discussion that the flame stabilization modes and their related physics are not well documented for swirling non-premixed flames. There is no published work which systematically characterizes different flame stabilization modes and thus the flame shapes based on the input flow parameters (i.e. swirl number and Reynolds number) in a swirling non-premixed flame. The present work aims to fill this research gap.

We next review the literature on stability limits and blowout of swirling and non-swirling flames. The blowout limit and mechanism of a non-swirling simple jet flame was studied by Kalghatgi
It was postulated that the flame blew out when centerline local gas velocity exceeded local turbulent burning velocity. Another theory [21] suggested that blowout occurred when local fluid mechanical mixing rate is greater than chemical reaction rate. The stability and blowout limits of swirling co-airflow non-premixed methane-air flames were investigated by Feikema et al [22-23]. The maximum blowout limit of fuel velocity (rich blowout) was reported in [22]. The fuel velocity, $U_F$, was measured by varying swirl number, coaxial air velocity, fuel tube diameter and fuel type. It was shown that Damkohler number based on swirl velocity was an appropriate governing parameter which collapsed the rich blowout limit to a single curve. Overall, the swirl was found to enhance the stability limits. In another study [23], maximum co-airflow velocity limit required to blowout the swirling non-premixed flame was investigated. It was shown that co-airflow with zero swirl resulted in twofold reduction in flame height. Introduction of swirl improved maximum-air blowout limit by a factor of 6. The improved stability was due to lower local velocities resulting in reduced local strain rates especially near the stagnation point of VB induced IRZ. The stability limits in biogas flames was studied in [18]. The effect of burner geometry and co-flow air velocity on the stability limits was investigated. Correlations (semi-empirical) for lifted biogas flame (rich and lean limits) were proposed. The present work measures the lean blowout limit at different fuel and co-airflow velocities. A possible explanation for such a blowout is documented based on the strain rate factor.

The present work is a continuation of our previous works on coaxial swirling jets [24-26]. While the previous studies dealt with non-reacting/isothermal flows, the present study is concerned with reacting flow (non-premixed flames). A possible connection between previously observed flow features in isothermal studies and the current non-premixed flame investigation is established. This paper is arranged as follows. Section 2 describes the co-flow atmospheric burner and PIV setup employed in the present experimental investigation in detail. Baseline flow cases are detailed in Section 3. Results and discussion of transitions in time-averaged flame topology, lean blowout limits and the corresponding mechanism is detailed in Section 4. Key conclusions are drawn in Section 5.
2. Experimental Setup and diagnostics

2.1 Coaxial atmospheric swirl burner

The geometry of swirl stabilized co-flow burner employed in the present work to study the swirl number dependent transition in time-averaged flame topology and its related dynamics has been described in detail in our previous works [24-26]. However, a brief description is provided here for completeness. The double concentric pipe assembly (Fig. 1) consists of a central fuel injection pipe (radius: \( R_f = 6 \text{mm} \)), which stands out 2mm above the burner dump plane, surrounded by a co-annular duct of radius \( R_o = 41.6 \text{mm} \). The co-flow annulus terminates into a swirler block which is used to impart swirl to the co-annular stream. This swirler block contains eight tangential ports of radius \( R_s = 3 \text{mm} \), drilled at an angle of 30 degrees with respect to the outward radial vector and placed circumferentially at an equal angular pith of 45\(^0\) (inset- Fig. 1). A cylindrical distribution header (\( d = 14.5\text{cm} \) and \( h = 20\text{cm} \)) is installed upstream of the swirler block to ensure uniform distribution of the tangential air supply to individual swirl ports. The degree of swirl imparted is characterized by a non-dimensional geometric swirl number (\( S_G \)) given by [22]:

\[
S_G = \frac{\pi r_0 D_o}{2 A_t} \left( \frac{m_\theta}{m_\theta + m_A} \right)^2
\]  

(1)
Fig. 1. Schematic of experimental set up involving atmospheric coaxial swirl burner and PIV. The plan view of the swirler block with tangential inlet ports is shown at right hand top corner. The figure is partially adopted with permission from R. Santhosh, A. Miglani, and S. Basu, Phys. Fluids 26, 043601 (2014). Copyright: American Institute of Physics, 2014.

where \( r_0 \) is the transverse distance between burner axis and tangential inlet. \( D_p \) is the diameter of the co-flow pipe. The combined cross sectional area of all swirl ports is denoted by \( A_t \). The quantities \( m_\theta \), \( m_A \) are the mass flow rates of tangential and axial air inlet respectively. Compressed air is supplied to the swirl ports and co-flow annulus from an 8 bar (gauge) compressor facility. The flow through each of them is monitored independently using variable area rotameters (range: 0-1000 lpm). The central injection pipe is supplied with research grade Methane fuel (99.5% pure). The flow of methane is controlled by a 0-50 lpm thermal mass flow controller (make: Aalborg; computer controlled with a repeatability of ±0.15% of the full scale;
calibrated for air). Gas correction factor (‘K’ factor) with respect to Nitrogen was chosen to be 0.75 (manufacturer’s specification) for adjusting the flow rate of Methane gas through the mass flow controller.

2.2 PIV in flame environment

High resolution 2D particle image velocimetry (PIV) was employed to measure the instantaneous velocity fields in meridional plane to study the transitions in flame structures. The imaging sub-system of PIV equipment consisted of (a) Litron nano PIV Nd:YAG solid-state laser (dual pulsed; pulse energy: 70 mJ/pulse; repetition rate: 10 Hz ) and (b) a divergent sheet optic cylindrical lens of focal length \( f = -10 \text{mm} \) to produce a laser sheet of thickness 1 mm. Image acquisition system comprised of (a) CCD camera (make: Imager Intense; pixel resolution: 1376 \( \times \) 1040; max frame rate: 5 fps) fitted with a 532\( \pm \)10 nm bandpass filter to transmit the scattered light centered at \( \lambda=532 \) nm and (b) a programmable timing unit (PTU) acting as a master synchronization device. The co-annular flow was seeded with aluminum oxide (\( \text{Al}_2\text{O}_3 \)) seed particles (mean diameter: 1 \( \mu \text{m} \)- manufacturer’s specification). The flow tracer fidelity in PIV experiments is measured by Stokes number (\( St \)), a non-dimensional quantity which represents the frequency response of seeded particles. The tracing accuracy is acceptable when the seeded particles closely follow the fluid streamlines. When \( St \ll 0.1 \) the tracing accuracy errors are less than 1% [27]. The calculations from analytical expressions reported by [28] and [29-30] show that for \( \text{Al}_2\text{O}_3 \) particles of diameters 0.78-2.46 \( \mu \text{m} \), \( St \) in the flame environment (~1800 K) is \( \approx 0.0113 \). As a result, the Stokes drag coefficients are \( \approx 10^{-2} \). Therefore the seed particles closely followed the flow. A set of 200 image-pairs were recorded by the CCD camera in double frame mode at each test condition. The acquisition frequency was 4.7fps (total acquisition time: 42.5 seconds). The corresponding laser pulse separation time \( dt \) was set at 75\( \mu \text{s} \). This time delay, however, was adjusted marginally (\( \pm 20\mu\text{s} \)) with the variation in geometric swirl number. This is to minimize the number of particles that convect out of plane from the illuminated region between two successive laser pulses. One of the difficulties associated with the PIV measurement in flames is that the flame luminosity overwhelms the laser signal scattered from seeding particles in the second frame of the image pair taken in a double-frame mode. This problem is due to longer exposure time of second frame when compared to the first. To
overcome this problem, a mechanical camera shutter was employed to significantly reduce the exposure time of the second frame.

DaVis 7.2 software from LaVision was used for velocity field calculations from the recorded image pairs. The velocity calculation was a three-pass operation: the interrogation window size of the first pass was 128×128 and that for next two passes was 32×32. The overlap was 50% in all the three passes. The correlation peak (determined from 3-D map of the cross-correlation function) was found to vary between 0.3 - 0.95 for any spatial point within the test domain. Spurious vector groups with less than five vectors were removed [31]. The calculation of errors associated with PIV measurement has been detailed in our previous work [24]. In particular, the errors in the PIV measurement can be broadly classified as: (a) mean bias errors and (b) random errors. Bias errors are negligibly small for a particle image diameter ($d_p$) to pixel resolution ratio ($Pi_r$) greater than 4. This ratio is determined to be around 6 in the present experiments and as such the mean bias errors are neglected. The random errors vary linearly with tracer image diameter [32] with a proportionality constant of about 0.05 (5%). For seed particle diameter of 1µm (in the present experiments), displacement uncertainty of each particle is .05 µm. For a pulse separation time of 55-95 µs (75±20µs) as employed in the present case, the upper and lower limit of error in velocity measurement is calculated to be 0.9 mm/s and 0.52 mm/s respectively. Further, the uncertainty due to grid generation and validation of correlation peak was neglected since the number of image-pairs considered for analysis was greater than 100 [33].

The ability of tracer particles to follow the flow is ascertained by fixing the particle response time (which is ~10^{-7} s for a 1µm diameter seeding particles) at a much lower value than the pulse separation time (75±20μs). The uncertainty associated with timing for PIV is around 1 ns (manufacturer specification), and can be neglected as compared to random error of displacement.

2.3 Chemiluminescence and High Speed imaging

The flame chemiluminescence images were acquired using LaVision Imager Intense camera with pixel resolution: 1376 × 1040 at 5fps. CH* chemiluminescence bandpass filter (wavelength range: 430 ± 10 nm) was employed for this purpose. 200 images were acquired over a time period of 40 seconds. The topology of flame was determined by time-averaged CH* chemiluminescence images. CH* chemiluminescence imaging was used to quantify the time
averaged flame topology. The transient flame dynamics was studied using OH* chemiluminescence. In particular, emission signatures from flame were captured by photo multiplier tube (PMT) coupled with OH* bandpass filter (wavelength range: 308 ± 10 nm). PMT signal was acquired using 16-Analog input Multifunction PCI-6251 NI Data acquisition card (1MS/s, 16-bit) along with LabView 7.1 software. The data was acquired at a frequency of 25 kHz for 20 seconds (500000 data samples). The acquired time series signal was directly proportional to the flame heat release ($q$). The heat release fluctuation was then calculated by $q' = q - \bar{q}$ where

$$\bar{q} = \frac{1}{t_p} \int_0^{t_p} q(t) dt$$  \hspace{1cm} (2)

where $t_p$ is the acquisition time period (20s).

In addition to chemiluminescence imaging, the flame dynamics in the present study was investigated by also employing high speed (HS) images. An ultra high-speed Photron SA5 camera at image resolution 1024 × 1024 was employed to record flame shape undulations at 1000 fps. The flame surface area from the HS images was estimated using grayscale image intensity-based threshold method. In this technique, a high speed image is converted to binary image by employing a threshold level. This threshold level was set between 0.1 and 0.35 for the swirl number range employed in the present study. The pixels with luminescence greater than threshold level are denoted by value of 1 (foreground). All other pixels are assigned a value of 0 (background). Sum of all foreground image pixels is a direct representation of flame surface area ($A$).

### 3. Experimental Conditions

The experimental flow conditions employed in the present study are shown in Table. 1. Two different Reynolds numbers are defined. $Re_f = U_f d_i / \nu_f$ corresponds to the Reynolds number of the fuel jet while $Re_a = U_a d_o / \nu_a$ signifies Reynolds number of the co-annular jet. The velocities $U_f$ and $U_a$ are calculated from the volumetric flow rate of the fuel flow ($Q_f$) and co-annular air flow ($Q_a$) respectively. $d_i$ and $d_o$ are diameters of the central fuel pipe and co-annular pipe respectively. $\nu_f$ and $\nu_a$ are the kinematic viscosities of fuel (Methane) and oxidizer.
(air) at STP. In coaxial swirling flame literature [22], another Reynolds number $Re_\theta = (U_\theta d_\theta / \nu_{air})$ is defined. Here, $U_\theta$ is characteristic magnitude of the angular velocity at co-annular jet exit. It is defined as $U_\theta = U_A \cdot \Sigma_G$. The magnitude of $U_\theta$ is directly proportional to the intensity of swirl imparted to co-airflow annulus. As such, $Re_\theta$ is indicative of swirling strength of co-airflow stream surrounding the central fuel jet. $d_\theta$ is the area averaged diameter which is given by:

$$d_\theta = \frac{A_a d_a + A_t d_t}{A_a + A_t}$$

where $A_a$ and $A_t$ are respectively the cross-sectional areas of co-flow burner annulus and the total area across all swirl inducing ports. $d_a$ and $d_t$ are the corresponding diameters of co-annular pipe and swirler port. $\nu_{air}$ is the kinematic viscosity of air at STP.

Three primary fuel flow cases within Reynolds number $Re_f = 107.52$-$537.64$ are studied (Table 1). The Damkohler number based on central fuel jet ($Da_f$) is defined as [34] $Da_f = \frac{S_L^2}{\alpha U_f d_f}$ where $S_L$ and $\alpha$ are laminar burning velocity and thermal diffusivity respectively. For methane-air flame, these values are taken from [22, 23]. The ratio $S_L^2/\alpha$ represents heat release reaction rate. The ratio $U_f/d_f$ is interpreted as global strain rate or inverse residence time [34]. For each of the fuel cases mentioned in Table 1, six different co-annular flow cases were tested. Case names for each of these are shown in parenthesis.

TABLE 1. Non-premixed swirling flame baseline test cases.

<table>
<thead>
<tr>
<th>Case name</th>
<th>Reynolds number of fuel jet ($Re_f = U_f d_i / \nu_f$)</th>
<th>Momentum flux of fuel jet ($\rho_f U_f^2 / kg/m - s^2$)</th>
<th>Damkohler number ($Da_f = \frac{S_L^2}{\alpha U_f d_f}$)</th>
<th>Reynolds number of co-annular air jet ($Re_a = U_a d_o / \nu_a$) [Case names are in parenthesis]</th>
<th>Pure-swirl blowout geometric swirl number ($S_{G,Re_a=0}$)</th>
<th>Pure-coflow no-swirl blow-off limit ($Re_{o,SG=0}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>107.52</td>
<td>0.01456</td>
<td>27.48</td>
<td>2647 (P1)</td>
<td>23.83</td>
<td>4933</td>
</tr>
<tr>
<td>F2</td>
<td>268.82</td>
<td>0.09082</td>
<td>10.98</td>
<td>3169 (P2)</td>
<td>23.64</td>
<td>5029</td>
</tr>
<tr>
<td>F3</td>
<td>537.64</td>
<td>0.3632</td>
<td>5.49</td>
<td>4235 (P4)</td>
<td>23.4</td>
<td>5294</td>
</tr>
</tbody>
</table>
Cases have been named as FxPy, where x and y denote the fuel and co-annular flow settings as shown in Table. 1. For instance, the second fuel flow case (F2) together with first co-annular setting (P1) is named as F2P1. This nomenclature is used throughout the text. At a particular fuel and co-annular flow setting (Re_f, Re_a), the transitions in the time-averaged flame topology are studied by increasing the inlet flow rate through the tangential ports i.e. increasing S_G in steps from zero till blowout. For pure-swirl blowout, corresponding geometric swirl number (S_G,Re_a=0) indicates the magnitude of S_G required to blow the flame out with zero co-annular flow i.e. Re_a = 0. On the other hand, pure-coflow no-swirl blow-off limit is the magnitude of Re_a required to blow the flame off when S_G =0. The difference between blowout and blowoff will be described in next section. Basically, S_G,Re_a=0 and Re_a,S_G=0 represent two limiting cases of flame extinction. This will be described in detail later in this paper.

4. Results

Key experimental results are discussed in three subsections. In the first section, a map (S_G vs. Re_a for constant Re_f) is proposed to explain the various regimes due to different flame stabilization modes. Next, primary and secondary transitions are described based on time-averaged transformations in flame topology. The effect of change in the vortex breakdown mode (hydrodynamic effect) on the flame topology is elucidated. Probable reasons for flame extinction due to excessive swirl and/or co-annular flow have been described. In the final section, flame dynamics of the primary and secondary transitions is characterized using high speed images and heat release rate signatures (measured using photomultiplier tube).

4.1 Swirl number dependent regime map

Fig. 2a shows the regime map (3D) and stability limits of time-averaged flame topology for three fuel flow rate settings (y axis- Re_f) at various annular flow rates (x axis- Re_a) as the geometric swirl number (z axis- S_G) is varied from zero till blowout. This map is constructed in following manner: For a particular fuel flow case (F1) and co-annular flow setting (P1) - as shown in Table. 1, the intensity of swirl is increased in steps (by increasing the flow rate through tangential swirl ports). Various flame topologies observed due to different flame stabilization
modes are determined from time-averaged CH* chemiluminescence images. Next, for the same fuel flow case F1, co-annular flow is changed to P2 and again the swirl number is increased from zero till blowout. This procedure is repeated for all co-annular flow rate cases P1 to P6. Subsequently, a regime map is constructed for that particular fuel flow rate setting F1. These steps were followed for other two fuel flow cases F2 and F3 as well. The regime map (in 2D) for fuel flow case F2 \((Re_f = 268.82)\) is shown in Fig. 2b. It consists of the following regions: (a) swirling seated flame (region marked by I in Fig. 2b), (b) Lifted blue flame (region II in Fig. 2b) and (c) No flame (regions IIIa and IIIb in Fig. 2b). It also shows critical points like blow-off and blowout marked as B1 and B2 on x and y axis respectively.
In a co-axial swirling flame configuration, three types of flame extinction are observed viz. (a) “rich-limit”- excessive fuel flow, (b) “lean-limit”- excessive co-annular air and/or swirl flow and (c) the disappearance of recirculation structure at minimum swirl limit \[22\]. The present study presents the investigation of ‘lean-limit’ flame extinctions which are of two types viz. blow-off and blowout. It is important to clearly delineate the difference. The phenomenon, by which the flame extinguishes by lifting-off from the burner lip, is called ‘blow-off’. On the other hand, if the flame extinguishes directly from burner lip (without lifting off), the phenomenon is called ‘blowout’. These definitions have been used in past \[35\].

The \(y\) axis of Fig. 2b represents a flow configuration in which co-annular flow is zero i.e. \(Re_a=0\). For fuel flow setting F2 (Table 1), as the geometric swirl number is increased in steps from zero, the flame is observed to blowout (‘lean-limit’) at \(S_{G,Re_a=0} \approx 24\). The pure-swirl blowout \(\left(S_{G,Re_a=0}\right)\) magnitude for other two fuel settings (F1 and F3) are shown in Table 1. It is interesting to note that the magnitude of \(S_{G,Re_a=0} \approx 24\) is common for all fuel flow settings. This can be understood by considering the definition of geometric swirl number, which is given by:

\[
S_G = \frac{\pi r_0 D_o}{2 A_t} \left(\frac{m_\theta}{m_\theta + m_A}\right)^2.
\]

Here \(m_\theta\) is the mass flow rate of tangential air input ports. \(m_A\) is combined fuel and co-annular mass flow rates. For low fuel flow rate (low \(Re_f\) and \(Re_a=0\), at pure-swirl blowout, \(m_\theta\) is much greater than \(m_A\) (observation from the present experiments). As a result the term marked ‘\(ii\)’ in the above equation \(\rightarrow 1\). Hence we can write \(S_{G,Re_a=0} = \frac{\pi r_0 D_o}{2 A_t}\). It is observed that the term marked ‘\(i\)’ depends on the geometry, since all the parameters involved are burner dimensions (\(r_0\) is the transverse distance between burner axis and tangential inlet. \(D_o\) is the diameter of the co-flow pipe. The combined cross sectional area of all swirl ports is denoted by \(A_t\)). In the present burner geometry, the magnitude of the quantity \(\frac{\pi r_0 D_o}{2 A_t} \approx 24\). Thus it can be concluded that in a coaxial tangential-swirl type burner, for low fuel flow rate (\(Re_f\)
≤~500) and non-premixed flame configurations, the pure-swirl blowout geometric swirl number (\(S_G, Re_a=0\)) is a function of burner geometry only.

The x axis of Fig. 2b denotes a flow configuration where flow through swirl ports is zero i.e. \(S_G=0\). The blow-off point for fuel flow rate setting F2 is marked as ‘B1’ in Fig. 2b. The destabilization effect generated by adding coaxial air has been described in past [22-23]. To explain it in a nutshell, the addition of coaxial air stream ensures that less ambient air is needed to dilute the fuel to stoichiometric proportions. As a result, the flame is shortened initially. Consequently, the reaction zone is shifted upstream and overlaps with a region of high velocity and strain. It is shown in [23] that as coaxial velocity is increased, the mixing rate or local strain rate (\(U/\delta\)) increases inducing a destabilizing effect. Here \(U\) and \(\delta\) are local centerline velocity and local jet width respectively. When \((U/\delta) > (S_L^2/\alpha)\)-characteristic chemical reaction rate, the flame blows-off. Furthermore, introduction of coaxial stream increases local gas velocity at any given streamwise location which adds to the destabilization effect. In the present study, pure-coflow no-swirl blow-off limit \((Re_{a,S_G=0})\) for all three fuel flow cases are shown in Table 1. It is observed that \(Re_{a,S_G=0}\) increases with \(Re_f\). Using the above arguments, it is intuitive that as the fuel flow rate increases, the coaxial air velocity required to increase the local strain rate (such that \(U/\delta) > (S_L^2/\alpha)\)) also increases. Hence, within the range of fuel flow rate employed in the present work, \(Re_{a,S_G=0}\) increases with \(Re_f\).

Point locations ‘B1’ and ‘B2’ in Fig. 2b represent critical cases of flame extinction at zero-swirl and zero co-airflow conditions respectively. The blowout also occurs when there is excessive swirl together with co-annular flow. This is denoted by a dotted line connecting ‘B1’ and ‘B2’. This line shows the various combinations of swirl intensities and coflow velocities at which blowout occurs for fuel flow case F2. The blowout graphs for fuel cases F1, F2 and F3 are shown in Fig. 2a. Eleven other fuel flow rates were tested within the \(Re_f\) limits of F1 and F3 (x axis-Fig 3) but not shown in Table 1 for brevity. It is interesting to note that the blowout curves (experimental data) for all the fuel cases collapse to a single curve with positive slope when \(Re_f\) is plotted against \(Re_\theta\) (Fig 3). The error bars in Fig. 3 represents the standard deviation which are within 5% of the mean \(Re_\theta\) values. The collapse of the lean limit onto a single curve is an important observation because for a given fuel flow Reynolds number (\(Re_f \sim 100-500\) range employed in the present study), the curve indicates a critical \(Re_\theta\) magnitude beyond which the
flame is non-existent (blows out). The map is quite useful in determining the stability limits in terms of a single input parameter ($Re_\theta$) in a coaxial swirl nozzle. This is because $Re_\theta$ takes into consideration the combined effect of co-annular flow rate and swirl intensity imparted through tangential ports. The positive slope of the curve implies that for higher $Re_j$, the representative swirling strength of the coflow annulus (represented by $Re_\theta$ magnitude) required to blowout the flame is higher.

Fig. 3. Collapse of lean blow out limits for different fuel flow cases considered in the present study onto a single curve. The y axis represents Reynolds number based on characteristic angular velocity at co-annular jet exit -$U_\theta$.

The parameter space of the regime map (Fig. 2b) consists of various regimes viz. swirling seated flame, lifted blue flame and no-flame. The transition from one regime to another is observed when geometric swirl number is increased in steps at a fixed co-annular flow rate ($Re_a$) for a given fuel flow setting ($Re_f$). This is described in detail in the next section.
4.2 Transitions in flame topology and lean blowout

In the present section, swirl number dependent transitions in time-averaged flame topology will be discussed. In particular, primary transitions from non-swirling straight jet flame to lifted flame with blue base and finally to swirling seated flame are described as the swirl number is increased in steps. Subsequently, secondary transitions from swirling seated flame to swirling flame with a conical tailpiece and finally to highly-swirled near blowout ultra-lean flame are discussed. The present section attempts to provide a hydrodynamic point of view to the flame topology.
4.2.1 Primary Transition in flame topology
Fig. 4. Primary and secondary transitions of time-averaged flame topology for flow case ‘F2P2’ (Refer Table 1 for flow cases). Contour plots represent time-mean CH* chemiluminescence images. The streamlines are obtained from 2D PIV in meridional plane.

The transitions in the flame topology are described by traversing different vertical paths (Path 1, 2 and 3) as shown in Fig. 2b. Vertical traverse along each path represents a change in geometric swirl number ($S_G$) at a fixed co-annular flow rate setting ($Re_a$) for a particular fuel case. The primary transition is observed at critical and super-critical $Re_a$ (as shown in Fig. 2b). The change in time-averaged flame topology during primary transition is shown in Fig. 4a-4f. It represents a transformation of flame topology from burner lip attached zero-swirl straight jet flame (Fig. 4a) to lifted flame with blue base (Fig. 4b-4d) and then to swirling seated flame (Fig. 4e and 4f) as the geometric swirl number is increased in steps from $S_G=0$ to 3.02. Each sub-figure in Fig 4 represents time-averaged streamline plot obtained from high resolution 2D PIV in mid-longitudinal plane. The background of the sub-figures represent time-averaged CH* chemiluminescence contours. The chemiluminescence imaging and PIV measurements were not conducted simultaneously. However, since the present work concerns the study of transition on the basis of time-averaged flame topology, such representation (CH* chemiluminescence superposed on streamlines) is pragmatic and can provide useful insights into different modes of flame stabilization.

The primary transition for fuel flow setting F2 occurs only after a critical co-annular Reynolds number ($Re_{a,critical}$) as shown in Fig. 2b. The flame shape transitions at sub-critical $Re_a$ (vertical traverse path- P1) will be discussed in next subsection. At $S_G=0$, the flame is a simple jet flame with fuel in the central pipe surrounded by the co-annular air jet (Fig 4a). The flame is yellow in color and is attached to nozzle tip. As the geometric swirl number is increased to $S_G=0.83$, the flame lifts-off from the burner lip and is stabilized at a normalized axial distance $h/R_0=0.43$ ($R_0$...
is the radius of co-annular pipe). This is shown in Fig. 5a (case name ‘F2P2’).

Fig. 5 Variation of a) normalized lift-off height- $h/R_0$ (primary axis) and flame height- $H/R_0$ (secondary axis) and b) CH* intensity per unit pixel ($I$) with respect to geometric swirl number for selected flow cases.
The lift-off height ($h$) is calculated as follows: the time-averaged CH* chemiluminescence intensity map imported from the DaVis software is subjected to a threshold technique wherein pixels with intensity values above 5%-of-background are considered to determine flame contour. The axial distance from the burner lip along the centerline at which first pixel of flame contour is observed is taken to be $h$. The ($Sc$, $Re_o$) parameter space within which such lifted flames are observed for fuel flow case F2 is marked as ‘regime II’ in Fig. 2b. This regime for other fuel cases (F1 and F3) considered in the present study is shown with dotted blue line in Fig. 2a.

The lifted flame is blue in color which indicates appreciable fuel-air mixing in the lift-off region. This is quantified in Fig. 5b which shows the average CH* intensity per unit pixel ($I$) (calculated from the same threshold image described above). It is observed from Fig. 5b that the intensity of lifted flame (present case: $F2P2$) decreases by ~20% from that of $Sc=0$ straight jet flame. This is true for other fuel cases F1 and F3 (Table 1) employed in the present study. Result for only one other fuel case F1 (case name: $F1P3$) along with F2 is shown in Fig. 5b. Further, it is observed from the time-mean streamline plot (Fig. 4b) that a wake-type recirculation zone (RZ) exists at the immediate exit of the nozzle. It is important to note that the recirculation zone observed at $Sc=0.83$ is not due to the phenomenon of vortex breakdown (this phenomenon is observed at higher $Sc$ later in this study). The lifted blue flame stabilizes along the vortex core center of the RZ. The lifted blue flame and its associated features are observed at $Sc=1.11$ as well (Fig. 4c).

As the geometric swirl number is increased to $Sc=1.47$, first occurrence of vortex-breakdown (VB)-associated internal recirculation zone (IRZ) is observed in the downstream of wake-type RZ (Fig. 4d). Vortex breakdown is a commonly observed phenomenon in swirling flows which occurs above critical swirl intensity. It is characterized by an abrupt deceleration of the streamwise flow leading to the formation of a free stagnation point on the swirling axis. The fluid downstream of the front stagnation point is observed to recirculate leading to the formation of an internal recirculation zone (IRZ). The normalized lift-off height ($h / R_o$) is observed to decrease by ~65% at $Sc=1.47$ as compared to $Sc=0.83$ case (Fig. 5a). However, the flame is still stabilized around the wake-type RZ (Fig. 4d). There is little change in the magnitude of $I$ when compared to $Sc=0.83$ (Fig. 5b) indicating that the flame is still blue in color. Next, as $Sc$ is increased to 1.84, the flow topology is characterized by burner-tip-attached VB-induced IRZ with a simultaneous collapse of wake-type RZ (Fig. 4e). As a result, the flame is now attached to
the nozzle tip. Therefore the lift-off height decreases to $h=0$ as shown in Fig. 5a (present case: F2P2). The flame is now anchored at the upstream stagnation point of the VB-IRZ and stabilized at the intermediate shear layer (ISL- marked in Fig. 4e) between the VB-IRZ and co-annular stream. This (moderately-swirled) attached flame is yellow in color. This can be qualitatively verified by the time-averaged CH* chemiluminescence image in Fig. 4e which shows higher intensity as compared to lifted flames (Fig. 4b,c,d). This is quantitatively shown in Fig. 5b (present case: F2P2) where $I$ is observed to increase by $\sim 25\%$ as compared to lifted flame at $S_G=0.83$. The magnitude of $I$ is now very close to $S_G=0$ (straight jet flame).

To summarize, with progressive increase in swirl intensity, the zero-swirl straight jet yellow flame transits to lifted blue flame which stabilizes at the vortex core center of the wake-type RZ. With further increase in swirl intensity, vortex breakdown (VB) induced IRZ is observed to coexist with wake-type RZ. The flame now travels upstream but is still lifted. Finally, at sufficiently high swirl, the VB induced IRZ is observed to anchor at the burner tip. Consequently the flame gets anchored at the upstream stagnation point of IRZ and stabilizes around the VB shear layer.

### 4.2.2 Secondary Transition in flame topology

In the present study, secondary transition is used to denote a transformation in the time-mean flame topology from seated yellow flame to a flame configuration with a conical tailpiece and finally to burner-tip attached bluish-yellow flame (just prior to blowout), as a direct function of increasing geometric swirl number. For the fuel flow cases (F1, F2 and F3- Table 1) considered, the secondary transition is observed at (a) critical and super-critical $Re_a$ after the occurrence of primary transition – as shown in Fig. 2a and (b) sub-critical $Re_a$ (example- Path 1 traverse in Fig. 2b). It is important to note that at sub-critical $Re_a$, primary transition discussed in the previous subsection is absent. The secondary transition will be discussed in detail now.

As the swirl number is increased to $S_G=3.78$ (Fig. 4g) from $S_G=1.84$(Fig. 4e) -the seated swirling flame at the end of primary transition is observed to transit to a configuration with a conical tailpiece. This flame shape is observed to exist for a broad range of $S_G$ i.e. $S_G=3.78$ to $S_G=6$ (Fig. 4g-4i). The increase in the flame height (defined as the axial distance along the burner centerline
from the burner exit to the tip of the flame) is quantified in Fig. 5a (present case: F2P2) which shows the variation of normalized flame height ($H / R_0$) as a function of geometric swirl number. It is observed that $H / R_0$ increases by $\sim 65\%$ at $S_G=3.78$ compared to $S_G=1.84$. The $I$ within $S_G=3.78-6$ band is observed to remain almost same as $S_G=1.84$ flames. This indicates that, although there is a significant change in the flame shape, the area averaged heat release magnitude almost remains identical. Further, as $S_G$ is increased to 7.19 (Fig. 4j), the conical tailpiece of the flame is observed to subside and finally merge with the flame base. Consequently normalized flame height ($H / R_0$) decreases by $\sim 50\%$ (Fig. 5a -present case: F2P2). However, there is little change in the $I$ as compared to $S_G=3.84-6$ band. As the geometric swirl number is further increased to a very high magnitude ($S_G=9.75$), which is close to blowout (for case F2P2), the flame moves upstream to anchor at a few millimeters below the burner exit. As a result the normalized flame height ($H / R_0$) further decreases by $\sim 50\%$ as compared to $S_G=7.19$. The $I$ decreases by $\sim 20\%$ (Fig. 5b -present case: F2P2) which shows that the flame near to blowout (at $S_G=9.75$) is much leaner (compared to $S_G=7.19$) due to partial premixing. The probable reason for this observation will be explained later in this section.

The above mentioned secondary transition is observed at sub-critical $Re_a$ as well. For instance, the flame shape transition along path 1 for fuel case F2 (case name: F2P1) is shown in Fig. 6. This path is also marked on regime map (Fig. 2b). At sub-critical $Re_a$ (path 1), primary transition from non-swirling straight jet to lifted blue flame and finally to seated swirling flame (as described in previous subsection) is not observed. The straight flame never lifts-off with increase in swirl number (Fig. 6a-6b).
Fig. 6. Secondary transitions in time-averaged flame topology for flow case ‘F2P1’ (Refer Table 1 for flow cases). Contour plots represent time-mean CH* chemiluminescence images. The streamlines are obtained from 2D PIV in meridional plane.

Instead, the swirling flame directly transits to a configuration with conical tailpiece (Fig. 6d) at $S_G=3.7$. The change in flame shape from $S_G=3.7$ to $S_G=11.02$ (Fig. 6i) is similar to the secondary transition described above for case F2P2 (Fig. 4g-4l). The associated changes in the normalized flame height ($H/R_0$) and $I$ are also similar. All the features are shown in Fig.5 as F2P1. The absence of primary transition at sub-critical $Re_a$ indicates that the time-averaged flame shape is sensitive to input parameters- $Re_a$, $Re_f$ and $S_G$ in the present study. As such, a detailed investigation (like the present study) involving effect of these parameters is essential as the time-
averaged flame shapes are found to influence the thermo-acoustic characteristics of the combustor.

The change in the flame shape during secondary transition may be a direct consequence of change in the topology of vortex-breakdown modes (VB) as the swirl number is varied which in turn determines the mode of flame stabilization. To elaborate, the time-averaged streamline plot of flame with conical tailpiece consists of two distinct regions: (a) central region which is dominated by high axial momentum jet which gyrates about the central axis and (b) recirculation region surrounding the central jet characterized by presence of two counter-rotating eddies as shown in Fig. 4g, 6d and 6e. The conical tailpiece of the flame is observed to stabilize around the central high axial momentum jet while the flame base is stabilized around the ‘dual-ring vortex breakdown (VB)’. As the swirl number is increased, the two regions merge to form a ‘modified type VB bubble (VBB)’ (Fig. 4j and 6g). This is characterized by a significant widening of the outer RZ of the ‘dual ring VB’ with a simultaneous deterioration of inner RZ.

The non-existence of a central high axial momentum jet with a simultaneous widening of the outer RZ of the ‘dual ring VB’ retracts the conical tailpiece part of the flame. Finally as the swirl number is increased to a magnitude which is immediate prior to blowout (Fig. 4l and 6i), the structure observed is ‘central toroidal recirculation zone (CTRZ)’- a flow feature commonly witnessed in vortex breakdown literature. It consists of two very large recirculation eddies. The inner RZ of the ‘dual ring VB’ has completely vanished. As a result, the conical tailpiece of the flame configuration is completely non-existent.

Interestingly, the kind of transition described above was observed in our previous work [24] for non-reacting flows. Time-averaged transformation of vortex breakdown structures over the geometric swirl number range $2.14 \leq S_G,_{isothermal} \leq 2.88$ as shown in Fig. 7 were studied [24]. Although, the non-reacting $S_G$ transition range is different from the range observed during combustible flow i.e. $\sim 4 \leq S_G,_{combustion} \leq \sim 10$, the essential flow features through the transition stages in both isothermal and combustible modes are strikingly similar. Hence we hypothesize a possible physics for secondary transition in flame topology based on our observations in the isothermal flow field.

Fig. 7a represents the dual ring VB mode (first occurrence of recirculation in isothermal flow) at $S_G=2.14$. The dual ring structure, similar to that observed in Fig. 4g, 6d and 6e previously, is
Fig. 7. Transition in vortex breakdown mode from dual ring VB bubble (a) to central toroidal recirculation zone (d) in non-reacting/isothermal flow field. Time-mean streamline plot obtained from 2D PIV in mid-longitudinal cut section is superimposed on contour plot of azimuthal vorticity [reproduced with permission from R. Santhosh, A. Migliani, and S. Basu, Phys. Fluids 25, 083601 (2013). Copyright American Institute of Physics, 2013]

marked as pairs L1 and L2 on the left side and R1 and R2 pair on the right hand side. Fig. 7b and 7d respectively are ‘modified type VB bubble (VBB)’ and ‘central toroidal recirculation zone (CTRZ)’ flow modes observed in isothermal flows which are similar in topology to VB modes observed in Fig. 6g and 6i of reacting flow. The physics behind the transition from dual-ring VB to CTRZ through modified VBB (Fig. 7a-7b-7d) is explained on the basis of dimensionless modified Rossby number ($R_{Om}$). It is defined as the ratio of velocity deficit
between co-flow streams to the characteristic tangential velocity at the burner exit [36]. It is

given by:

\[
Ro_m = \frac{|\Delta u_y|}{u_{\theta,avg}}
\]  

(4)

\(u_{\theta,avg}\) is the spatio-temporal averaged tangential velocity at the exit of the burner measured by
hotwire anemometer (CTA) in the non-reacting flow. Although, this quantity could not be measured in the present reacting flow study, the strikingly similar flow features between the transitions in these two flows (reacting and non-reacting) hints the possibility of applying same
\(Ro_m\) concept for both flows. The modified Rossby number (\(Ro_m\)) represents combined effect of
two competing radial pressure gradients due to (a) entrainment effect (between co-flowing
stream) and (b) centrifugal force imparted due to tangential momentum of swirl. The pressure
gradient arising due to radial inward diffusion of angular momentum imparted to the co-annular
stream scales as \(\rho u_\theta^2\) where \(u_\theta\) is the characteristic tangential velocity. The inward penetration
of this tangential momentum is opposed by pressure gradient arising from entrainment effect at
the shear layer between central jet and co-annulus. This pressure difference scales as \(\rho |\Delta u_y|^2\),
where \(\Delta u_y\) is the velocity difference between two streams of a coaxial jet \([37]\). The resultant of
these two competing pressure gradients determines the net size of the vortex core \([24-25]\). The
ratio of these two pressure drops scales as \((\rho |\Delta u_y|^2)/(\rho u_\theta^2) = Ro_m^2\). Thus, a flow case for with
\(Ro_m > 1\) is dominated by pressure deficit arising due to entrainment effect \((\Delta u_y)\) as compared to
rotational influence \((u_\theta)\). As a result, the swirl effect fails to penetrate till the central axis. This is
substantiated by the fact that topology of the high axial momentum center jet is unaltered \(\text{(shown in Fig. 4g, 6d and 7a)}\) even in the presence of induced swirl momentum. In such a scenario, the
section of the flame stabilized around high axial momentum central jet is observed as conical
tailpiece in the flame topology. The base of the flame is still stabilized in the shear layer
separating ‘\text{dual-ring vortex breakdown (VB)}’ and co-annular jet (ISL-intermediate shear layer).

As the swirl number is increased, \(Ro_m < 1\) \(\text{(Fig. 4l, 6i and 7d)}\). This implies a lower resistance
(from entrainment effect) to the radially inward penetration of angular momentum till the central
axis. As a result, the zone of swirl influence is significantly widened and the effect of tangential
momentum penetrates till the central axis. This is substantiated by the absence of high axial
momentum central jet in the flow field. In such a case, the conical tailpiece (which was
previously stabilized around the central jet) retracts and merges with the base of the flame and the entire flame is now effectively stabilized only in the ISL. The flow mode $Ro_m \approx 1$ (Fig. 4j, 6g and 7b) represents a metastable structure that demarcates the flow regimes dominated by inter-stream velocity difference- $\Delta u_y$ ($Ro_m > 1$) with those governed by the centrifugal effects-$u_\theta$ ($Ro_m < 1$). It represents the first occurrence of disappearance of the axial momentum jet and conical tailpiece of flame topology. The above mentioned arguments are summarized in Fig. 8.

![Diagram](image)

**Fig. 8.** Schematic of possible physics behind the secondary transitions in flame topology observed in the present work. Flow field (IRZ) is shown to the right side of the centerline in each subfigure. The pressure gradients are shown in the left.
4.2.3 Lean blowout

After secondary transition (discussed in the previous subsection), any increase in $S_g$ thereafter (beyond $S_g=9.75$ for case F2P2 as shown in Fig. 4i and $S_g=11.02$ for case F2P1 shown in Fig. 6i) leads to blowout i.e. flame extinguishes directly from burner lip without lifting off. In the present subsection, possible reasons for the blowout are discussed.
Fig. 9. Variation of a) normalized mass flow recirculated- \( m \) and b) overall fuel-air equivalence ratio based on inlet mass flows \( (\varphi_0) \) with respect to geometric swirl number \( (S_G) \) for flow cases ‘F2P1’ and ‘F2P2’ (Refer Table 1 for flow case nomenclature).

\( \text{Fig. 9a} \) represents the plot of normalized recirculation mass flow \( (m) \) versus \( S_G \) for both paths \( P1 \) and \( P2 \) for fuel flow case \( F2 \) during the secondary transition. \( m \) is given by [2]:

\[
m = \frac{2\pi \int_0^{r_{vcc}} \rho u y r dr}{m_{in}}
\]

where \( r_{vcc} \), \( \rho \) and \( m_{in} \) are the radius of vortex core center, fluid density and inlet total mass flow rate respectively. Fluid density is taken to be the statistical mean of methane (fuel) and air (oxidizer) densities. The integral in the above expression is evaluated at axial planes containing vortex core centre as they correspond to the planes of maximum mean recirculation velocity, mass flow and radial width of IRZ. Normalized recirculation mass flow \( (m) \) signifies the fraction of input fluid mass that is recirculated inside the IRZ at a given \( S_G \). In the present study, since an increase in \( S_G \) is realized by increasing the flow rate through the swirl ports (air) at fixed fuel flow case (either \( F2P1 \) or \( F2P2 \) case) an increase in \( m \) with respect to \( S_G \) signifies increased mass of oxidizer (air in the present study) in the IRZ. It is observed that the \( m \) increases by 4-6 times for cases \( F2P1 \) and \( F2P2 \) (\textbf{Fig. 9a}) within \( S_G \) range of \( S_G=3.7-11.02 \) and \( S_G=3.78-9.75 \) respectively. This is expected, as the IRZ size significantly increases in both cases (\textbf{Fig. 4 and 6}). This implies that the amount of oxidizer in the interior of the IRZ is maximum at \( S_G=11.02 \) and \( S_G=9.75 \) for cases \( F2P1 \) and \( F2P2 \) respectively. As a result, the flames become ultra-lean at these conditions. This is verified by the plot of overall fuel-air equivalence ratio based on inlet mass flows \( (\varphi_0) \) - \textbf{Fig. 9b} which is defined as (at a given \( S_G \)):

\[
\varphi_0 = \frac{m_f}{m_a} \left( \frac{m_f}{m_a} \right)_{stoic}
\]
where $\dot{m}_f$ and $\dot{m}_a$ are respectively the mass flow rates of fuel and air. Mass flow rate of air (oxidizer) at a given $Sc$ is taken to be the sum of mass flow rates through the co-annular pipe and all swirl ports. Denominator represents the stoichiometric fuel-air ratio. It is observed that $\varphi_0$ decreases by 70-75% at $Sc=11.02$ and $Sc=9.75$ for $F2P1$ and $F2P2$ respectively from $Sc=0$. Besides, the magnitude is very close to zero (ultra-lean) at these swirl numbers ($Sc=11.02$ and $Sc=9.75$). This provides conclusive evidence that increase in $Sc$ leads to increase in IRZ size.
Fig. 10. Contour plot of strain rate ($\varepsilon$) during primary and secondary transitions observed in the present study for flow case 'F2P2' (Refer Table 1 for flow case nomenclature).
which in turn leads to increased mass of oxidizer in the interior of the IRZ around which the flame is stabilized. Consequently, the flame at very high $S_G$ becomes ultra-lean and blows out.

Another concurrent effect of increasing $S_G$ is that the flame is increasingly strained. **Fig. 10** shows the contour plot of time-averaged strain rate ($\epsilon$) obtained from 2D velocity data in meridional cut plane for the case $F2P2$ during the secondary transition. $\epsilon$ (units: s$^{-1}$) which represents the average 2D shear is defined as $(\epsilon_{xy} + \epsilon_{yx}/2)$ where $\epsilon_{xy}$ and $\epsilon_{yx}$ are $\frac{\partial u}{\partial y}$ and $\frac{\partial v}{\partial x}$ respectively. It is observed that the strain rate ($\epsilon$) is mainly concentrated in shear layers between (a) vortex breakdown bubble (VBB) and co-annular jet- shown as ISL (intermediate shear layer) in **Fig. 10l** and (b) co-annular jet and quiescent surrounding- shown as OSL (outer shear layer) in **Fig. 10l**. As the swirl number is increased in steps, the stain rate in these shear layers increase. In addition, there is redistribution of $\epsilon$ in radially inward direction from the ISL towards the vortex core (compare **Fig 10l with 10j**). This is quantified by considering strain-rate distribution factor ($\xi$) which is defined as:

$$\xi = \frac{\int_{0}^{R_S} \epsilon \, rdr}{\int_{0}^{R} \epsilon \, rdr}$$

(7)

where $R_S$ represents the radial distance from central axis to the edge of the vortex core (ISL) – marked in **Fig. 10l**. $R$ is the radial distance from centerline to the outer shear layer (OSL)-marked in **Fig. 10l**. The OSL is delineated by the outermost streamline travelling around the bubble that originates from the annulus. In other words, this is the first streamline marking the interaction of co-annular stream with the ambient. Numerator of $\xi$ ($y$) represents $\epsilon$ distributed till the edge of the vortex core ($0 - R_S$). The denominator indicates $\epsilon$ distributed across the entire recirculation structure till its OSL i.e. ($0 - R$). In essence, $\xi$ quantifies the effectiveness with which $\epsilon$ is redistributed radially inwards from the ISL towards the vortex core. The radial distribution of $\xi$ is depicted in **Fig. 11a-11b** at two axial planes given by $y = 0.5R_o$ and $1R_o$ respectively (marked in **Fig. 10l**) for the two cases $F2P1$ and $F2P2$ during the secondary transition. It is observed that $\xi$ increases by 0.9-1.5 times at $y = 0.5R_o$ and $1R_o$ for both $F2P1$ and $F2P2$ at high swirl numbers i.e. beyond $S_G=7.5$. This indicates an intense redistribution of strain rate from ISL to vortex core. As a result, the IRZ, around which the flame is stabilized,
intensely strained at high swirl numbers. Effectively, the flame is ‘strained-out’ leading to its extinction (blowout).

Fig. 11. Geometric swirl number dependent variation of strain-rate distribution factor ($\xi$) at axial planes a) $y/R_o = 0.5$ and b) $y/R_o = 1$. 
4.3 Flame dynamics during transition and near blowout

Fig. 12. Power spectral density (arbitrary units) of heat release fluctuation ($q'$) at different swirl numbers through the primary and secondary transitions observed in the present study for flow case (a) ‘F2P1’ and (b) ‘F2P2’. Refer Table 1 for flow case nomenclature.

Previous two sections dealt with the description of transitions and lean blowout with the help of time-averaged flame topology and statistics. The present section describes flame dynamics which provide more useful insights into the transitions and blowout. Figs. 12a and 12b show the power
spectral density (PSD) of heat release fluctuation ($q'$) for cases $F2P1$ and $F2P2$ respectively at various $Sc$. Each flow case has been named as previously described, except that now the magnitude of the geometric swirl number ($Sc$) is also indicated. The following are the key observations: (a) The PSD of straight jet flame ($Sc=0$) in both Figs. 12a and 12b do not show any frequency content, as expected, because the jet flame with co-annular flow is quite stable devoid of any fluctuation. (b) As the swirl number increases, the relative peak of PSD increases and is maximum at $Sc=11.02$ and $Sc=9.75$ for $F2P1$ and $F2P2$ respectively, which are just prior to blowout. Thus, very high PSD of PMT signal can be taken to be a precursor to blowout. (c) Natural frequencies (self excited frequencies) at all swirl intensities for $F2P1$ and $F2P2$ case lie in the 8-10 Hz and 8-12 Hz bands respectively. This implies the presence of low frequency oscillations throughout the transition and near blowout.
Fig. 13. (a) Power spectral density (arbitrary units) of square of flame area fluctuation ($A'^2$) for flow case ‘F2P2’ at different swirl numbers through primary and secondary transitions and (b) Comparison of PSD ($A'^2$) of ‘cone’ and ‘base’ part of swirling flame with conical tailpiece with flames at other swirl numbers.
Fig. 14. High speed image snapshots depicting the dynamics of swirling flame with conical tailpiece at \( S_G = 4.52 \) for flow case- \( F2P2 \). The snapshots are chosen at different time intervals to depict key features.

**Fig. 13a** shows PSD of square of area fluctuation \( (A^{'2}) \) for case \( F2P2 \) at different swirl numbers through the transitions. The low frequency content (as previously observed) is evident. This indicates that flame area fluctuation and heat release fluctuation \( (q^{'}) \) are correlated. Two swirl settings are further probed to understand the dynamics. They are: (a) the flame configuration with conical tailpiece (**Fig. 14**), \( S_G = 4.52 \) and (b) flame just prior to blowout (**Fig 15**), \( S_G = 9.75 \). It is observed from HS images that the downstream part of \( S_G = 4.52 \) flame i.e. conical tailpiece is
dominated by helix type instability (helical instabilities are observed in swirl flames [38]). Fig. 14 shows one complete sequence of helix travel. Images are shown at different time intervals to capture essential dynamics. It is seen that one cycle of helix travel occurs in $\tau=0.087$ s. This corresponds to a frequency of $f = 1/0.087 = 11.49$ Hz. This frequency is observed in both PSD of PMT signal and $A'^2$ (8-12 Hz) as shown previously in Fig. 12a and 13a respectively. Further, the HS images of $S_G=4.52$ flames were divided into two sections: (a) conical part (downstream region) of the flame and (b) upstream base section as shown in one of the sub-figures in Fig. 14. The square of surface area fluctuation ($A'^2$) was calculated for these two sections separately. The PSD plots are shown in Fig. 13b. It is observed that the PSD peak for $A_{cone}'^2$ is significantly higher than the $A_{base}'^2$. This indicates intense dynamics/twisting in the conical section when compared to the base. It is observed from HS images [at other $S_G$ during secondary transition (not shown here)] that as the conical flame subsides, the intense twisting is now imparted to entire base section of the flame. The HS images at $S_G=9.75$ (Fig. 15) shows intensified dynamics of the entire flame surface. This is confirmed from Fig. 13b where the PSD peak of $A_{S_G=9.75}'^2$ is higher than the $A_{S_G=4.52,base}'^2$. 
Fig. 15 High speed image snapshots depicting the dynamics of swirling flame just before blowout at $S_G=9.75$ for flow case- $F2P2$. The snapshots are chosen at different time intervals to depict key features.

The above discussion clearly indicates that the flame stabilization mode affecting the time-averaged flame topology affects the dynamics of the flame as well. The flame dynamics of one flame mode may be different from another depending on the input parameters like Reynolds and swirl number. The present section was aimed primarily to demonstrate this fact using preliminary analysis of HS images and PMT signals. Some high fidelity experiments (like high speed 3D PIV) and numerical stability analysis would be required to understand the dynamics completely. However, the aim of the present experimental investigation was to study the effect of swirl intensity on the time-averaged topology of the flame to characterize the transitions in flame shapes.

5. Conclusion

The tackling of combustion instability problem involves studying flame dynamics to understand dynamic coupling of heat release fluctuation with pressure and velocity perturbations, at combustor natural acoustic mode. Flame dynamics is controlled by a number of processes, one of them being flame stabilization, which determines the global flame structure. The present study focused on effect of swirl intensity on the global flame (non-premixed) shape (time-averaged) in a co-airflow type atmospheric tangential-swirl burner. For this purpose, CH* chemiluminescence imaging and 2D PIV in meridional planes were employed. Three baseline fuel flow rates through the central fuel injection pipe were considered. For each of the fuel flow cases ($Re_f$), six different co-airflow rate settings ($Re_a$) were employed. The geometric swirl number ($S_G$) was increased in steps from zero till blowout for a particular fuel and co-airflow setting. A regime map ($S_G$ vs $Re_a$) depicting different regions of flame stabilization were then drawn for each fuel flow case. It was observed that within the fuel flow rates tested, the magnitude of pure-swirl geometric swirl number ($S_{G,Re_a=0}$) required to blowout (flame extinction directly from burner lip without once lifting off) the flame was a function of burner dimension only i.e. $r_0$ - transverse distance between burner axis and tangential inlet, $D_o$ -diameter of the co-flow pipe and $A_t$- combined cross sectional area of all swirl ports. However, within the $Re_f$ range employed in the present
work, pure-coflow no-swirl blow-off (flame extinction by lift-off mode) limit -ReₐSₐ=₀ increased with Re. The lean flame blowout also occurs with a combination of excessive swirl and co-airflow. It is observed that the blowout curve for all the fuel cases approximately collapsed to a single curve when Re was plotted against Re. Re was given by Re = U₀dₒ/νₐir where U₀ was characteristic magnitude of the angular velocity at co-annular jet exit defined as U₀ = UₐSₐ where Uₐ is the velocity co-annular stream calculated from volumetric flow rate of the (Qₐ).

The transformation in time-averaged flame structure was classified as primary and secondary transitions. With a stepwise increase in swirl intensity, primary transition consisted of a transformation from zero-swirl straight jet flame to lifted flame with blue base and finally to swirling seated flame. The transition from burner attached jet flame to lifted blue flame was characterized by a normalized lift-off height h/R₀=0.43 (R₀ is the radius of co-annular pipe) and a decrease in average CH* chemiluminescence intensity per pixel (I) of ~20%. The flow field was characterized by a wake-like recirculation zone (RZ) at the burner exit and the flame stabilized along the vortex core center. As swirl intensity was increased, IRZ due to vortex-breakdown (VB) was observed with a simultaneous collapse of wake-like RZ. The flame now anchored at upstream stagnation point (as a result the flame was burner tip attached) of VB bubble and stabilized around the shear layer separating VB bubble and co-annular stream. The secondary transition was observed when the VB bubble transformed from a dual ring structure to central toroidal recirculation zone (CTRZ). The global flame structure consequently transited from swirling seated flame to swirling flame with a conical tailpiece and finally to highly-swirled near blowout ultra-lean flame. This transformation was explained based on modified Rossby number (Rom) which was defined as ratio of velocity deficit between co-flow streams to the characteristic tangential velocity at the burner exit. A magnitude of Rom>1 implies a domination of radial pressure gradients due to entrainment effect (between co-flowing stream) over the centrifugal force imparted due to tangential momentum of swirl. In such a scenario, the swirl effect failed to penetrate till the central axis. This case was observed in ‘dual-ring vortex breakdown (VB) where a high axial momentum central stream was present. The corresponding global flame structure was swirling seated flame with conical tailpiece. CTRZ flow structure was observed when Rom ≈ 0 i.e. the pressure gradient due to rotational effect dominated over the
pressure gradient arising due to entrainment influence. The dual ring VB collapsed (the high axial momentum central stream also subsided) to form a significantly large IRZ. Consequently, the conical tailpiece also subsided. When swirl number was increased to a high magnitude ($S_G \sim 10$), the swirling flame blew out due to excessive straining.

The flame dynamics was studied using PSD of heat release fluctuation ($q'$) and square of area fluctuation ($A'^2$) obtained respectively from PMT signal and high speed images at different swirl numbers through the primary and secondary transition. Both PSDs showed low frequency content (8-12 Hz) representative of self excited oscillations. The peaks of PSD curve at greater swirl numbers carried greater energy representative of greater unsteadiness. It was also shown that the dynamics of a flame configuration depends on its mode of stabilization. For instance, the most dynamics of the swirling seated flame with conical tailpiece was concentrated in the conical section of the flame configuration when compared to its base portion. This underlined the importance of understanding flame stabilization as it is one of the processes determining the dynamics. The present study involved a preliminary analysis of flame dynamics. A more sophisticated experimental facility like high speed 3D PIV is required to completely understand the dynamics, which is the aim of the future experimental investigations.
References


[27] Cameron Tropea, Alexander L. Yarin, John F. Foss, Springer Handbook of Experimental Fluid Mechanics; Sect 5.3; pg 289 (Springer. 2007).


