Effect of Nozzle-Nozzle Interaction on Lean Flame Transitions in a Multi-Swirler Combustor

by

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
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Abstract

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University of Toronto
2019

This thesis investigates the transition between different flame stabilization modes in a gas turbine model combustor consisting of a linear array of five interacting nozzles, which is representative of advanced designs for next generation engines. Simultaneous multi-kHz repetition rate OH planar laser induced fluorescence (OH-PLIF) and stereoscopic particle image velocimetry (S-PIV) were used to examine the hydrodynamics and nozzle-nozzle interactions during the transient process of flame liftoff and reattachment. Two different reactants feeding configurations were designed to isolate the effects of different operating and geometric parameters on the combustor’s fuel lean performance. The first configuration consisted of a common plenum, and reactants to each nozzle were fed through it and distributed among the nozzles. In the second configuration, each nozzle had an independent plenum that was fed from a dedicated set of electromechanical mass flow controllers.

The lean blowoff point was tested for different inter-nozzle spacing, by changing the nozzles receiving reactants. The combustor’s lean operability did not have a monotonic relationship with inter-nozzle spacing, but was optimized in the two-nozzle configuration, which can be explained by the complex interaction between the cross-nozzle flame transport, fluid dynamic strain field, and the recirculation strength. For combustor with different inter-nozzle spacings, blowoff occurred at a relatively constant Damköhler number when the ratio of the recirculation zone length to bulk velocity was used as the fluid
time scale.

On the other hand, the presence of uneven reactant distribution and equivalence ratio stratification do not change the blowoff limits for individual nozzles, as the Damköhler number for each nozzle in different scenarios collapsed into a single point. In particular, it was found that the overall combustor’s lean operability can be improved by distributing the reactants to nozzles such that the flow condition for individual nozzle was above the corresponding critical Damköhler number.

The blowoff/reattachment process for an individual flame was initiated in a similar manner to isolated bluff-body stabilized flames, though with cross-nozzle flame interactions providing additional means of re-stabilizing a partially extinguished flame. In the connected plenum configuration, it was found that the blowoff/reattachment dynamics of the three investigated nozzles were coupled to each other. Blowoff transitions were preferentially initiated in one of the off-center nozzles, with the transition of subsequent nozzles occurring in a random order. Similarly, the center nozzle tended to be the last nozzle to reattach. However, such temporal coincidence of the blowoff/reattachment transitions were not observed in the individual plenum configuration, which suggests the upstream coupling is significant in the combustor dynamics. A statistical analysis demonstrated that changes in downstream conditions would lead to flow re-distribution inside the connected plenum. It was found that both in chamber and upstream cross-nozzle interactions are equally important in flame blowoff transitions inside a practical combustor, while the in chamber cross-nozzle interaction plays a more important role in reattachment transitions.
Acknowledgements

I would like to take this opportunity to thank University of Toronto Institute for Aerospace Studies (UTIAS), Siemens Canada Ltd., and Natural Sciences and Engineering (NSERC) for providing me the opportunity and financial support that made this research possible. Especially, I would like to express my deepest appreciation to the following people who contributed to the accomplishment of this dissertation.

I would like to express my gratitude to my supervisor, Professor Adam Steinberg, who is always looking out for the best interest of his students. His patience and confidence in my academic and research is demonstrably more than what I could have expected.

I would like to thank my colleagues from UTIAS for always bringing up interesting conversations in the office.

Last but not least, I would like to thank my parents for their endless love and support throughout my life. Thank you both for giving me a chance to chase my dream. Without you, I would not be able to be here. I will be grateful forever for your love. This thesis is only a beginning of my journey. I will try my best in future and will never let you down.

Wing Yin Kwong
Toronto, January 2019
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Nomenclature

Acronyms

BP-TR  Broadened preheat-thin reaction
BR    Broken reaction zone
BVK   Bernard-Von Kármán instability
CF    Corrugated flamelet
CL    Chemiluminescence
CRZ   Central recirculation zone
DLE   Dry low emission
FSD   Flame surface density
FTF   Flame transfer function
KH    Kelvin-Helmholtz instability
LP    Lean premixed
LSA   Linear stability analysis
Nd:YAG Neodymium-doped yttrium aluminium garnet
ORZ   Outer recirculation zone
PIV   Particle image velocimetry
PLIF Planar laser induced fluorescence

PVC Precessing vortex core

S-PIV Stereoscopic particle image velocimetry

VB Vortex breakdown

WD Wet diffusion

WF Wrinkled flamelet

WSR Well stirred reactor

**Subscript**

\( \delta \) Property of reaction layer, related to the Karlovitz number \( Ka \)

\( \eta \) Kolmogorov scale property

\( f \) Flow property

\( \Lambda \) Integral scale property

\( \mathcal{P} \) Seeding particle property

\( a \) Property determined at the attached state

\( B \) Related to the velocity measured from the probe box in the plenum region

\( b \) Property determined at the blown-off state

\( BO \) Property measured at blow-off condition

\( C \) Property measured in connected plenum configuration

\( c \) Chemical property

\( crz \) Property determined from the central recirculation zone only

\( F \) Temporal fluctuation a property
\textbf{G} Trend of a property determined from the Gaussian kernel

\textbf{I} Property measured in individual plenum configuration

\textbf{i} Nozzle number

\textbf{ign} Chemical ignition property

\textbf{p} Property of burnt gas

\textbf{u} Property of unburnt gas

\textbf{Dimensionless Number}

\textbf{S} Swirl number

\textbf{S}_g Geometric swirl number

\textbf{Da} Damköhler number

\textbf{Ka} Karlovitz number

\textbf{Re} Reynolds number

\textbf{St} Strouhal number

\textbf{St}_P Stoke number

\textbf{Mathematical}

\textbf{(·)} Temporal average

\textbf{Δ} An increment or change in a variable

\textbf{δ}_{ij} Kronecker delta function

\textbf{⟨•⟩} Spatial average

\textbf{μ} Mean

\textbf{σ} Standard deviation
Magnitude of a vector

$\text{sgn}(\cdot)$ Sign function

**Variables**

$\tau_T$ Taylor length scale

$(\alpha_T D)_p$ Diffusion coefficient of thermophoresis

$\alpha_A$ Amount of stratification of air mass flow rate

$\alpha_F$ Amount of stratification of fuel mass flow rate

$\Delta \phi_s$ Amount of stratification of equivalence ratio

$\Delta \vec{x}$ Displacement of seeding particles within interrogation region

$\delta_f$ Laminar flame thickness

$\delta_r$ Reaction layer thickness

$\dot{\omega}_r$ Volumetric heat release

$\dot{m}_{A,i}$ Air mass flow rate

$\dot{m}_{F,i}$ Fuel mass flow rate

$\epsilon$ Energy dissipation rate

$\eta$ Kolmogorov length scale

$\hat{n}$ Unit normal vector

$\kappa$ Flame stretch

$\kappa_c$ Curvature

$\Lambda$ Integral length scale

$\mathcal{J}$ Time lag in calculating the temporal autocorrelation
\( \mathcal{U} \) Characteristic velocity scale of the flow

\( \dot{\omega} \) Vorticity

\( \dot{V}_F \) Flame tip displacement velocity

\( \dot{V}_P \) Local flow velocity at the flame tip

\( \dot{V}_T \) Induced velocity associated to thermophoretic effects

\( \dot{V} \) Velocity of the flow

\( \dot{x} \) Position

\( \nu \) Kinematic viscosity

\( \Omega_i \) OH intensity of the corresponding nozzle

\( \Omega_{CL,i} \) OH* intensity of the corresponding nozzle

\( \overline{\mathbf{H}} \) Viscous stress tensor

\( \phi \) Equivalence ratio

\( \rho \) Density

\( \Sigma \) Flame surface density

\( \alpha \) Complex streamwise wave number determined from linear stability analysis (LSA)

\( \omega \) Complex frequency determined from linear stability analysis (LSA)

\( a_t \) Tangential strain rate exerted on the flame

\( D \) Characteristic length of the burner

\( D_n \) Nozzle diameter

\( d_p \) Diameter of the seeding particles

\( f \) Frequency
\( I_0 \)  Flame stretch factor

\( l_i \)  Spatial lag in calculating the spatial autocorrelation

\( L_{crz} \)  Time averaged length of central recirculation zone

\( M \)  Magnification of the particle image velocimetry (PIV) imaging system

\( m \)  Real azimuthal wave number determined from linear stability analysis (LSA)

\( N_i \)  Nozzle of the combustor array

\( P_{i,j} \)  Penetration height of the swirling jet between the \( i^{th} \) and \( j^{th} \) nozzles

\( Q \)  Volumetric flow rate

\( R_h \)  Inner radius of the swirler

\( R_n \)  Outer radius of the swirler

\( S \)  Magnitude of in-plane strain

\( S_d \)  Velocity of flame surface

\( S^0_L \)  Unstretched laminar flame speed

\( S_{eff} \)  Effective inter-nozzle spacing

\( T \)  Temperature

\( t \)  Time

\( T_{ad} \)  Adiabatic flame temperature

\( T_R \)  Reactants temperature

\( u_\eta \)  Kolmogorov velocity scale

\( v' \)  Root-mean-squared of velocity fluctuations

\( v''_i \)  Velocity fluctuations at the \( i^{th} \) direction
$V_{bulk}$  Bulk velocity

$V_x, V_y, V_z$  Transverse, axial, and azimuthal components of the velocity

$x, y, z$  Spatial coordinate
Chapter 1

Introduction and Theory

1.1 Motivation

This thesis investigates the transition of flames between attached and blown-off states, in a gas turbine model combustor comprised of several interacting nozzles, which is representative of advanced design for next generation engines. The objective is to understand the effect of different geometric and operating parameters on the combustor stability near the lean operability limit. Air pollution and climate change concerns have led to legislation on emission of carbon monoxide (CO), carbonaceous particulate (PM), and nitrogen oxides (NO$_x$). Nowadays, a main challenge faced by gas-turbine engine manufacturers in designing the next generation engines is to increase the thermal efficiency while meeting the progressively stringent pollutants emission regulations, which are often conflicting goals as increasing the thermal efficiency will also increase the thermal NO$_x$ production. The conflict has ultimately led to increasingly complicated combustor designs, involving flames that are meant to interact in a particular manner. However, this interaction is poorly understood.

There are several NO$_x$ formation mechanisms [1], but NO$_x$ is primarily produced through the Zeldovich mechanism in practical gas turbine combustor conditions, with the production rate depending exponentially on temperature. As a result, most of the NO$_x$ and particulate matter emission reduction strategies are based on reducing the flame temperature, and consequently minimizing the thermal NO$_x$ formation. These led
to widespread use of both wet diffusion (WD) and dry low emission (DLE) combustors [2] in gas turbine engines. WD combustors reduce the flame temperature by injecting water or steam into the primary reaction zone, and the level of NO\textsubscript{x} emission is controlled by the amount of steam flow rate. However, there is a limit on the amount of steam injected, as it also inhibits CO oxidation to CO\textsubscript{2}, thus increasing CO emissions [3]. Nowadays, WD combustors are now being displaced since this approach reduces the thermodynamic cycle efficiency, leads to mechanical corrosion of turbine due to the presence of water impurities and substantially raises operating costs.

In contrast, DLE combustors do not rely on diluent injection, instead achieving lower primary zone temperatures by using fuel-lean (non-ideally) premixed combustion (LP) [4]. However, operating the combustor at fuel-lean conditions (i.e. near the lean blowoff limit) presents challenges for robust flame anchoring and ignition. Blowoff refers to the situations where the flame becomes detached from the location where it is anchored and is physically blown out of the burner [5]. The occurrence of blowoff can require the engine to be restarted, resulting in expensive downtime [6]. The emerging picture is that blowoff often begins with local extinction. A relatively small degree of local extinction may feedback to promote blowoff, e.g. through enabling entertainment of cold reactants into the recirculation zone and/or triggering the growth of hydrodynamic instabilities that increase the strain-rate on the flame [5]. A detailed literature review on the blowoff mechanisms will be given in Section 1.4. The aim of this project is to improve the performance of the LP-DLE combustors by studying the coupled flow and flame dynamics during blowoff and reattachment in a model gas turbine combustor that reflects many of the complexities inside the practical engines.

1.2 Combustion

Combustion is a rapid exothermic chemical reaction of fuel and oxidizer that generates light, heat, and combustion products [1]. In general, combustion can be categorized into premixed and diffusion flames depending on the degree of reactant mixing. In premixed flames, the fuel and oxidizer are perfectly mixed on the molecular level prior
to the combustion, and the flame propagates from the region of burnt products toward the fresh gas mixture. In diffusion flames, both fuel and oxidizer are transported into the reaction zone primarily by diffusion. That being said, the mixing and combustion take place quasi-simultaneously in the reaction zone. Since the chemical reactions are fast, the burning rate is often limited by the transportation and mixing process. This project only focuses on premixed flames, and a brief review is given here. Note that this is not meant as a comprehensive review of premixed combustion theory, but only a brief survey of material pertinent to this thesis. More detailed reviews are available in Refs. [7–9].

1.2.1 Laminar Premixed Combustion

Figure 1.1 illustrates the main structure of premixed laminar flames, consisting of preheat, reaction, and equilibrium zones. The preheat zone is mostly chemically inert, where the reactant gases are heated to the ignition temperature by conduction. The reaction zone can further be divided into inner and oxidation layers. Most of the fuel is consumed in the inner layer through initiation of chaining-branching reactions, where large amount of combustion radicals are formed. These radicals are oxidized and form the final product species in the oxidation layer, where the temperature reaches its maximum. In the equilibrium zone, all species reach their equilibrium states and no more heat release occurs in this region.
Three important parameters usually are used to characterize the flames. The first parameter is the equivalence ratio \( \phi \), which is defined as the ratio of actual fuel/air mass ratio to the stoichiometric fuel/air mass ratio. Stoichiometric combustion \( \phi = 1 \) occurs when all the oxygen \( (O_2) \) is consumed in the chemical reaction. The combustion process is fuel lean when \( \phi < 1 \), and fuel rich when \( \phi > 1 \). The second parameter is unstretched laminar flame speed \( S_0^L \), which is the propagation velocity of a laminar planar flame front into the unburned premixed gas. It depends on the fuel type, \( \phi \), reactant temperature \( (T_R) \), and pressure. The third parameter is laminar flame thickness \( \delta_f \) \[10\]. Various definitions have been proposed \[10, 11\], but common practice is to define the flame thermal thickness as

\[
\delta_f = \frac{T_p - T_u}{\max |\frac{dT}{dx}|}
\]  

where \( T_p \) and \( T_u \) are the burnt and unburnt temperatures, respectively, and \( \max |\frac{dT}{dx}| \) is the maximum temperature gradient.

### 1.2.2 Turbulent Premixed Combustion

Most practical combustion processes take place in turbulent environments, where the presence of turbulence in the flow can interact with the flame front and complicates the flame structure. The turbulence alters the flame surface area by inducing tangential strain-rate and wrinkling the flame \[12,13\]. Meanwhile, the heat release from combustion leads to changes in fluid properties that are crucial to turbulence, such as density and viscosity, which closes the feedback loop.

#### Characteristics of Turbulence

Turbulent flows contain eddies of wide range of length scales interacting with each other \[9\]. As a result, the instantaneous velocity at any point inside the flow field exhibits random fluctuations. The interaction between the eddies with different length scales results in an energy cascade process, where the kinetic energy of the large-scale eddies is transferred to a series of progressively smaller eddies, and finally being dissipated into thermal energy by molecular viscosity \[9\]. The characteristics of the turbulences in both
reacting and isothermal flows are usually described by length, time, and velocity scales, as well as non-dimensional parameters derived from them [9].

The size of the largest eddies in the flow is characterized by the integral length scale ($\Lambda$) [7]. $\Lambda$ depends on the flow geometric configuration and is usually on the same order of magnitude with the size of the domain, such as the nozzle diameter. The eddies of this size contain the most kinetic energy, and the time scale for the energy to transfer to eddies of smaller scales is integral time scale ($\tau_\Lambda$). The longitudinal $\Lambda$ and $\tau_\Lambda$ along the $i^{th}$ direction at location ($\vec{x}$) can be determined by calculating the spatial and temporal autocorrelations of the fluctuations of the $i^{th}$ velocity component ($v_i''$):

\begin{equation}
\Lambda = \int_0^\infty \frac{v_i''(x_i, t) v_i''(x_i + l_i, t)}{v_i''(x_i, t)^2} dt_i
\end{equation}

\begin{equation}
\tau_\Lambda = \int_0^\infty \frac{v_i''(x_i, t) v_i''(x_i, t + \mathcal{T})}{v_i''(x_i, t)^2} d\mathcal{T}
\end{equation}

where $l_i$ is the spatial lag parallel to the $i^{th}$ direction, and $\mathcal{T}$ is the time lag.

The size of the smallest eddies is proportional to the Kolmogorov length scale ($\eta$), and arises due to a balance between non-linear inertia and linear diffusion [9]. The majority of the dissipation occurs at these small scales. Kolmogorov [15] hypothesized that the eddies of this length scale were statistically isotropic and the energy transferred from larger eddies would be dissipated by viscosity, such that $\eta$, the Kolmogorov time scale ($\tau_\eta$), and the Kolmogorov velocity scale ($u_\eta$) can be determined by the energy dissipation rate ($\epsilon$) and kinematic viscosity ($\nu$) [9, 15]:

\begin{equation}
\eta = \left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}}
\end{equation}

\begin{equation}
\tau_\eta = \left(\frac{\nu}{\epsilon}\right)^{\frac{1}{2}}
\end{equation}

\begin{equation}
u u_\eta = (\nu \epsilon)^{\frac{4}{3}}
\end{equation}
Another common length scale used to describe the intensity of the turbulence is the Taylor length scale ($\tau_T$). In contrary to $\Lambda$ and $\eta$, $\tau_T$ is not a characteristic length of the dissipation eddies, rather it should be interpreted as the distance required by a large eddy convecting to a Kolmogorov eddy during its turnover time [9]. For homogeneous isotropic turbulence, $\tau_T$ can be expressed as

$$\tau_T = \sqrt{\frac{15\nu'v'}{\epsilon}} \quad (1.7)$$

where $\nu'$ is the root-mean-squared of velocity fluctuations.

Several non-dimensional numbers are commonly used to characterize turbulent premixed flames. Turbulent Reynolds number $Re_\Lambda = v'\Lambda/\nu$, where $\nu$ is the kinematic viscosity, is normally used to characterize the turbulence level in the flow. $Re_\Lambda$ is a measure of the ratio of inertial forces to viscous forces acting on a fluid.

The Damköhler number ($Da$), defined as the ratio of characteristics turnover time of a turbulent eddy within the range of $\Lambda$ ($\tau_\Lambda$) to the fluid residence time in laminar flame ($\tau_c$), which is given as

$$Da = \frac{\tau_\Lambda}{\tau_c} = \frac{\Lambda/v'}{\delta_f/S_L} \quad (1.8)$$

Flames at $Da < 1$ are characterized by turnover times of the largest eddies being shorter than the characteristic propagation time of the laminar flame. Large Damköhler number ($Da >> 1$) refers to a flame with fast chemical reaction, and the flame front structure is thin and unperturbed.

Karlovitz numbers typically are used to characterize the effect of the Kolmogorov scale eddies on the flame. Two different Karlovitz numbers ($Ka, Ka_\delta$) are commonly used. The first is defined as the ratio of $\tau_c$ to the characteristics turnover time of a Kolmogorov eddies ($\tau_\eta$), which is given as:

$$Ka = \frac{\tau_c}{\tau_\eta} = \frac{\delta_f S_L^0}{(\nu/\epsilon)^{1/2}} \quad (1.9)$$

The dissipation rate can be simplified to $\epsilon \sim \frac{\nu'^3}{\Lambda}$ according to Kolmogorov’s similarity hypothesis [15]. Assuming the molecular and momentum diffusivities are equal, this gives
\[ \nu = S_L^0 \delta_f. \text{ Eqn. (1.9) can be expressed as} \]

\[ Ka = \frac{\tau_c}{\tau_\eta} = \frac{(v'/S_L)^{3/2}}{\left(\delta_f/\Lambda\right)^{1/2}} \tag{1.10} \]

The turnover time for Kolmogorov eddies is faster than the chemical reaction at \( Ka > 1 \), such that they can penetrate into the preheat layer and enhance mixing. As for \( Ka < 1 \), turbulent motions are too slow to affect the flame front structure.

As the flow becomes more turbulent, eventually it will reach a point where the eddies in \( \eta \) are smaller than the reaction layer thickness \( (\delta_r) \), which is only a fraction of the laminar flame thickness \( (\delta_r = \delta \cdot \delta_f, 0 \leq \delta \leq 1) \). This is characterized by \( Ka_\delta \) given as:

\[ Ka_\delta = \frac{\tau_c}{\tau_\eta} = \frac{\delta_r^2}{\eta^2} = \delta^2 Da \tag{1.11} \]

For \( Ka_\delta > 1 \), the turbulent motions are fast enough to perturb the chemical reaction, and vice versa for \( Ka_\delta < 1 \).

**Combustion Regimes**

To facilitate the modelling of the effect of the turbulence with different length scales on the flame front, researchers have categorized the flame-turbulence interaction into multiple regimes based on different groups of dimensionless numbers \([16, 18]\). Figure 1.2 shows the regime diagram proposed by Peters \([17]\), which is presented in terms of the ratio of integral length scale to laminar flame thickness \( (\Lambda/f) \) and the ratio of root mean square of velocity fluctuation and the laminar flame speed \( (v'/S_L^0) \). In Fig. 1.2, the line \( Re = 1 \) separates all the turbulent flame and laminar flame regimes, situated at the lower left corner. The turbulent flame regimes can be divided into three different regimes.

The flamelet regime is in the lower right corner of the regime diagram, it can be further divided into wrinkled (WF) and corrugated (CF) flamelet regimes based on \( v'/S_L^0 \). In the wrinkled flamelet regime \( (v'/S_L^0 < 1) \), turbulence can only wrinkle or distort the laminar flame front but not interfering the chemical reaction within the flame front. The corrugated flamelet regime \( (v'/S_L^0 > 1) \) is characterised by formation of pockets of fresh
and burnt gas. In this regime, the entire reactive-diffusive flame structure is embedded within the Kolmogorov eddies \[7\]. The large eddies can push the flame front around, and cause substantial corrugation. This turbulence-flame interaction increases the flame surface area, and leads to higher consumption speed.

The broadened preheat-thin reaction (BP-TR) regime \(1 < Ka < 100\) is characterized by the broadening of the preheat layer due to penetration of small scale eddies and strong flame stretch. In this regime, the Kolmogorov scale eddies can penetrate into the preheat layer and enhance the heat transfer from the reaction zone to regions ahead of the preheat layer \[19\]–\[21\]. However, it is still larger than the thickness of the inner layer, therefore the chemical reactions are remained unperturbed.

In the broken reaction zone (BR) regime, the Kolmogorov eddies are small enough to penetrate into the inner layer and perturb the chemical reaction. The excessive heat loss to the preheat layer due to turbulence mixing may lead to local flame extinction. In this regime, there is no clear flame front and the flame propagates in a distributed way.

![Combustion regime diagram proposed by Peters \[7\].](image)

The premixed combustion regimes were based on order-of-magnitude analysis. Nu-
merous experimental studies have been performed to validate the assumptions and accesses the accuracy of the boundaries for all of the regimes in the past decade. For example, Wabel et al. [22] experimentally visualized the preheat and reaction layers for six different flames with turbulence intensities ranging from $10 \leq v'/S_L^0 \leq 243$ using simultaneous planar laser induced fluorescence of hydroxyl (OH) and formaldehyde (CH$_2$O) molecules. According to the regime diagram proposed by Peters [7], four cases belonged to the BP-TR regime, while the rest were situated in the BR zone. They found that the flame structures of BP-TR cases agreed with the prediction, however, the BR cases did not. Instead of observing broken reaction layers as Peters suggested [7], thin reaction layers, thickened preheat layers, and low local extinction rate were observed. All of these matched the characteristics BP-TR type of flames. This observation suggests the boundary of the BR regime was not correctly determined. However, more experimental data should be collected for different burner configurations to access this conclusion.

### 1.3 Flame Stabilization

Most practical gas turbine engines require high volumetric heat release rates, and the flow velocities are in the order of $10 - 100$ m/s [24]. In contrast, laminar flame speeds at gas turbine conditions are on the order of $0.1 - 10$ m/s, and turbulent burning velocities tend to be about on order of magnitude greater [25]. A major challenge faced by the gas-turbine designer is determining how to hold and stabilize the slowly propagating flame
against the high-speed flow. The general practice is to create a recirculation region, such
that the hot products are allowed to continuously interact with the incoming reactants
to sustain the combustion process. Generally, this can be achieved by several means as
shown in Fig. 1.3: (1) by directing part of the flow opposed-to or normal-to the main
stream (i.e. aerodynamically stabilized), (2) by inserting a bluff-body in the stream, or
(3) by introducing sudden expansion or a step in the enclosure (dump combustors) [26].
Aerodynamic stabilization often is achieved through swirl-induced vortex-breakdown. All
of them are well-established and only a brief discussion on the first two methods is given
here.

1.3.1 Swirl Stabilization

The addition of swirl to stabilize the flame is commonly found in gas turbine combustors
[1, 27]. The swirling flow can be generated using an array of vanes positioned either axially
or radially, through inlet tangential flow injection, or by other means. The strength of
the swirl is quantified by the swirl number ($S$), which is defined as the ratio of axial flux
of tangential momentum to axial flux of axial momentum [28]:

$$S = \frac{\int_0^\infty \rho (V_y V_z) r^2 dr}{L \int_0^\infty (\rho V_y^2 + (P - P_\infty)) r dr}$$

where $L$ is the characteristic length, $V_y$ is the mean axial velocity, $V_z$ is the mean azimuthal
velocity, $\rho$ is the fluid density, $P$ is the fluid pressure, and $P_\infty$ is the ambient pressure,
respectively.

Due to the difficulties in determining the swirl number experimentally, the geometric
swirl number, $S_g$, is frequently used to characterize the swirl based on the geometry of
the swirl-generating system. For vane-type swirlers, it can be expressed as [2]:

$$S_g = 2 \left[ \frac{1 - \left( \frac{R_h}{R_n} \right)^3}{1 - \left( \frac{R_h}{R_n} \right)^2} \right] \tan \varphi$$
where $R_h$ and $R_n$ are the inner and outer radii of the nozzle, $\varphi$ is the effective swirler vane angle ($\tan \varphi = \frac{V_y}{V_z}$).

Two phenomena are of particular importance in swirling flow for combustors, which are vortex breakdown (VB) and formation of precessing vortex cores (PVC).

**Vortex breakdown**

Vortex breakdown (VB) refers to a sudden and significant change in characteristic ratio of tangential and axial velocity components in a vortex [29]. Faler and Leibovich studied VB with water flow visualization, and classified VB into seven types depending on the $Re$ and swirl velocity at the wall, namely bubble, conical, spiral, helix, and combinations thereof [30]. In turbulent flows, only the first three modes were observed [29]. The bubble mode is usually observed in gas turbines [2].

Figure 1.4 shows the mean flow structure in a typical gas turbine combustor [2]. The bubble type of VB is characterised by the formation of central recirculation zone (CRZ), which is a region with an internal stagnation point on the vortex axis that is followed by reversed axial flow. The formation of a CRZ is due to coupling between the axial and tangential velocity components. The centrifugal force arising from the swirling flow generates a radial pressure gradient that entrains non-swirling fluid from the periphery to the center and forms a vortex core. At the same time, an adverse axial pressure gradient is formed as the swirl intensity decreases along the axis. At a sufficiently high swirl level, the kinetic energy of the fluid cannot overcome the adverse axial pressure gradient, and flow reversal occurs. In a confined environment, VB may also lead to formation of outer recirculation zones (ORZ), located between the swirling jet boundary and the confinement wall as shown in Fig. 1.4.

**Precessing vortex core**

A precessing vortex core (PVC) is three-dimensional unsteady asymmetric flow structure, developed when a central vortex core begins precessing around the axis of symmetry at a well-defined frequency. Figure 1.5 shows a single PVC structure in an isothermal flow [31]. Syred and Beer observed that PVCs are usually located on the boundary of the
reverse flow zone, as shown in Fig. 1.4. The onset of PVC is related to VB. For example, Anacleto et al. [32] found that the PVC was formed along with the triggering of VB when $S > 0.5$ in isothermal flow.

The precession frequency for a given geometry and thermal state is usually characterised by constant Strouhal number

$$St = f_{PVC} D^3 / Q$$  \hspace{1cm} (1.14)
where $f_{PVC}$ is the frequency, $D$ is the characteristic length of the burner, and $Q$ is the volumetric flow rate. The frequency and amplitude of the precession are complicated functions of equivalence ratio ($\phi$), swirl strength, flow rate, and combustion mode. The PVC precession frequency increases with swirl strength and $\phi$. Once a critical swirl strength is reached, the PVC transforms from a single to a double helix structure precessing at a much lower frequency. Syred et al. also found that premixed or partially premixed combustion tended to increase the PVC strength, while non-premixed combustion suppressed the amplitude by at least an order of magnitude.

The presence of PVC may enhance mixing of the reactants by increasing the turbulence, but at the same time it can induce flame stretching and lead to local extinction. Several studies have shown that PVC is linked to various forms of combustion instabilities, such as flame blowoff, and thermoacoustics oscillation in swirl-stabilized combustors. Therefore, it is beneficial to predict the occurrence and origins of the PVC while designing the combustor. In recent years, numerous researchers have successfully applied linear stability analysis (LSA) to do so. LSA involves first decomposing the velocity profile at certain axial location into three components, namely mean, coherent, and stochastic fluctuation, then substituting into the Navier-Stokes equations. The stability properties of the flow, namely complex streamwise wave number ($\alpha$), complex frequency ($\omega$), and real azimuthal wave number ($m$), can be obtained by solving the eigenvalue problems. In LSA, PVC often appears as a co-rotating single-helical mode with $m = 1$ after the flow undergoes a supercritical Hopf bifurcation to a self-excited oscillatory global mode.

### 1.3.2 Bluff-Body Stabilization

Figure 1.6 shows the main flow features in the bluff-body flow field, which consists of boundary layer along the bluff-body, separated free shear layers enclosing the recirculation zone, and the wake region. For flow falls with Reynolds numbers $Re = \frac{UL}{\nu} \leq 200,000$, where $U$ is the characteristic flow velocity, $D$ is the characteristic length of the bluff body, and $\nu$ is the kinematic viscosity, the dynamics of the downstream flow field is governed by the interaction between turbulence, shear layer and the wake processes, and they
are subjected to two different forms of hydrodynamic instability, namely the Bernard-Von Kármán (BVK) and Kelvin-Helmholtz (KH) instabilities. The BVK instability is periodic and it is characterized by large-scale asymmetric vortex shedding, leading to sinuous wake structure with a characteristic frequency \( f_{BVK} \) given as (1.15):

\[
f_{BVK} = \frac{St}{D} U
\]

where \( St \) is the Strouhal number.

BVK disturbances are absolute instabilities, as they are self-excited and independent of external disturbances [5]. This type of instability dominates the flow field near the bluff-body and decays with downstream distance, while the dissipation rate increases with turbulence intensity [41]. Roshko et al. [41] experimentally showed the periodic oscillation associated with BVK instability could be detected at downstream distances up to 100 times of the bluff-body diameter \( y/D = 100 \) in laminar flow \( (Re = 150) \), but no trace of it was found even at a further upstream location \( y/D = 50 \) in flow with
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$Re = 10,000$.

KH instability originates within the separated shear layers. Owing to its convective nature, small disturbances amplify in the streamwise direction and roll up into vortices. The small vortical structures may roll up to stronger vortices as they convect downstream, which is known as pairing. The characteristic frequency of the vortex shedding is

$$f_{KH} = 0.0235 f_{BVK} Re^{0.67} \quad (1.16)$$

For flow with high $Re$, the frequency of KH instability is much higher than BVK instability.

Heat release from combustion can substantially modify the flow behind the bluff-body. The impact of heat release on the hydrodynamic instabilities can be deduced from the vorticity ($\vec{\omega}$) transport equation:

$$\frac{D \vec{\omega}}{Dt} = \left( \vec{\omega} \cdot \nabla \right) \vec{V} - \vec{\omega} \left( \nabla \cdot \vec{V} \right) - \frac{\nabla \rho \times \nabla P}{\rho^2} + \frac{\nabla \times \nabla \cdot \overline{H}}{\rho} \quad (1.17)$$

where $\vec{V}$ is the velocity field and $\overline{H}$ is the viscous stress tensor. The different terms in Eqn. (1.17) represents the effects of vortex stretching, volumetric expansion (dilatation), baroclinic torque due to inclination of the flame with respect of the flow (or misalignment between density and pressure gradients), and contribution of viscous diffusion and dissipation. The flame predominantly impacts vorticity transport through dilation, baroclinic torque, and the impact of temperature on viscosity.

Erickson et al. computationally demonstrated that at high temperature ratios ($T_p/T_u > 1.5$), BVK instability was suppressed by the dilatation and baroclinic generated vorticity; the wake was dominated by the BVK instabilities at low temperature ratios ($T_p/T_u < 1.5$) as demonstrated in Fig. 1.7 [42]. Similarly, Emerson et al. [43] experimentally confirmed that the types of hydrodynamic instability presented in the flow depended on the density ratio between unburnt reactants and burnt products ($\rho_u/\rho_p$). However, the instability transition did not happen abruptly at certain density ratio. Rather, intermittent
behaviours were observed at multiple intermediate density ratios. Numerous studies suggested that hydrodynamic instability played an important role in flame liftoff, which will be discussed in Section 1.4.
1.4 Lean Blowoff Mechanism

Blowoff refers to the situations where the flame becomes detached from the location where it is anchored and is physically blown out of the burner [44]. As previously mentioned the trend towards LP-DLE combustion gives rise to concerns regarding flame blowoff. The occurrence of blowoff can require the engine to be restarted, resulting in expensive downtime [45].

Flame blowoff has been extensively studied in different single-nozzle combustors to elucidate the underlying mechanisms, and a wide variety of blowoff correlations have been proposed. An early study by Longwell et al. [46] considered the bluff-body recirculation zone as a well stirred reactor (WSR), and blowoff was proposed to occur when the rate of entrainment of reactants is out-of-balance with the rate of burning. However, the bluff body recirculation zone is not perfectly mixed in practical combustor, which makes the WSR model inadequate in explaining the blowoff process [5, 47]. Kundu et al. [48] also proposed a similar idea based on energy transfer between the recirculation zone to the fresh reactants in the bluff body stabilized flame. They suggested that the outer edge of the central recirculation zone and the mainstream closely resembled a turbulent mixing zone between the combustible stream and hot recirculating gas. A flame was developed at some distance downstream of the bluff-body due to mixing and heat exchange, where flame blowoff occurred when the heat required by the combustible stream exceeds those available from the recirculating flow [48]. However, it is noted that premixed flame act as an interface between products and reactants, there is no direct contact between them, except from the possible penetration of the Kolmogorov eddies into the preheat layer. Hence, the heat exchange is only possible when extensive local extinction events occur [5]. Zukoski and Marble [49] considered the onset of blowoff from a slightly different perspective. They suggested that blowoff occurred when the time scale of reactant and product interaction in the shear layer exceeded the chemical ignition time ($\tau_{ign}$). The correlation they proposed relates the blowoff velocity with the $\tau_{ign}$ and the characteristic length of the flame holder. Instead of considering the heat transfer alone, Yamaguchi suggested hydrodynamics also played an important role in flame blowoff. The
local extinction due to excessive flame stretching allowed entrainment of cool reactants into the recirculation zone [50], and blowoff occurred when the temperature inside the recirculation zone was below the critical temperature. Nevertheless, all of these criterion can be essentially reduced to a similar form of Damköhler number blowoff criterion, which is the ratio of fluid mechanic and chemical kinetic time, $Da_{BO} = \frac{\tau_{res}}{\tau_{chem}}$. However, it is difficult to determine which phenomenon best described the blowoff process based on the $Da_{BO}$ correlations alone, since the definition of the length and time scales varied, which leads to significant scattering of data [5, 51].

Flame Dynamics Near Lean Blowoff

It is well known that the flame blowoff is not an abrupt process, rather the flames are highly unsteady when they are approaching blowoff [6, 35, 36, 51–58]. Nicholson and Field [52] visualized the large-scale pulsation of the bluff-body stabilized flame as it approached to lean blowoff condition using Schlieren photography, where the flame repeatedly lifted and reattached from the bluff-body and continuously shrunk in size before completely extinguished. Hertzberg et al. [53] also observed a similar kind of oscillation. In addition, the spectra of the velocity fluctuation measurement in the bluff-body wakes demonstrated a growing amplitude of a narrow peak frequency, indicating the emergence of the BVK instability. They suggested the velocity fluctuation prior the flame lean blowoff was a result of complex interaction between an increment of ignition time, local extinction, and emergence of absolute instability.

Advances in multi-kHz repetition rate diagnostic techniques have allowed researchers to examine the flame dynamics near the blowoff limits more closely. Nair et al. [6] used particle image velocimetry (PIV) and Mie scattering measurements to describe blowoff of bluff-body stabilized flames as a two stages process. The first stage was characterized by frequent local extinction and re-ignition due to high local strain-rate/dissipation-rate along the flame front, the flame could theoretically stay in this intermediate state indefinitely. Complete flame blowoff was the result of coupling between the large-scale wake dynamics and flame local extinctions. High degrees of local extinction resulted in emergence of hydrodynamically unstable BVK vortex shedding that was previously
suppressed by heat release in the near-wake region of the bluff-body. The combination of vortex shedding and flame local extinction allowed entrainment of high density cold reactants into the recirculation zone, which further weakened the flame stabilization, and eventually led to complete blowoff. Numerous studies have reported similar local extinctions and emergence of hydrodynamic instabilities, such as BVK and PVC vortical structures, that were previously suppressed by the flame heat release prior to blowoff in different bluff-body and swirl stabilized flames \[35, 36, 51, 55, 56\].

However, some studies suggested the emergence of the hydrodynamic instabilities may not be always necessary. For example, Chaudhuri et al. \[54\] also observed a series of local flame extinctions in the shear layers due to high local stretch rate prior blowoff. However, they argued that the high stretch rate was due to the overlapping of the flame front with the convecting KH vortices along the shear layer rather than the emergence of BVK instability. Dawson et al. \[57\] and Kariuki et al. \[58\] argued that the large-scale vortical structure are not important for the blowoff of flames that are short relative to the flame holder size. Instead they suggested blowoff in this type of flames was primarily attributed to excessive flame stretching and heat loss associated with entrainment of cold reactants. Kariuki et al. \[58\] showed that the flame contracted towards to the bluff-body and formed a ‘M’ shape flame as the blowoff condition was approached. The high rate of curvature experienced by the flame base, along with heat loss to the reactants, promote further flame extinction, until the flame was completely extinguished.

1.5 **Effect of Nozzle-Nozzle Interaction**

While majority of the experimental studies on flame blowoff have been conducted in single-nozzle combustors, practical systems often employ more complex arrangements. For instance, practical DLE combustors generally consist of multiple fuel nozzles in which a monolithic flame breaks into multiple small flame systems to further reduce the NO\textsubscript{x} emission and improve the operational characteristics \[59\], where the flow and flames between nozzles are allowed to interact in a complex manner.

Numerous researchers have demonstrated that cross-nozzle interaction has a pro-
found impact on the basic flow structure, even without the presence of combustion. For example, Kucukgokoglan et al. [60] showed that the decay of swirl from the four counter-rorating swirling flows produced by a $2 \times 2$ array of uniform nozzles was asymmetrical, with the two nozzles at the right decaying much faster. Kao et al. [61] studied the aerodynamics in a linear array of five radial swirlers. The flow structure was asymmetric in isothermal conditions, with the size of the recirculation zones alternating along the array in a pattern that depended on the inter-swirler spacing and wall confinement.

The presence of combustion further complicates cross-nozzle interactions. Numerous studies have demonstrated that the presence of multiple interacting flames in the system will change both global and local flame behavior [57, 62, 63], which affects the flame structure, operating envelope, response to different combustion instabilities, and combustor ignitability.

For instance, Worth and Dawson [64] addressed the effect of inter-nozzle spacing on the flame topology of the interacting region between two bluff-body stabilized flames. The merging location moved upstream as inter-nozzle spacing decreased, and eventually formed a vertical turbulent jet-like flame structure in the interacting region. In addition, reducing the inter-nozzle spacing significantly increased the flame cusp formation as a result of higher turbulence level, hence localized merging of the flame fronts was promoted. Fanaca et al. [62] showed that, for the same internal nozzle geometry, the flow changed from a wall jet flow in a single-nozzle combustor to a free jet flow in an annular combustor, which resulted in changes to the flame transfer function (FTF) for longitudinal thermoacoustic instabilities. Furthermore, couple of studies reported additional forms of thermoacoustic instabilities, in the form of either spinning or standing waves, were also observed in the multi-nozzle combustor [65–67]. Worth et al. examined the circumferential instabilities with OH$^*$-CL in an annular combustor consisted of 12, 15 or 18 turbulent premixed bluff-body stabilized flames, corresponded to inter-nozzle spacings of 2.33, 1.87, and 1.56 times of the nozzle diameter. With this combustor, they demonstrated that the flame asymmetry, and the frequency and amplitude of the spinning waves increased with decreasing inter-nozzle spacing as shown in Fig. 1.8.

Dolan et al. [68, 69] found that, in a two-swirler combustor with small inter-swirler
spacing, the presence of nozzle-nozzle interaction caused dramatic asymmetry in reacting conditions and subsequently penalized the lean operability limit relative to configurations with larger inter-swirler spacing. Kariuki et al. visualized the blowoff behavior of two interacting non-swirling and swirling bluff-body stabilized premixed flames with 5 kHz OH$^*$ chemiluminescence, and compared this to the blowoff behavior of the flames in a single nozzle environment [70]. Similar to the finding in Dolan et al. [68], the presence of inter-nozzle interaction penalized the lean operability limit. In particular, the inter-nozzle spacing played a crucial role in the flame behaviours prior to blowoff. The blowoff began with disintegration of the flame near the anchoring point for the combustor with low inter-nozzle spacing, whereas the blowoff process started with local extinction of downstream flame fragments when the inter-nozzle was large. The authors showed that, during the later part of the blowoff process, the lifted nozzle attempted to re-ignite the attachment point by propagating upstream through the recirculation zone or along the wall of the combustor enclosure. In addition, the authors demonstrated that the swirling direction can affect the flame shape and the duration of the blowoff event, which was attributed to the changes in flow pattern and recirculation zones.

The effect of inter-swirling spacing on ignition in annular combustors has been investigated by several recent studies, e.g. [63, 71]. Figure 1.9 demonstrates the two different ignition mechanisms observed in a five-swirler linear-array combustor with two different
inter-nozzle spacings; the ignition process was achieved by spanwise flame propagation in combustors with low inter-nozzle spacing, and by streamwise convection with high inter-nozzle spacing. The spanwise propagation involved flame kernels rapidly being captured by the adjacent swirling flow, propagating/convecting laterally into the central recirculation zone of the adjacent nozzle, and subsequently developing along the axial direction. This process was enabled by the short travel time of flame segments from one nozzle to another. The time required for flame motion across nozzles increased with inter-nozzle spacing, and was subjected to higher variability, eventually resulting in a transition to the streamwise mechanism at a particular nozzle spacing.

1.6 Main Objectives

The main objective of this thesis is to improve the ability to understand lean blow-off in LP-DLE combustors with inter-nozzle interactions. To achieve the main objective, the project can be further classified into three specific objectives. 1) To develop a laboratory-scale multi-nozzle combustor that replicates geometric features of practical interest to LP-DLE combustors. 2) To explain the effect of different geometric and operating parameters, such as inter-nozzle spacing, reactant feeding configuration, \( \phi \), and stratification, on the stability limit of the combustor. 3) To understand the coupled flame-flow dynamics during blowoff and reattachment events with high-repetition rate
laser diagnostics.

1.7 Overview

The thesis is organized as follows. The fundamental background regarding turbulent combustion, flame blowoff mechanisms, and cross-nozzle interaction revealed in previous experimental studies have been reviewed in the current chapter. The remainder of this thesis are dedicated to understanding the blowoff mechanism and examining the effect of different geometric and operating parameters on the lean performance of a multi-nozzle combustor, consisting of a linear array of five swirlers, that was explicitly designed to allow rigorous control of the reactant feed. In particular, two different feeding configurations were of the interest. Chapter 2 details the laser-based diagnostics techniques used to measure the flow field and the flame topology, the design of the multi-nozzle combustor, and the reactant feeding configurations. The calculation of the several parameters used to interpret the experimental measurements will also be discussed in this chapter. Chapter 3 and 4 present the results obtained from the multi-nozzle combustor operating with different feeding configurations. In the first configuration, reactants to each nozzle were fed through a common plenum, and the flow was allowed to freely distribute across the rig in a similar fashion to the practical combustors. Chapter 3 will discuss the effect of the coupling occurred inside the plenum region on the intermittent blowoff dynamics inside the multi-nozzle combustor. In the second configuration, each nozzle had an independent plenum that was fed from a dedicated set of electromechanical mass flow controllers, thereby allowing us to identify the effect nozzle-spacing, uneven flow distribution, and stratification on the lean performance. The effect of each on the lean blowoff limits will be discussed in Chapter 4. It was found that the flames in both reactant feeding configurations behaved differently. It is hypothesized that the upstream cross-nozzle coupling played an important role in this, and statistical analysis has been performed to further understand the role of it. The discussion of it will be covered in Chapter 4. The thesis is closed in Chapter 5, with conclusions and suggestions for further development to understand the multi-nozzle interaction on different combustion instabilities.
Chapter 2
Experimental Approach

This chapter describes the methodology that was applied during the experiments, including a brief review of the laser diagnostics used to acquire the data and a description of the combustor geometry. Non-intrusive optical measurement techniques were used to measure the flame-flow interactions at different operating conditions. The first section provides an overview of the physical principles of each measurement technique. The details of the combustor design and the experimental setup are described in the following section. Lastly, the analysis of essential parameters will be discussed.

2.1 Diagnostic Techniques

2.1.1 Chemiluminescence Imaging

Chemiluminescence (CL) refers to the radiative emission from electrically excited atoms or molecules formed by chemical reactions. The first application of chemiluminescence to flame characterization date back to the 1950s, when Clark correlated the chemiluminescence of CH\textsuperscript{*}, OH\textsuperscript{*}, CO\textsubscript{2}\textsuperscript{*}, and C\textsubscript{2}\textsuperscript{*} to flow rate, fuel-mixture, and equivalence ratio (\(\phi\)) of a Bunsen burner flame [72]. He found that the intensity of the chemiluminescence is proportional to \(\phi\) under lean conditions for the ethylene-air flame, however the sensitivity is species specific. The finding from Clark drew the attention in the combustion community to explore the feasibility in utilizing CL imaging for flame characterization. With the
assumption that chemiluminescence is proportional to the heat release rate, numerous studies obtained the spatially-resolved flame heat release rate by measuring the CL of the aforementioned species [73]. However, Najm et al. [74] pointed out that this proportionality assumption breaks down if the dilution, radiation loss, or strain/curvature effects are not negligible. Therefore, the CL measurements in such flow conditions must be interpreted carefully. Furthermore, since CL is a line-of-sight integrated technique, the measured signal can only be used as a qualitative indicator of the global flame heat release distribution and dynamics. In this work, OH*-CL is used to characterize basic features of the flame during the initial combustor characterization.

2.1.2 Planar Laser-Induced Fluorescence

Laser induced fluorescence (LIF) is a common technique used in combustion diagnostics to gain information about the physico-chemical state of the flame within the measurement volume by measuring the fluorescence signal emitted by the probed species. The probed species, which generally are molecules, can be combustion-relevant radicals, naturally occurring molecules, or fuel tracers. For example, hydroxyl (OH), formaldehyde (CH\(_2\)O), carbon monoxide (CO), acetone (CHO\(_3\)) and 3-pentanone are commonly used fluorescent species [75].

LIF is based on the excitation of probe molecules from a lower energy state, usually the ground state, to a higher energy state using laser radiation, with the wavelength tuned to the specific absorption line of the targeted molecules. The concentration of the probe molecule or temperature can theoretically be determined by measuring the subsequent spontaneous fluorescence emitted by the excited probe molecules as they return to the ground state. This property is useful for combustion research, since knowing the location and relative quantities of certain species of interest provides information about the reaction progress.

To decide which combustion species should be used as probe molecules for LIF, or its planar equivalent PLIF, one should consider the following properties. First of all, the targeted molecule must have an absorption wavelength that is accessible to a radiation source. On the other hand, the rate of radiative decay of the excited state also plays
an important role, as the intensity of the emission is inversely proportional to radiative decay rate. Hence, the radiative decay must be slow enough such that the intensity of the fluorescence emitted by the probe molecules is strong enough to be captured with a measurement device [75]. Finally, the species must represent some useful information regarding combustion.

In this project, two intermediate species of particular interest are the hydroxyl radical (OH) and the formaldehyde molecule (CH$_2$O). The effective fluorescence lifetime of OH radicals is only of a few nanoseconds, hence, the fluorescence process can be assumed to be instantaneous. In the turbulent combustion regime of relevance here, OH is rapidly formed in the reaction zone, reaching super equilibrium concentrations before relaxing to equilibrium in the products. While OH is present in all hot products above approximately 1500 K, its rapid formation in the reaction zone suggests that the reaction zone topology can be deduced from the gradient of OH [13]. Nevertheless, some ambiguity exists in using OH gradients to detect reaction zones, as this requires an arbitrary threshold on the gradient.

Whether or not a particular OH boundary represents reacting flames or is locally extinguished can be sensitive to selection of this threshold. Hence, CH$_2$O-PLIF was also used to gain additional insight on the flame structure in the initial analysis. In contrast to OH, CH$_2$O is produced in the initial stages of fuel oxidation and consumed in the exothermic reaction layer. However, CH$_2$O diffuses upstream and therefore is generally taken to be a good indicator of the preheat layer. The pixel-by-pixel multiplication of OH and CH$_2$O-PLIF signals can be used to visualize the local reaction structure [22] [76] [77]. Paul et al. [78] showed that the product of these two PLIF signals was proportional to the rate of HCO radical formation due to the reaction CH$_2$O + OH $\rightarrow$ HCO + CO. Meanwhile the formation of HCO is the final step along one of the major pathways to the production of CO and a substantial amount of heat is released along this pathway [79]. As a result, HCO concentration is correlated directly with the heat release rate. Since measuring the HCO concentration directly with PLIF is problematic owing to its short fluorescence lifetime, low fluorescence signal, and relatively low concentration, it is common to use the product of simultaneous OH and CH$_2$O-PLIF measurement as an
alternative approach to measure HCO \cite{79,80}.

### 2.1.3 Stereoscopic Particle Image Velocimetry

Particle image velocimetry (PIV) is an imaging-based technique that has been widely adopted to capture the two or three components of the velocity field within a planar slice of a flow \cite{12,14,54,81}. The planar nature of this technique allows one to visualize the spatial flow features, such as shear layers and recirculation zones. The principle behind PIV involves first seeding tiny tracer particles to the flow, illuminating the particles within the plane of interest, and capturing the light scattered by the particles with a camera. In PIV, two particle scattering images are recorded within a known separation time $\Delta t$. Each image is then divided into interrogation areas, from which a velocity vector at each measurement instance is obtained by measuring the displacement of the group of seeding particles within the interrogation area. The overall particle displacement within a interrogation area, $\Delta \vec{x}$, is identified by the peak in the cross-correlation between the intensities in images $I_1(x,y)$ and $I_2(x+dx(x,y),y+dy(x,y))$. The velocity vector $(\vec{V})$ for each individual interrogation box can be estimated as:

$$V_i = \frac{\Delta x_i}{M \cdot \Delta t} \quad (2.1)$$

where $M$ is the magnification of the imaging system.

The limitation of the classical PIV technique is that out-of-plane motion cannot be measured. For example, a particle with purely out-of-plane displacement (in the direction perpendicular to the laser sheet) can be erroneously interpreted as a non-zero in-plane displacement with the classical PIV technique \cite{82}. This type of out-of-plane motion is potentially significant in highly turbulent and/or three dimensional flow. To account for the out-of-plane component, the stereoscopic PIV (S-PIV) technique was developed. The measurement setup for a S-PIV system is similar to the classical two-component PIV, except now a second camera is added to the system and both cameras are arranged along different viewing axes. Figure 2.1 shows several examples of camera light-sheet configurations typically used in S-PIV acquisition \cite{81}. Among these three configurations,
configuration A receives strong forward-scattering signal for both cameras. In configuration B, one of the cameras receives weaker backward-scattering signal, which leads to imbalance image intensity for both cameras. The scattering signal for configuration C is weaker than configuration A, where both cameras receive backward scattering signal, but the image intensity for both cameras is similar. By having the displacement vector projected into two planes with different directions, the out-of-plane velocity component can be reconstructed by comparing the differences in the calculated particle displacements from each camera, while the accuracy and precision of this component increases as the angle between both cameras approaches $90^\circ$ [81].

However, due to the limited depth of field of the camera lenses, this configuration
Chapter 2. Experimental Approach

suffers from non-uniform focusing across the field of view. To overcome this defocusing issue, one should arrange the cameras and lenses such that they satisfy the Scheimpflug criterion as shown in Fig. 2.2 in which the object plane, lens plane, and image plane are nominally collinear [81]. However, this optical arrangement introduces perspective distortion or warping, which leads to an inhomogeneous magnification factor within the field-of-view. Hence, a full spatial calibration matrix has to be determined for each camera. This can be done by mapping a common image space before calculating the instantaneous velocity in each interrogation region.

The quality of the PIV/S-PIV measurements depend on the properties of the tracer particles. An important parameter is the ability of the tracer particles to follow the smallest resolved flow time-scales, which is characterized by the particle Stokes number \((St_p)\). \(St\) is defined as the ratio of the particle relaxation time \((\tau_p)\) to the relevant flow time \((\tau_f)\), given as [81]

\[
St_p = \frac{\tau_p}{\tau_f} = \frac{\rho_p d_p^2}{\mu 18 \tau_f} \quad (2.2)
\]

where \(\rho_p\) is the particle density, \(d_p\) is the particle diameter, and \(\mu\) is the dynamic viscosity of the fluid. The tracer particles can accurately follow the flow when \(St_p \leq 1\). However, there is caveat to that, as the scattering intensity decreases quadratically with \(d_p\). Hence, one needs to find the optimal particle size that is small enough to trace the flow accurately while providing sufficient scattering intensity. Typically, the diameter of the solid seeding particles used in combustion diagnostics is approximately 0.1 to 5 \(\mu\)m [81].

The second important parameter is how the particles respond to the presence of heat release. The presence of high temperature gradient will push the seeding particles within the flow down the temperature gradient from the hot to the cold gases due to the difference of momentum, which is known as the thermophoretic effect [83, 84]. The induced velocity associated to thermophoretic effects can be estimated as:

\[
\vec{V}_T = (\alpha_T D)_p \left( \frac{-\nabla T}{T} \right) \quad (2.3)
\]

where \((\alpha_T D)_p\) is the diffusion coefficient of thermophoresis.

Along with the properties of the seeding particles, the number of the tracer particle
within an interrogation region (seeding density) also plays an important role [85]. For a given interrogation size, as the number of tracer particles increases, the probability of finding another finite region with similar intensity and pattern decreases. This increases the accuracy of the measured displacement, as it is calculated based on image correlation. However, high seeding density can alter the characteristics of the flow. Hence, the density should be sufficiently high to observe particles in each interrogation box, but low enough such that it will not impact the flow field.

## 2.2 Experimental Setup

### 2.2.1 Combustor Rig

The multi-nozzle combustor test facility used in this research was designed by the Experimental Engine Laboratory in collaboration with Siemens Canada to replicate geometric
features of practical interest in DLE combustors. In addition, two reactants feeding config-
urations were designed to isolate the effects of different aspects of the system on the
combustor’s fuel-lean performance.

Figure 2.3 shows a schematic drawing of the combustor in its two configurations. In
general, the combustor rig consists of an array of five axial swirlers with inter-nozzle
spacing of 1.34 times of the nozzle diameter ($D_n = 16.4$ mm). The center of each swirler
is comprised of a bluff-body with a flat trailing edge as shown in Fig. 2.4. The outer
nozzle on each side of the combustor ($N_0$ and $N_4$ in Fig. 2.4) serve to isolate the center
nozzles from effects of the walls; laser diagnostics were performed only at the centre three
swirlers ($N_1$ – $N_3$ in Fig. 2.4).

**Connected Plenum Configuration**

The first configuration consists of a common plenum, in which the flow was allowed to
naturally distribute between the nozzles. This configuration more closely resembles the
feeding system in practical combustors. The multi-nozzle combustor was operated with
two different fuels, namely pure methane (CH$_4$), and a blend of 20%:80% H$_2$:CH$_4$ by vol-
ume. The air was preheated by an air heater (Tutco-Farnam 7550-A40) to a temperature
slightly higher than the targeted $T_R$ and mixed with the fuel far upstream of the settling
chamber. The temperature of the perfectly premixed fuel-air mixture was monitored by
a Type K thermocouple upstream of the settling chamber as shown in Fig. 2.5. The
reactants at $T_R$ entered settling chamber through the four symmetrically aligned 3/4”
holes and straightened by the homogenizing perforated plate inside the settling chamber. The fuel-air mixtures were then supplied to the common feed plenum via the plenum-premixer plate, before entering the optically accessible combustion chamber through the five nozzles.

Figure 2.6 shows representative time-averaged OH\(^*\)-CL fields taken from 5000 consecutive CL measurements for multiple conditions with the same flame characteristics \((T_{ad} = 1735 \text{ K}, \ T_R = 500 \text{ K})\) but different \(V_{bulk}\). At conditions that were far from blowoff (Fig. 2.6a), there was no interaction between the adjacent nozzles near the dump plate, and the heat release was relatively weak near the flame base. At approximately \(y/D_n = 0.5\), the flames from adjacent nozzles merged together and formed a main heat release region located at \(0.6 \leq y/D_n \leq 1\). The heat release region shifted further downstream with increasing \(V_{bulk}\). When the \(V_{bulk}\) was increased to 20.9 m/s, the three central flames began to undergo an on-going process of detaching and reattaching to the bluff-bodies in a stochastic manner (Fig. 2.6b), which is referred to intermittent liftoff here.
Chapter 2. Experimental Approach

(a) Stably Attached $V_{bulk} = 20.9$ m/s
(b) Intermittent Liftoff $V_{bulk} = 24.0$ m/s
(c) Intermittent Liftoff $V_{bulk} = 28.6$ m/s
(d) Competely Liftoff $V_{bulk} = 36.9$ m/s

Figure 2.6: Representative time-averaged OH* fields taken from 5000 consecutive CL measurements for cases with the same flame characteristics ($T_{ad} = 1735$ K, $T_R = 500$ K) but different $V_{bulk}$.

This is a statistically stable state, in that the flames could maintain these transitions indefinitely. The flames spent a greater portion of the time in the lifted configuration with further increases in $V_{bulk}$, as indicated in Fig. 2.6c. All five flames were lifted 100% of the time when $V_{bulk}$ was increased to 36.9 m/s, and merged into one ‘U’ shape flame stabilized at a certain downstream location as demonstrated in Fig. 2.7. The location where the flames stabilized moved downstream as $V_{bulk}$ was further increased.

Similar changes in flame dynamics with respect to the $V_{bulk}$ were observed for flames with different combinations of $T_{ad} = 1650, 1735$ K and $T_R = 300 - 500$ K. Each experiment was started at a $V_{bulk}$ at which all the flames were stably attached to the
Chapter 2. Experimental Approach

(a) Wall nozzles intermittent liftoff and three central nozzles liftoff $V_{\text{bulk}} = 20.9$ m/s

(b) Completely Liftoff $V_{\text{bulk}} = 36.9$ m/s

Figure 2.7: Representative image of the flames at higher $V_{\text{bulk}}$.

bluff-bodies. The flow rates of both air and fuel then were simultaneously increased while keeping the $T_{ad}$ to be constant. Eventually the combustor reached a small range of operating conditions at which the flames exhibited intermittent behavior; the flames intermitently blew-off and subsequently reattached to the bluff-bodies. Further increasing the $V_{\text{bulk}}$ would lead to complete blowoff of the combustor. Figure 2.8 shows the stability characteristics of the combustor.

Over 30 cases were measured as part of the experimental campaign. To ensure repeatability, at least three measurements were performed for each condition. However, only a subset of important conditions is presented in this thesis. The operating conditions, including characteristics of flame and turbulence, are summarized in Table 2.1. The $Ka$ and $Da$ numbers are estimated at the exit plane, while the laminar flame thermal thickness and speed were calculated using Cantera with the GRIMech 3.0 chemical mechanism.
Figure 2.8: Stability characteristics of the combustor with normal premixer-plate configuration (△ stable, □ intermittent liftoff, ◦ liftoff).

Table 2.1: Test conditions performed in connected plenum configuration.

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_R$ [K]</th>
<th>Fuel</th>
<th>Observation</th>
<th>$\phi$</th>
<th>$S^0_L$ [cm/s]</th>
<th>$V_{\text{bulk}}$ [m/s]</th>
<th>$\delta_f$ [mm]</th>
<th>$v'/S^0_L$</th>
<th>Da</th>
<th>$K_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI1</td>
<td>300</td>
<td>-</td>
<td>Isothermal</td>
<td>-</td>
<td>-</td>
<td>16.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CI2</td>
<td>500</td>
<td>-</td>
<td>Isothermal</td>
<td>-</td>
<td>-</td>
<td>26.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CR1</td>
<td>300</td>
<td>F1</td>
<td>Stably Attached</td>
<td>0.59</td>
<td>10.9</td>
<td>8.0</td>
<td>1.1</td>
<td>19.3</td>
<td>0.1</td>
<td>180</td>
</tr>
<tr>
<td>CR2</td>
<td>300</td>
<td>F1</td>
<td>Intermittent Liftoff</td>
<td>0.59</td>
<td>10.9</td>
<td>11.1</td>
<td>1.1</td>
<td>25</td>
<td>0.1</td>
<td>140</td>
</tr>
<tr>
<td>CR3</td>
<td>300</td>
<td>F1</td>
<td>Liftoff</td>
<td>0.59</td>
<td>10.9</td>
<td>14.6</td>
<td>1.1</td>
<td>31</td>
<td>0.2</td>
<td>183</td>
</tr>
<tr>
<td>CR4</td>
<td>300</td>
<td>F1</td>
<td>Stably Attached</td>
<td>0.63</td>
<td>14.5</td>
<td>16.0</td>
<td>0.8</td>
<td>26</td>
<td>0.1</td>
<td>271</td>
</tr>
<tr>
<td>CR5</td>
<td>300</td>
<td>F2</td>
<td>Intermittent Liftoff</td>
<td>0.58</td>
<td>12.3</td>
<td>14.8</td>
<td>1.0</td>
<td>16</td>
<td>0.5</td>
<td>177</td>
</tr>
<tr>
<td>CR6</td>
<td>300</td>
<td>F2</td>
<td>Stably Attached</td>
<td>0.63</td>
<td>16.4</td>
<td>16.0</td>
<td>0.8</td>
<td>19</td>
<td>0.2</td>
<td>183</td>
</tr>
<tr>
<td>CR7</td>
<td>500</td>
<td>F1</td>
<td>Intermittent Liftoff</td>
<td>0.51</td>
<td>22.8</td>
<td>14.9</td>
<td>0.89</td>
<td>19</td>
<td>0.2</td>
<td>140</td>
</tr>
<tr>
<td>CR8</td>
<td>500</td>
<td>F1</td>
<td>Intermittent Liftoff</td>
<td>0.55</td>
<td>30.6</td>
<td>23.2</td>
<td>0.71</td>
<td>24</td>
<td>0.2</td>
<td>150</td>
</tr>
</tbody>
</table>

Individual Plenum Configuration

In the second configuration, the flow to each nozzle was isolated in the plenum as shown in Fig.2.3a. Each nozzle had an independent plenum that was fed from a dedicated set of electromechanical mass flow controllers. With this configuration, we can investigate the effect of multiple parameters on the combustor stability, such as the inter-nozzle spacing, stratification, and unequal flow distribution along the combustor array. The inter-nozzle spacing was varied by changing the nozzles receiving reactants; the configurations studied
correspond to reactants supplied to $N_2$, $N_1$ & $N_3$, and $N_0 - N_4$. Perfectly premixed CH$_4$ air mixtures with targeted $\phi$ were supplied to plenum of the operating nozzle(s) through the 3/8” holes located at the bottom of the plenum(s), and flowed through a nickel chromium foam flow-straightener before entering to the optically accessible combustor chamber. A large number of tests were performed to characterize the combustor behavior. Of these, a subset was then selected to study using the laser diagnostics. These are summarized in Table 2.2 where $S_{eff}$ is the effective nozzle spacing when not all nozzles were in use. Three independent sets of measurements were acquired at each condition to ensure repeatability.

The behavior of the combustor with various inter-nozzle spacings was studied with the same flow rate and equivalence ratio supplied to each nozzle. Three equivalence ratios were used ($\phi = 0.62, 0.65, 0.67$) with reactant temperature $T_R = 300 \text{ K}$. It is noted that the combustor could not be ignited in the single-nozzle configuration for $\phi = 0.62$; only two equivalence ratios were studied in this case.

Fig. 2.9 shows time-averaged OH$^*$-CL fields at multiple conditions with the $\phi = 0.65$ but with different bulk velocities ($V_{bulk}$, volume flow rate divided by nozzle exit area) and different numbers of operating nozzle. In the single nozzle configuration, the heat release region shifted downstream with increasing $V_{bulk}$. When $V_{bulk}$ was increased to 28.6 m/s, the flame began to undergo an on-going process of detaching and reattaching to the bluff-body. The portion of time spent in the lifted configuration increased as $V_{bulk}$ increased, until no reattachment occurred at $V_{bulk} = 38.8 \text{ m/s}$.

In the configurations with multiple operating nozzles, the flame for each nozzle behaved similar to the one observed in single-nozzle configuration. However, the $V_{bulk}$ leading to the (intermittent) liftoff was different for each operating nozzle. In the two-nozzle configuration, only $N_3$ was intermittently lifted at $V_{bulk} = 41.1 \text{ m/s}$ (Fig. 2.9g). Further increasing the $V_{bulk}$, $N_1$ also intermittently lifted from the nozzle while $N_3$ spent a larger portion of time in the lifted state. Eventually, both nozzles fully lifted at $V_{bulk} = 72.5 \text{ m/s}$ (Fig. 2.9j). The difference in $V_{bulk}$ leading to the liftoff of each nozzle is more significant in the five flames configuration. For instance, $N_3$, $N_1$, and $N_2$ were lifted at $V_{bulk} = 17.1 \text{ m/s}$ (Fig. 2.9m), $V_{bulk} = 18.9 \text{ m/s}$ (Fig. 2.9n) and $V_{bulk} = 25 \text{ m/s}$ (Fig. 2.9o), respectively.
Chapter 2. Experimental Approach

Figure 2.9: Representative time-averaged OH fields taken from 5000 consecutive CL measurements. Each row contains multiple cases with the same flame characteristics ($\phi = 0.65$, $T_R = 300$ K) and operating configuration but with different $V_{bulk}$.
Chapter 2. Experimental Approach

Figure 2.10: Stability characteristics for the combustor with reactants supplied to different nozzles. Symbols denote: * (\(N_2\) only, where the flame was lifted), • (\(N_1\) and \(N_3\), where \(N_3\) intermittently lifted), ∗ (\(N_1\) and \(N_3\), where both nozzles intermittently lifted), ▲ (\(N_1\) and \(N_3\), where all flames were stably attached), △ (\(N_0\) – \(N_4\), where all five nozzles were lifted), □ (\(N_0\) – \(N_4\), where \(N_1\) and \(N_3\) were lifted), ◦ (\(N_0\) – \(N_4\), where \(N_3\) was lifted), ▶ (\(N_0\) – \(N_4\), where \(N_3\) intermittently lifted), and × (\(N_0\) – \(N_4\), where all flames were stably attached).

The stability characteristics of the combustor with all three nozzle spacings is shown in Fig. 2.10. For the sake of clarity, only the lean blowoff point is shown in Fig. 2.10 for the single-nozzle configuration.

Laser measurements were performed on the \(\phi = 0.65\) cases, since the general behaviour of the combustor did not change with \(\phi\). Two different \(V_{bulk}\) were analysed for each nozzle spacing. The \(V_{bulk}\) for cases ISR1, ITR1, and IFR1 was 13.7 m/s, at which every operating flame was stably attached to the nozzle. These three cases are used as control, such that we can determine the hydrodynamic strain inherent in the combustor with different \(S_{eft}\). The \(V_{bulk}\) for cases ISR2, ITR2, and IFR2 corresponded to the lowest \(V_{bulk}\) at which at least one of the operating flames intermittently lifted from the nozzle(s). These cases
allow us to investigate the role of $S_{eft}$ on the flame dynamics near blowoff.

The effect of uneven reactants mass flow rate distribution and stratification across the rig were studied with reactants supplied to all nozzles. Two different sets of tests were performed, one in which the equivalence ratio to all nozzles was maintained at $\phi = 0.65$ but the total flow rate to each nozzle was varied, and one in which the fuel flow rates to each nozzle was held constant and the air mass flow rate was varied resulting in different $\phi$ across the nozzles. For these cases, $\dot{m}_{A,2}$ refers to the air mass flow rate supplied to $N_2$. While $\alpha_A$ and $\alpha_F$ are the percentage differences of the air and fuel mass flow rates between $N_2$ and $N_i$, such that the mass flow rate of air and fuel ($\dot{m}_{A_i}$, $\dot{m}_{F_i}$) supplied to

---

Table 2.2: Test conditions performed in individual plenum configuration.

<table>
<thead>
<tr>
<th>Case</th>
<th>Configuration</th>
<th>$S_{eft}$</th>
<th>Observation</th>
<th>$V_{bulk}$</th>
<th>$\dot{m}_{A,2}$</th>
<th>$\alpha_A$</th>
<th>$\alpha_F$</th>
<th>$\Delta \phi_s$</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[m/s]</td>
<td>[SLPM]</td>
<td>%</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Effect of nozzle spacing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISI1</td>
<td>$N_2$</td>
<td>n/a</td>
<td>Isothermal</td>
<td>13.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ITI1</td>
<td>$N_1 &amp; N_3$</td>
<td>2.68</td>
<td>Isothermal</td>
<td>13.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IFI1</td>
<td>$N_0 \sim N_4$</td>
<td>1.34</td>
<td>Isothermal</td>
<td>13.7</td>
<td>-</td>
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<td>-</td>
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<td>ISR1</td>
<td>$N_2$</td>
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<td>Stably Attached</td>
<td>13.7</td>
<td>-</td>
<td>-</td>
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<td>$N_2$</td>
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<td>34.3</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
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<td>$N_1 &amp; N_3$</td>
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<td>Stably Attached</td>
<td>13.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>$N_1 &amp; N_3$</td>
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<td>$N_3$ Intermittent Liftoff</td>
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<td>-</td>
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<td>Stably Attached</td>
<td>13.7</td>
<td>-</td>
<td>-</td>
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</tr>
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<td>$N_1$ Liftoff</td>
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<td>13.9</td>
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<td>$N_1$ Lifted</td>
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<td>20.8</td>
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<td>$N_0 \sim N_4$</td>
<td>1.34</td>
<td>Stably Attached</td>
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<td>0</td>
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<td>$N_1$ Lifted</td>
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<td>144</td>
<td>2.1</td>
<td>0</td>
<td>0.013</td>
</tr>
</tbody>
</table>

---

$^1V_{bulk}$ is characterized at $N_2$; $V_{bulk,2}$
Figure 2.11: Schematic drawing of the laser diagnostics system.

Each nozzle can be expressed as:

\[
\dot{m}_{A,i} = (1 + \text{sgn}(i) \cdot \alpha_A) \cdot \dot{m}_{A,2} \tag{2.4}
\]

\[
\dot{m}_{F,i} = (1 + \text{sgn}(i) \cdot \alpha_F) \cdot \dot{m}_{F,2} \tag{2.5}
\]

\[
\text{sgn}(i) = \begin{cases} 
+1 & i < 2 \\
-1 & i > 2 
\end{cases}
\]

Similarly, \(\Delta \phi_s\) refers to the difference in \(\phi\) between \(N_2\) and \(N_i\). The equivalence ratio of the reactants mixture supplied to each nozzle \((\phi_i)\) is given as

\[
\phi_i = (1 + \text{sgn}(i) \cdot \Delta \phi_s) \cdot \phi_2 \tag{2.6}
\]

\[
\text{sgn}(i) = \begin{cases} 
-1 & i < 2 \\
+1 & i > 2 
\end{cases}
\]

It is noted that \(\phi_2 = 0.65\) for all test conditions listed in Table 2.2.
2.2.2 Laser Diagnostics System

The basic behavior of the aforementioned combustor was determined using OH*-CL measurements with repetition rates of 5 kHz. Simultaneous high-speed OH-PLIF and S-PIV measurements with repetition rates of up to 10 kHz were then conducted at selected conditions to study the flow-flame interactions. Furthermore, simultaneous OH-PLIF and CH\textsubscript{2}O-PLIF with repetition rate of 10 Hz were applied at a subset of the conditions to obtain more insight regarding the flame structure.

Three-component planar velocity fields were measured using S-PIV. Initial measurements were made at 10 kHz repetition rate. This was reduced to 5 kHz in later measurements, which was sufficient to resolve the dynamics of interest. The system consisted of a high repetition rate, dual cavity, diode-pumped, solid-state, Nd:YAG laser (Quantronix Hawk Duo) and a pair of high speed complementary metal-oxide semiconductor (CMOS) cameras (Photron SA-5) equipped with commercial camera lenses (Tokina, \( f = 100 \text{ mm}, f/\# = 5.6 \)). To track the flow, zirconium oxide (ZrO\textsubscript{2}, American Element) particles with nominal diameter of 1 µm were seeded into the reactants. Laser pulses pairs at 532 nm with separation time of 8 - 16 µs were expanded and collimated in the vertical direction, and then contracted to a waist using three cylindrical lenses to illuminate the particles. The light scattered by the seeding particles was simultaneously recorded by the two cameras, which were mounted equidistant from the opposite sides of the laser sheet at forward-scatter angles of approximately 30°. Image defocusing was corrected using Scheimpflug adapters and the cameras were calibrated using a 3D dot target (LaVision).

In the OH-PLIF system, a solid state Nd:YAG laser (EdgeWave), operating at a repetition rate of either 5 or 10 kHz delivered a 532 nm beam to pump a frequency double dye laser (Sirah Credo, Rhodamine 6G dye solution). The frequency-doubled dye laser was tuned to produce a laser beam exciting the \( Q_1(7) \) transition of OH at approximately 283.2 nm, with an average output power of 2 W. The laser beam was then formed into a collimated sheet with a height of 48 mm in the same manner as the S-PIV system, and overlapped with the S-PIV laser sheet along the combustor centerline using a dichroic mirror. The OH fluorescence signal in the range of 305-315 nm was first
isolated with bandpass filter (> 90% at 310 ± 5 nm), and then collected using a UV lens (Sodern Cerco, \( f = 45 \text{ mm}, \ f/\#= 1.8 \)) coupled with an electrically synchronized image intensifier (Invisible Vision UVi, 200 ns gate) and high-speed CMOS camera (Photron SAZ). The obtained images were corrected for the mean laser sheet inhomogeneity and the intensifier whitefield response. It is noted that the OH*-CL imaging system was as used for the OH-PLIF measurements, except the intensifier gate was increased to 100 \( \mu s \) and no excitation source was required.

The CH\(_2\)O setup used the third harmonic of a Nd:YAG laser (355 nm) to excite the \( A - X_4^1 \) side band of CH\(_2\)O at approximately 355 nm. Similar to OH-PLIF, the fluorescence signal was collected with an image intensifier (Lavision IRO) and CMOS camera (Andor Zyla). A pair of long and short pass filters were used to reduce the background luminosity.

A pulse/delay generator (BNC Model 575) was used to synchronize the cameras and intensifiers with the laser pulses. Also, the triggering of the dye laser for OH-PLIF measurement was configured such that each dye laser pulses was in between the laser pulses pair for the S-PIV measurement. The timing diagram for the experimental setup is shown in Fig. 2.12.

**Figure 2.12:** Timing diagram of the simultaneous OH-PLIF and S-PIV measurements. All experimental components were externally triggered and synchronized as shown.
2.3 Analysis Techniques

2.3.1 Vector Field Processing

In this work, instantaneous vector fields were computed from the planar particle scattering images with a commercial PIV software package (LaVision DaVis 8.3). The fields-of-view from the different cameras were calibrated with a 3-D dot calibration target (LaVision 058-5). The particle scattering images were then reconstructed to the physical planar particle field. It is noted that strong background reflections were observed. Hence, prior to any processing, the background reflections were removed with Davis’s Butterworth high pass filter. The next step involves removing the noise within the particle fields by applying a series of spatial filters, namely sliding mean and minimum subtractions. The particle displacements during the inter-pulse period were computed from the filtered, preprocessed particle images using multiple-pass cross-correlation analysis with a final interrogation region size of $16 \times 16$ pixels and 50% overlap. This resulted in instantaneous velocity fields with spatial resolution of approximately 1.7 mm and a vector spacing of approximately 0.85 mm over a $62 \times 41$ mm field-of-view, covering the three central nozzles in the combustor.

Since PIV is based on the statistical correlation between two particle scattering images, the obtained velocity vectors are susceptible to several sources of uncertainty. Wienke and Sciacchitano [86] have summarized the possible sources of error that may arise during different stages of the experiment, which is shown in Fig. 2.13. These errors propagate through the whole vector processing procedures and lead to systematic and random errors.

Even though PIV has been widely used in the past few decades, there is still no widely accepted method to quantify the uncertainty for a given measurement. Several uncertainty estimation methods based on calculating the peak ratios [87], image-matching [88], and cross-correlation [86, 89, 90] have been proposed.

Charonko et al. [87] suggested the uncertainty could be quantified by calculating the ratio between the highest and the second highest correlation peaks. An empirical relationship was derived to relate the aforementioned ratios and the displacement uncer-
Figure 2.13: Overview of PIV error sources summarized by Wienke and Sciacchitano[86].

tainty. However, this technique only provides a single uncertainty value for all velocity components. In the image-matching method proposed by Sciacchitano et al. [88], the measured velocity field along with the original particle images are used to quantify uncertainty. It involved overlaying the dewarped particle images from the two exposures, and calculating the residual distance between centroids of the matched particles (matched particle image disparity). The uncertainty of the velocity vector is estimated by the mean and statistical dispersion of the disparity vectors in the corresponding interrogation window. Due to the nature of this technique, the uncertainty is sensitive to the seeding density. Sciacchitano et al. [88] suggested that at least about six particles per interrogation window is required for accurate error estimation.

The cross-correlation technique developed by Wienke et al. [86, 89, 90] is similar to the image-matching technique. However, rather than analysing the particle disparities, this method estimates the uncertainty by relating the asymmetry in the correlation peak to the covariance matrix of the pixel-wise intensity difference between two almost matching interrogation windows. In this study, the uncertainties of the velocity vectors were quantified with Wienke’s method for all the test cases, since it is readily available in DaVis. The relative error at each point was calculated as the ratio of the uncertainty in the velocity magnitude to the corresponding velocity magnitude (|V|). Any vectors
with relative error higher than 10% were treated as outlier and removed from the vector field. Figure 2.14 shows a representative instantaneous velocity magnitude field and the corresponding relative error field, with all the outliers removed.

![Representative instantaneous velocity magnitude field and the corresponding relative error field](image)

**Figure 2.14:** Representative instantaneous $|\vec{V}|$ field and the corresponding relative error for case CR8.

### 2.3.2 OH and CH$_2$O Fields Processing

The OH and CH$_2$O fields were mapped to the same physical coordinates as the S-PIV field using the same calibration target. Processing of the OH and CH$_2$O fields involved applying a $4 \times 4$ and $5 \times 5$ pixels bins, representatively, subtracting the background noise, and applying a $3 \times 3$ median filter to remove the noise 'speckles'. Strong reflection from the dump-plate was observed in the CH$_2$O images. Hence, a mask was applied to remove the unwanted reflection.

Figure 2.15 shows representative processed OH-PLIF and CH$_2$O-PLIF images for a time instant at which all nozzles had stably attached flames. It is noted that $\phi$ was uniform across all nozzles in the combustor here, the non-uniformity in signal intensity
observed in the OH field is strictly due to absorption of the laser energy along the laser path traversing from $N_4$ to $N_0$ (from left to right). For this reason, a local OH threshold value was required to determine the reaction zone topology. The local reaction structure can be determined by calculating the pixel-by-pixel multiplication of OH and CH$_2$O fields.

![Figure 2.15: Representative instantaneous OH and CH$_2$O fields.](image)

Figure 2.15: Representative instantaneous OH and CH$_2$O fields.

![Figure 2.16: Representative CH$_2$O overlapping on the OH fields showing the instantaneous preheat (blue), reaction (green), and product (red) zones for two representative cases.](image)

Figure 2.16: Representative CH$_2$O overlapping on the OH fields showing the instantaneous preheat (blue), reaction (green), and product (red) zones for two representative cases.

Figure 2.16 shows representative instantaneous CH$_2$O and OH fields, along with the reaction layer (CH$_2$O x OH) fields for cases with and without preheat. Large-scale flame wrinkling, thin reaction layers, and broadened CH$_2$O layers were observed for all studied
cases regardless of the reactant preheating temperature. Based on these observations, all cases fall within the thickened preheat zone/thin reaction zone regime of turbulent premixed combustion as mentioned in Section 2.1. In this regime, the preheat layer is thickened due to the motion of vortical structures, but the chemical reactions remained similar to those in a laminar flame.

### 2.3.3 Flame Surface Density

Flame surface density (FSD) is used to characterize the flames due to its relationship to the volumetric heat release \([91]\), namely

\[
\dot{\omega}_r = \rho_u S_L^0 I_0 \Sigma
\]

where \(\rho_u\) is the density of the unburnt reactants, \(S_L^0\) is the unstretched laminar flame speed, \(I_0\) is the stretch factor, and \(\Sigma\) is FSD.

FSD is defined as the flame sheet surface per unit volume, which can be reduced to flame surface length per unit area in two dimensional measurements. Physically speaking in the limit of thin flame surfaces, FSD is a measure of frequency that a flame front exists in a certain region within the volume. In this work, the flame surface is deduced from the OH gradient field. Figure. 2.17 shows the obtained instantaneous flame front overlaying on the corresponding OH and OH gradient fields, in which the flame front was located at the region with highest OH gradient.

Numerous approaches have been proposed to calculate the FSD \([13, 91]\). In this study, the method proposed by Steinberg et al. \([13]\) is adopted. It involves first dividing the OH-PLIF measurement plane into grids with resolution five times lower than the OH field as illustrated in Fig. 2.18. The total flame sheet length of a given cell was then taken as the sum of the lengths of every instantaneous flame front that fell within that cell. The FSD of a given cell was computed by dividing the total flame sheet length by the grid’s area.
Chapter 2. Experimental Approach

Figure 2.17: Representative instantaneous flame front OH overlaying on the corresponding OH and OH gradient fields: case CR1 (a,b), and case CR5 (c,d). The black and white lines are the instantaneous flame front.

2.3.4 Hydrodynamic Strain

Numerous studies have demonstrated that flame stretch plays an important role in blowoff \[6, 50, 51, 54, 55\], where local flame extinctions occur when the flame stretch exceeded the extinction strain rate. Flame stretch ($\kappa$) refers to the change in infinitesimal area of the flame surface ($\delta A(t)$) with time due to hydrodynamic strain ($a_t$) and curvature ($\kappa_c$) \[8\].

\[
\kappa = \frac{1}{\delta A(t)} \frac{d(\delta A(t))}{Dt} = \nabla_t \cdot \vec{V} + S_d(\nabla \cdot \hat{n}) \tag{2.8}
\]

where $S_d$ is the velocity of the flame surface.

The term $a_t$ describes the flame stretching due to the presence of tangential velocity
gradient along the flame front, while the term $\kappa_c$ describes the flame stretching due to the motion of curved flame surface.

Further arranging the terms, the hydrodynamic strain tangential to the flame front is expressed in terms of velocity gradients as [92]

$$a_t = - (\hat{n} \cdot (\hat{n} \cdot \nabla)) \vec{V} + \nabla \cdot \vec{V} = (\delta_{ij} - n_i n_j) \frac{dV_i}{dx_j}$$  \hspace{1cm} (2.9)

By calculating the velocity gradients along the flame front, one can obtain $a_t$ experimentally. It is noted that, inside the flame front, the presence of thermophoretic force in the direction opposite to the temperature gradient will significantly increase the particle lag [83], introducing error to the velocity and the associated gradients along the flame front. In order to minimize the potential error, strain rate measurements were made at the leading edge of the flame (towards the reactants) where the effect of heat release is relatively smaller.

Figure 2.18: Demonstration of the grid division of the OH-PLIF measurement plane used to calculate the FSD. It is noted that the actual grid size of the FSD field is much smaller, represented by the black square.
Chapter 3

Connected Plenum Configuration

In the this configuration, reactants to each nozzle were fed through a common plenum and the flow was allowed to naturally distribute between the nozzles. This configuration closely resembles the feeding system in practical combustors. The blowoff dynamics of any individual nozzle was similar to those observed in single bluff-body stabilized flames, in which a series of local extinctions and re-ignitions occurred prior to the blowoff, though with cross-nozzle interactions providing additional means of re-stabilizing a partially extinguished flame. In particular, flame cross-nozzle transport events were observed, and this chapter will investigate the driving mechanism behind them, that is whether the flame was transported through convection or self propagation. Subsequent to blowoff/reattachment of the first nozzle, the other nozzles underwent similar blowoff/reattachment processes. It is hypothesized that blowoff/reattachment of any nozzle leads to upstream flow redistribution in a manner that promotes the blowoff/reattachment of the other nozzles; various evidence supporting this hypothesis is presented.

3.1 Multi-Nozzle Combustor Characterization

For convenience of reference, the operating conditions to be discussed in the chapter (originally presented in Table 2.1) are replicated here in Table 3.1.
Table 3.1: Test conditions performed in connected plenum configuration.

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_R$ [K]</th>
<th>Fuel</th>
<th>Observation</th>
<th>$\phi$</th>
<th>$S_L^{0}$ [cm/s]</th>
<th>$V_{bulk}$ [m/s]</th>
<th>$\delta_f$</th>
<th>$v'/S_L^{0}$</th>
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<th>$Ka$</th>
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<td>CI1</td>
<td>300</td>
<td>-</td>
<td>Isothermal</td>
<td>-</td>
<td>-</td>
<td>16.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CI2</td>
<td>500</td>
<td>-</td>
<td>Isothermal</td>
<td>-</td>
<td>-</td>
<td>26.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>CR1</td>
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<td>0.59</td>
<td>10.9</td>
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<td>F1</td>
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<td>0.59</td>
<td>10.9</td>
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<td>25</td>
<td>0.1</td>
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<td>300</td>
<td>F2</td>
<td>Stably Attached</td>
<td>0.63</td>
<td>16.4</td>
<td>16.0</td>
<td>0.8</td>
<td>19</td>
<td>0.2</td>
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<td>0.71</td>
<td>24</td>
<td>0.2</td>
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</tbody>
</table>

3.1.1 Isothermal Field

Figure 3.1 shows the representative transverse ($V_x$), axial ($V_y$) and azimuthal ($V_z$) components of the average isothermal velocity fields inside the combustion chamber for case CI1 ($V_{bulk} = 16.0$ m/s). Each of the flow field images are the result of an average of 10000 consecutive S-PIV acquisitions. The center of these plots ($x/D_n = 0$) is located approximately at the middle of the center nozzle. These flow fields are typical of all non-reacting cases.

The general structure of the flow field consisted of central recirculation zones (CRZ), outer recirculation zones (ORZ), and high momentum swirling jets. In all cases, the jets expanded radially outward with downstream distance due to the swirling flow. However, this expansion is aerodynamically confined by the presence of adjacent jets. It is noted that there is a systematic asymmetry to the flow from each nozzle, with $V_y$ on the left side of the nozzle for each jet being higher. This is attributed by the position of the vanes in the axial swirl nozzle. That is, there is a momentum deficit due to the wake behind the swirl vanes, which appears on the left of the jets in our images. In addition, it is observed that the recirculation strength of $N_1$ was significantly lower than the other nozzles, which is an indication of uneven flow distribution, as the flow was free to distribute itself among all five nozzles across the rig in the connected plenum configuration.
Figure 3.1: Representative $V_x$, $V_y$, and $V_z$ fields inside the combustion chamber normalized by $V_{bulk}$ in case CI1. The black lines show the locations with $V_y = 0$ m/s. One in every 3 vectors shown for clarity.

Figure 3.2: Representative OH field with all flames stably attached in case CR4, where the regions used to calculate the normalized OH intensity for each nozzle marked in red boxes.

3.2 Reacting Flow

Figure 3.2 shows a representative OH-PLIF image for case CR4 for a time instant at which all nozzles had stably attached flames. The flames from each nozzle merged at an axial location in the range $1.5 \leq y/D_n \leq 2$. It is noted that the $\phi$ was uniform across all
Chapter 3. Connected Plenum Configuration

Figure 3.3: Time-average of 10000 FSD images for cases with the same $V_{bulk}$ and $T_{ad}$ but different fuels.

Figure 3.4: $\overline{V_y}$ taken over times as which all flames were stably attached in cases CR4 and CR6, normalized by $V_{bulk}$. The black lines show the locations with $\overline{V_y} = 0$ m/s. One in every 3 vectors shown for clarity.

nozzles in the combustor; the non-uniform intensity observed in the OH field is strictly due to absorption of the laser energy along the laser path traversing from $N_3$ to $N_1$.

Figure 3.3 shows the FSD for cases CR4 and CR6, in which the $V_{bulk}$ and $T_{ad}$ for both cases are the same. However, case CR4 uses pure CH$_4$ fuel, whereas the fuel used in case CR6 contains 20% H$_2$ by volume. The flame structure for both cases are similar, but the presence of hydrogen results in flames merging with the adjacent flames at a more upstream position, likely due to the higher flame speed.

Figure 3.4 shows the $\overline{V_y}$ taken over time instants at which all flames were stably attached in cases CR4 and CR6. The flow structures were similar to those observed in the isothermal condition. However, the flow was more asymmetric and the CRZ of $N_3$
Figure 3.5: Normalized OH-PLIF signal intensity ($\Omega_i$) for different nozzles in case CR8: $N_1$ (black), $N_2$ (red), and $N_3$ (blue).

was more compact than the other nozzles in the reacting cases.

3.3 Intermittent Liftoff and Reattachment

As mentioned in Chapter 2, at statistically stationary operating conditions, the flames would undergo intermittent blowoff and reattachment. In the connected plenum configuration, the transitions of one nozzle was followed shortly by transition of the other nozzles. These coupled dynamics are elucidated in this section.

3.3.1 Basic Dynamics and Statistics

For quantitative analysis of flame dynamics, the measurement field-of-view was divided into three regions, each encompassing the flame from one nozzle, labelled as $N_i$ in Fig. 3.2. The state of flame $i$ at any instant during the measurements (i.e. attached or blown-off) was determined by the total OH-PLIF signal intensity in region $i$, normalized by each region’s maximum over the time sequence ($\Omega_i$). Nozzle-by-nozzle normalization was required to account for laser power absorption through the combustor, which resulted in different absolute signal intensities for the different regions. Based on $\Omega_i$, the measurement time sequence can be divided into three distinct states, namely attached ($\Omega_i \approx 1$),
blown-off ($\Omega_i \approx 0.25$), and transitional. Transitional refers to the short time periods during which the flame was changing between attached and detached states.

Figure 3.5 shows a typical time sequence of $\Omega_i$ for the three center nozzles for case CR8. Transition in flame attachment state (blowoff or reattachment) occurred first in one random nozzle, followed by the other nozzles a short time later. It is noted that the blowoff/reattachment process is stochastic, and the amount of time that a nozzle spent transitioning between states varied significantly between events. To identify whether there was any preferential ordering of the transitions of individual nozzles during an overall multi-nozzle transition, 55 overall transition events were categorized into three groups: outer-inner-outer ($OIO$), outer-outer-inner ($OOI$), and inner-outer-outer ($IOO$). In this context, $N_1$ and $N_3$ are the outer nozzles, while $N_2$ is the inner nozzle. The probabilities of these different sequences are shown in Fig. 3.6. To help the readers understanding the statistics better, Fig. 3.7 demonstrates the most commonly observed blowoff and reattachment sequences.

Blowoff is more likely to be initiated in one of the outer nozzles ($OIO$ or $OOI$), with $N_3$ having the highest probability. After blowoff of the first outer nozzle, there is no preference on whether the next blowoff occurs in the middle nozzle ($OIO$) or the other outer nozzle ($OOI$); the probability of either transition was similar. This indicates that direct cross-nozzle flame interactions in the combustion chamber (heat transfer and flow

**Figure 3.6:** Probability of different blowoff/reattachment sequences, viz. outer-inner-outer ($OIO$), outer-outer-inner ($OOI$), inner-outer-outer ($IOO$).
field coupling) may not be the cause of the coupled blowoff, which will be discussed in Section 4.4.

Similarly, the reattachment process was preferentially initiated by one of the outer nozzles, with $N_3$ being the most likely. However, in contrast to the blowoff transitions, this is more likely to be followed by the reattachment of the adjacent nozzle ($OIO$), indicating potential direct cross-nozzle interaction. Nevertheless, there is a significant probability of $OOI$ transitions.

Figure 3.8 shows a sequence of OH-PLIF images illustrating the transition from the
Figure 3.8: Sequence of OH-PLIF images showing typical transition from attached to detached flames in case CR8, white circles highlight the local extinction events, red circles highlight the flame fragment spanwise transport events, and black circles highlight the flame segment upstream propagation events.

attached to lifted flame states for $N_3$ at selected instants during the time period $t = 600-681.5$ ms from Fig. 3.5. The blowoff mechanism for an individual flame was similar to that observed in single bluff-body combustors [6, 54, 55, 93], though with some additional effects caused by the adjacent flames. Prior to the blowoff of $N_3$, a series of local extinction events occurred at axial locations downstream of the bluff-body ($1 < y/D_n < 2$) during $t = 659.9 - 687.6$ ms. The local extinction results in flame fragmentation, where the flame attached to the bluff-body separated from the merged flames located downstream and the reaction front situated inside the CRZ.

The presence of adjacent flames allowed four possible behaviors after local extinction. Firstly, the upstream bluff-body anchored flame could re-establish into a fully burning configuration through downstream flame convection in a similar manner to single bluff-body stabilized flames ($t = 660.2 - 660.5$ ms). Secondly, burning flame fragments from adjacent flames could be transported into the partially extinguished flame’s recirculation zone to help re-establish the flame ($t = 661.7 - 662.0$ ms), which is similar to the spanwise ignition mechanism observed in annular combustors [63]. Effort was made to distinguish whether the observed cross-nozzle flame transportation is attributed to the convection by the mean flow or propagation, which will be discussed in Section 3.3.2. Thirdly, flame
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Figure 3.9: Sequence of OH-PLIF images showing typical transition from attached to detached flames after one of the flames lifted in case CR8, white circles highlight the local extinction events, red circles highlight the flame fragment spanwise transport events, and black circles highlight the flame segment upstream propagation events.

segments from the region downstream of the flame merging could enter the recirculation zone of the partially extinguished flame, again aiding in re-establishing the flame \((t = 661.4 - 661.6 \text{ ms})\). Flame re-ignition by this mean was also observed in the two-nozzle combustor used in Ref. [70]. Finally, if the flame was not re-established by one of the aforementioned means, it proceeded to complete blowoff in a similar manner to single flames [54, 55], i.e. through increasing local extinction causing flame contraction towards the bluff-body and eventual complete extinction \((t = 680.1 - 681.5 \text{ ms})\). This behavior is hypothesized to be due to increased entrainment of cold reactants into the recirculation zone. From the above discussion, it is apparent that the presence of multiple flames can enhance stability by adding heat to the recirculation zone of a partially extinguished neighbour.

However, the rapid subsequent blowoff of the other flames after the (stochastically-triggered) blowoff of \(N_3\) indicates that the presence of a single blown-off flame can detract from the stability of the overall combustor array. Selected images from the rest of the blowoff process is shown in Fig. 3.9. Again, several phenomena were observed after \(N_3\) was lifted. First of all, the flames of \(N_1\) and \(N_2\) went through a similar physical process as \(N_3\). In this particular sequence, blowoff of \(N_3\) was followed by \(N_1\) at \(t = 733.7 \text{ ms}\), and
N\textsubscript{2} at \( t = 756.5 \) ms. It is possible that the subsequent blowoff events are promoted by entrainment of cold reactants from the extinguished nozzle into the recirculation zone of the burning nozzles. However, this would be expected to preferentially promote blowoff of the adjacent nozzle, i.e. \( N\textsubscript{2} \). As mentioned above and demonstrated in Fig. \ref{fig:3.9}, no preference was found regarding order in which nozzles blew-off after the first nozzle transition. Hence, cold gas entrainment likely is not the leading cause of the coupled transition. Instead, it is hypothesized that blowoff of one nozzle leads to a redistribution of the flow to the other nozzles in a manner that promote blowoff. This is explored further in Section \ref{sec:3.3.2}.

Simultaneous with the extinction and eventual blowoff, re-attachment of the lifted flame(s) was promoted by flame fragments from adjacent nozzles. For instance, a flame fragment from \( N\textsubscript{2} \) was transported towards \( N\textsubscript{3} \) over \( t = 708.0 - 708.6 \) ms, resulting in a flame segment moving upstream through the \( N\textsubscript{3} \) recirculation zone to the bluff-body. However, the heat release from this flame segment was insufficient to re-ignite \( N\textsubscript{3} \). A similar event from \( N\textsubscript{2} \) to \( N\textsubscript{1} \) was observed from \( t = 737.9 - 738.4 \) ms. The loss of heat from the attached flames to the extinguished nozzles through such flame fragments also may play a role in the subsequent blowoff. However, as above, the lack of preference regarding the second nozzle to blowout indicates that this may not be the leading cause.

Beyond inter-nozzle interactions, the presence of the attached flames (including the flames from the outer two nozzles near the combustor walls) effectively served as a pilot for the unburnt reactants issuing from the blown-out nozzles. This resulted in a stable flame downstream of the blown-out nozzles at \( x/D_n \approx 2 \), similar to where the flames from the attached nozzles merged. The downstream-stabilized flame occasionally propagated upstream through the recirculation zone of a blown-out nozzle, as seen from \( t = 737.9 - 744.3 \) ms for \( N\textsubscript{3} \). In this event, the flame fragment originating from downstream provided sufficient heat to re-ignite \( N\textsubscript{3} \) temporarily at \( t = 738.0 \) ms, but it blew off again at \( t = 752.5 \) ms. It is noted that the possibility of attached nozzles serving as pilots for the reactants issuing from blown-out nozzles has implications for practical design considerations such as heat transfer and cooling.

The particular confinement configuration of this combustor allows the flame to re-
Figure 3.10: Sequence of OH-PLIF images showing typical transition from detached to attached flames in case CR8, red circles highlight the flame fragment spanwise transport events, and black circles highlight the flame segment upstream propagation events.

main in the combustion chamber after all three central nozzles have detached, stabilized slightly downstream of the recirculation zones. This likely is due to relatively low velocity regions downstream of the recirculation zones and near the walls. Once in this blowoff configuration, the flames could spontaneously reattach to the nozzles, as shown in Fig. 3.10 segments of the downstream-stabilized flame entered a recirculation zone and subsequently transported towards the bluff-body. This process occurred continuously for all nozzles, generally not resulting in stable flame attachment, until one such event established a stable flame (e.g. for \( N_3 \) during \( t = 1170.1 - 1273.6 \) ms). Similar to the blowoff process, reattachment of one nozzle was quickly followed by reattachment of the other nozzles, indicating inter-nozzle coupling. After the flame for \( N_3 \) was attached, a flame fragment from \( N_3 \) was transported across the swirling jets to merge with the flame downstream of \( N_2 \) \( (t = 1278.3 - 1279.0 \) ms), though this did not result in stable reattachment of \( N_2 \). Both \( N_1 \) and \( N_2 \) were re-ignited by the upstream propagation from the detached flame through the recirculation zones at \( t = 1286.3 \) ms and \( t = 1296.5 \) ms, respectively.
3.3.2 Cross-Nozzle Flame Transport

The above discussion has identified two inter-nozzle interactions that influence the combustor stability, namely cross-nozzle transport and flow redistribution. Similar observations were made in all cases using the connected plenum. We now aim to explore these mechanisms more quantitatively, beginning with the cross-nozzle transport of flame fragments. Specifically, we address whether this is due to convection or flame propagation. Convection refers to the situations where the flame fragment is moved across nozzle by the flow, such that the flame fragment is travelling at a speed approximately equal to the local flow velocity. In the second scenario, the flame fragment movement is driven by the heat lost from the burnt product at temperature near the $T_{ad}$ to the cold reactants at temperature $T_R$ issuing out from the blowoff nozzle(s) [94, 95]. The released energy is transported by thermal conduction to the next reactant layer resulting in propagation of the reaction front with speed approximately equal to $S_{L}^0$.

To distinguish which one is the driving mechanism of the observed cross-nozzle flame transport events, we need to examine the movement of the flame fragment relative to the flow. The movement of the flame was quantified by calculating the displacement travelled by the flame tips obtained from the two consecutive OH-PLIF acquisitions, which is referred as flame displacement velocity ($\vec{V}_{F}$). It is noted that the definition of $\vec{V}_{F}$ here is different from the definition of the three common burning velocities described in Ref. [17]. Figure 3.11 demonstrates how $\vec{V}_{F}$ is calculated in an ideal situation. The black solid and dashed lines are the flame fronts at two consecutive instances, $t = t_0$ to $t = t_0 + 1$, respectively.

![Figure 3.11](image)
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(a) OH field at $t = t_o$

(b) OH field at $t = t_o + 1$

(c) Flame fronts at these two instances

(d) OH field at $t = t_o + 1$

(e) OH field at $t = t_o + 2$

(f) Flame fronts at these two instances

Figure 3.12: Demonstration on how $\vec{V}_F$ is estimated in case CR2. The dash and solid lines in (c,f) are the zoom in of the instantaneous flame fronts within the regions marked in the white boxes at (a,d) and (b,e), respectively. The red arrows represent the estimated $\vec{V}_F$.

$t = t_o + 1$. The flame tips at both instances are circled, which are the convex points of the corresponding flame fronts; $\vec{V}_F$ can be deduced by calculating the displacement travelled by the flame tip within the separation time of two OH-PLIF acquisitions. This is compared to $\vec{V}_P$, which is the local flow velocity at the flame tip measured by the S-PIV at $t = t_o$. If $\vec{V}_F \approx \vec{V}_P$, this implies that the flame dynamics are controlled by convection.

However, the flow studied here was highly turbulent and three-dimensional, while OH-PLIF only visualized the flame dynamics within a two-dimensional plane. The swirling flow constantly transported the out-of-plane flame fragments into the imaging plane of the OH-PLIF system. As a result, the shape of the flame was constantly evolving. This increases the difficulties in determining the location of the flame tip, which may potentially lead to a wrong estimation of the $\vec{V}_F$. Hence, careful visual inspection is required.
Figure 3.13: Comparison of $\vec{V}_F$ and $\vec{V}_P$ obtained from thirty instances at which the cross-nozzle flame transport occurred for different cases: CR2 (a,b), CR5 (c,d), and CR8 (e,f). The red and magenta lines are the linear regressions and the 95% prediction interval, respectively.
In the process of determining $\vec{V}_F$, the flame fronts obtained from consecutive OH fields were first compared, to make sure the out-of-plane flame movement effect was negligible. Figure 3.12 shows the OH fields, and the corresponding flame fronts at time instances $t = t_0$ to $t = t_0 + 2$ for case CR2 to demonstrate how $\vec{V}_F$ is estimated with the actual experimental data. In the experiment, the flame structure is not as simple shown in Fig 3.11. A point approximately located at the flame tip was selected for the flame fronts at time instances $t = t_o$ and $t = t_o + 1$, which are labelled as A and B, respectively. $\vec{V}_F$ is estimated from the displacement between points A and B, divided by the separation time of the OH-PLIF laser pulses, while $\vec{V}_P$ is the local velocity at point A measured by the S-PIV experiment.

In this analysis, thirty instances at which cross-nozzle flame transport occurred were considered for cases CR2, CR5, and CR8, respectively. At each instance, $\vec{V}_F$ and $\vec{V}_P$ were estimated using the method described above and compared to each other. The transverse and axial components of local flow velocities ($V_{P,x}$, $V_{P,y}$) estimated for each case are plotted against the corresponding flame tip velocities ($V_{F,x}$, $V_{F,y}$) in Fig. 3.13. In addition, the linear regressions and 95% prediction interval are shown to illustrate the relationship between $\vec{V}_F$ and $\vec{V}_P$.

The data demonstrate that $\vec{V}_F$ was close to $\vec{V}_P$ in all cases. Both $\vec{V}_P$ and $\vec{V}_F$ were significantly higher than the $S^0_L$, which are within the range of $S^0_L = 0.1 - 0.3$ m/s. This demonstrates that the cross-nozzle flame transportation was dominated by the local convection, and the presence of preheating did not change the driving mechanism of the observed events.

### 3.3.3 Flow Field Coupling

The temporal coincidence of the blowoff and reattachment transitions, combined with the only slight preference regarding the sequencing of the transitions between nozzles (no preference in blowoff and slight preference in reattachment), indicates some form of global coupling beyond direct cross-nozzle interactions within the combustion chamber. Figure 3.14 shows the average axial velocity field from the time sequence in Fig. 3.5 over
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(a) After $N_3$ was lifted while $N_1$ and $N_2$ still attached $t = 681.6 - 722.8$ ms, $\overline{V_y}|_i$

(b) After three central flames blowoff $\overline{V_y}|_b$

Figure 3.14: Mean $\overline{V_y}$ field in different flames attachment states normalized by the $V_{bulk}$ in case CR8.

the time instants after the liftoff of $N_3$ but before the liftoff of $N_1$ and $N_2$ ($\overline{V_y}|_i$), and when all three flames were blown-off ($\overline{V_y}|_b$), which can be compared to the $\overline{V_y}|_a$ fields in Fig. 3.4. The average flow fields in these three states were qualitatively similar. A higher degree of asymmetry occurred for the attached state compared to the lifted state, which likely is attributed to flow acceleration through an asymmetric flame.

Nevertheless, several changes in the flow field are notable between $\overline{V_y}|_a$ and $\overline{V_y}|_i$. In particular, the shape and the strength of the CRZs for $N_1$ and $N_2$ changed after blowoff of $N_3$ and prior to the blowoff of their respective flames. Additionally, the velocity of the swirling jets decreased. This clearly indicates that the flow fields downstream of all nozzles in the combustor were coupled to each other.

Two different aspects of the flow field were quantified in order to better understand the changes occurring during state transitions. The instantaneous strength of the recirculation zone was quantified by the spatially averaged axial velocity over the region of negative axial velocity for each nozzle normalized by the $V_{bulk}$, $\langle V_{y,crz,i} \rangle$. The penetration depth of the inflow jets was quantified by the maximum axial location at which $V_y > 0.8V_{bulk}$ between each pair of nozzles, $P_{i,j}$, where $i, j = 1, 2$ or 2, 3.

Gaussian detrending was used to delineate bulk changes from the fluctuations around the local trend. Figure 3.15 shows the variation in $\langle V_{y,crz,i} \rangle$, which was typical of any nozzle. The red line, $\langle V_{y,crz,i} \rangle_G$, indicates the overall trend deduced from a Gaussian kernel having a width of 10% of the time sequence and standard deviation of 2% of the width. Similar processing was applied to all other signals. There was no sensitivity of
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Figure 3.15: Representative diagram showing the Gaussian de-trending of any time series data used for case CR8.

The qualitative results to the particulars of the detrending.

The variations in the trend of \( \langle V_{y,crz,i} \rangle_G \) and \( P_{i,jG} \) during typical blowoff and reattachment events in case CR8 are shown in Fig. 3.16 and Fig. 3.17, respectively. These figures demonstrate that the flow fields for all three nozzles are coupled; changes to any one of them will affect the other as well. For example, as shown in Fig. 3.16b, the initial blowoff of the \( N_3 \) flame was preceded by a weakening of the \( N_3 \) CRZ, which was triggered by the local extinctions that stochastically initiate the blowoff. This weakening of the \( N_3 \) CRZ was accompanied by decreased jet penetration between \( N_2 \) and \( N_3 \) \( (P_{2,3G}) \) due to the lower thermal expansion. Blowoff of \( N_3 \) at \( t = 681.4 \text{ ms} \) was followed by weakening of \( \langle V_{y,crz,1} \rangle_G \) and \( \langle V_{y,crz,2} \rangle_G \), as well as further decreased jet penetration between \( N_2 \) and \( N_3 \). The magnitude of \( \langle V_{y,crz,1} \rangle_G \) decreases faster than \( \langle V_{y,crz,2} \rangle_G \), leading to blowoff of \( N_1 \) at \( t = 730.7 \text{ ms} \). After this blowoff event, the magnitude of \( \langle V_{y,crz,2} \rangle_G \) and \( P_{1,2G} \) decreased sharply, while \( \langle V_{y,crz,3} \rangle_G, \langle V_{y,crz,2} \rangle_G \) and \( P_{1,2G} \) steadily weakened. Blowoff of \( N_2 \) occurred once the CRZ strength was weakened to a similar value as that of \( N_1 \) and \( N_3 \) at the time of blowoff for these nozzles.

Similar inter-nozzle coupling was observed during the reattachment process. Reattachment was preceded by a slight strengthening of the CRZs and increasing jet penetration, which is associated with brief intermittent and partial reattachment of the flames. Subsequent to the steady reattachment of \( N_3 \) at \( t = 1247.8 \text{ ms} \), all CRZs strengthened and jet penetrations increased, which promoted the stable reattachment of the other flames.

Clearly, blowoff or reattachment of one flame affects the flow fields of the other nozzles. In this combustor, as in practical systems, a common reactant plenum is used to feed all
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Figure 3.16: Different aspects of the flow field from stably attached to blowoff in case CR8.

nozzles. It is hypothesized that the change in conditions downstream of a nozzle after blowoff causes a re-distribution of the flow to the other nozzles that promotes their blowoff. That is, the higher density fluid downstream of the blown-off nozzle presents greater resistance to the flow compared to the nozzles with attached flames, thereby increasing the flow rate to the attached nozzles and leading to their blowoff. An analogous process

Figure 3.17: Different aspects of the flow field from blowoff to stably attached in case CR8.
occurs for reattachment, with the first reattached flame decreasing the flow rates to the other nozzles and promoting their reattachment. This flow redistribution combines with the direct inter-nozzle flame interactions described above (i.e. entrainment of flame pockets or cold reactants between nozzles) to present a complicated picture of flame stability in multi-nozzle combustors. The next chapter will further investigate the role of upstream cross-nozzle flow coupling on the flame blowoff by replacing the plenum configuration, such that upstream cross-nozzle interaction was eliminated.
Chapter 4

Individual Plenum Configuration

In the individual plenum configuration, each nozzle had an independent plenum that was fed from a dedicated set of electromechanical mass flow controllers. The effect of several geometric and operating parameters on the lean performance were studied, including inter-nozzle spacing (by changing the nozzles receiving reactants), uneven reactant distribution, and equivalence ratio stratification.

4.1 Multi-Nozzle Combustor Characterization

For convenience of reference, the operating conditions to be discussed in the chapter (originally presented in Table 2.2) are replicated here in Table 4.1.

4.1.1 Isothermal Field

Figure 4.1 shows the $V_x$, $V_y$ and $V_z$ fields for the isothermal flow inside the combustion chamber at $V_{bulk} = 13.7$ m/s with different numbers of operating nozzles, i.e. with various effective nozzle-spacing $S_{eft}$. Each of the flow fields is the result of averaging 10000 consecutive S-PIV acquisitions. The center of this plot ($x/D_n = 0$) is located approximately at the middle of the center nozzle.

The general structure of the flow field was similar to that observed in the connected.

\[ V_{bulk} \] is characterized at $N_2$, $V_{bulk,2}$
Table 4.1: Test conditions performed in individual plenum configuration.

<table>
<thead>
<tr>
<th>Case</th>
<th>Configuration</th>
<th>$S_{efl}$</th>
<th>Observation</th>
<th>$V_{bulk}$ [m/s]</th>
<th>$\dot{m}_{A,2}$ [SLPM]</th>
<th>$\alpha_A$ %</th>
<th>$\alpha_F$ %</th>
<th>$\Delta \phi_s$</th>
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<td>-</td>
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<td>0</td>
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<td>$N_1$ Lifted</td>
<td>11.4$^1$</td>
<td>100</td>
<td>8</td>
<td>0</td>
<td>0.09</td>
</tr>
<tr>
<td>IFR11</td>
<td>$N_0 - N_4$</td>
<td>1.34</td>
<td>$N_1$ Lifted</td>
<td>16.4$^1$</td>
<td>144</td>
<td>1.3</td>
<td>0</td>
<td>0.08</td>
</tr>
<tr>
<td>IFR12</td>
<td>$N_0 - N_4$</td>
<td>1.34</td>
<td>$N_1$ Lifted</td>
<td>16.4$^1$</td>
<td>144</td>
<td>2.1</td>
<td>0</td>
<td>0.013</td>
</tr>
</tbody>
</table>

plenum configuration, consisting of CRZ, ORZ, and high momentum swirling jets. In all cases, the jets expanded radially outward with downstream distance due to the swirling flow. However, this expansion is aerodynamically confined by the presence of the adjacent jets in cases with two and five operating nozzles (Fig. 4.16). The location where the adjacent jets merged into a single jet shifted upstream and the central recirculation zones became more compact as the inter-nozzle spacing decreased. The shape and size of the CRZs were significantly affected by inter-nozzle spacing, but the magnitude of the reverse flow velocity only changed slightly, as demonstrated in Fig. 4.2. Similar to the average flow fields in the connected plenum configuration, systematic asymmetry to the flow from each nozzle was observed, except the recirculation strength of $N_1$ was similar to the
recirculation strength of other nozzles in case IFI1.

4.1.2 Reacting Flow

Figure 4.3 shows the time-averaged FSD for cases ISR1, ITR1, and IFR1. The flame structures for all cases were quite different. In all cases, the flame stabilized along the inner shear layer created by the bluff-body. However, systematic asymmetry was observed in case IFR1. In addition, secondary flame stabilization in the outer shear layers is observed in the region between the operating nozzles in case ITR1, this secondary flame promoted the flame-flame interaction and the flame fronts merged at a further upstream location ($y/D_n \approx 1$). In cases IFR1 and ISR1, intermittent flame stabilization in the outer shear layer were observed and the outer flames were significantly smaller than the one observed in ITR1.

Figure 4.4 shows the $V_x$, $V_y$, and $V_z$ fields inside the combustion chamber for cases ISR1, ITR1, and IFR1, in which all the flames were stably attached to the operating nozzles. The general features of the flow fields were similar to the one observed in the isothermal flow. The largest differences were observed in the IFR1, in which the $S_{eft}$ is the smallest. The flow was more asymmetric and the CRZ of $N_3$ was more compact than other nozzles in the reacting case.

4.2 Effect of Nozzle Spacing On Lean Blowoff

The stability characteristics of the combustor with different $S_{eft}$, shown in Fig. 2.10, indicates that the combustor’s lean operability did not have a monotonic relationship with $S_{eft}$. Instead it was optimized with $S_{eft} = 2.68$. That is, the two-nozzle configuration was more stable than the one-nozzle configuration, which was more stable than the five-nozzle configuration. This is in contrast to the findings from Kariuki et al. [70] and Dolan et al. [69], in which the presence of adjacent nozzles always penalized the lean blowoff performance. This suggests the combustor stability characteristics are governed by complicated inter-nozzle interactions. In this section, the role of the flame and flow dynamics on flame blowoff in the multi-nozzle combustor will be examined.
Figure 4.1: $\vec{V}_x$, $\vec{V}_y$, and $\vec{V}_z$ fields inside the combustion chamber normalized by the $V_{\text{bulk}}$ with air fed into different nozzles: $N_2$ only (a,d,g), $N_1$ and $N_3$ (b,e,h), and $N_0 - N_4$ (c,f,i). The black lines show the locations with $\vec{V}_y = 0$ m/s. The $V_{\text{bulk}}$ through each nozzle is the same for each case shown. One in every 3 vectors shown for clarity.
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Figure 4.2: $\bar{V}_y/V_{bulk}$ profiles at different downstream locations for cases with different number of operating nozzles. The black, red, and blue lines represent cases with $N_2$ (case ISI1), $N_1N_3$ (case ITI1), and $N_0 - N_4$ (case IFI1) operated, respectively.

4.2.1 Blowoff Dynamics

Single-Nozzle Configuration

The sequence of OH-PLIF images in Fig. 4.5 shows a typical blowoff event observed in the single flame configuration at case ISR2. Prior to blowoff, a series of local extinction and re-ignition events were observed at axial location several $D_n$ downstream of the bluff-body, similar to previous studies on blow-off of bluff-body stabilized flames [6, 54, 55, 93]. The local extinction results in flame fragmentation (i.e. $t = 1488.2, 1501.8, 1507.0$ ms), after which unburnt reactants were entrained into the CRZ. Depending on the local balance between the entrainment of cold products and heat release from combustion, the flame could re-establish into a fully burning configuration through downstream flame
convection (i.e. $t = 1488.8 - 1489.6$ ms, c.f. [51, 55]) or continue to extinguish (i.e. $t = 1506.4 - 1510.2$ ms).

**Multi-Nozzle Configuration**

In contrast to the connected plenum configuration detailed in Chapter 3, blowoff of an individual nozzle in the isolated plenum configuration did not lead to blowoff of the other nozzles. This further supports our hypothesis that flow redistribution is a significant contributor to the dynamics of the connected plenum burner.

While the blowoff dynamics for each individual flame in the multi-nozzle configurations with isolated plenums (cases ITR2 and IFR2) were similar to those observed in the single-nozzle configuration (case ISR2), the presence of adjacent flames complicated the blowoff process as shown in Figs. 4.6 and 4.7. It is noted that the measurements were performed at $1.4 \leq y/D_n \leq 3.5$ downstream of the dump plate. In both cases, flame frag-
Figure 4.4: The $V_x$, $V_y$, and $V_z$ fields inside the combustion chamber normalized by the $V_{bulk}$ with air fed into different nozzles: $N_2$ only (a,d,g), $N_1$ and $N_3$ (b,e,h), and $N_0 - N_4$ (c,f,i). The black lines show the locations with $V_y = 0$ m/s. The $V_{bulk}$ through each nozzle is the same for each case shown. One in every 3 vectors shown for clarity.
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Figure 4.5: Sequence of OH-PLIF images showing typical transition from attached to detached states in case ISR2, white circle highlight the local extinction events.

Figure 4.6: Sequence of OH-PLIF images showing typical transition from attached to detached states in case ITR2, white circles highlight the local extinction events, and red circles highlight the cross-nozzle flame transportation.

ments from the adjacent nozzles could be transported through convection, as mentioned in Chapter 3, into the partially extinguished flame’s recirculation zone to help re-establish the flame (i.e. \( t = 385.0 - 385.7 \) ms in Fig. 4.6 and \( t = 1984.4 - 1985.4 \) ms in Fig. 4.7). In addition, the presence of adjacent flames could serve as a pilot for the unburnt reactants issuing out from the (partially) blown out-nozzles to promote reattachment (i.e. \( t = 427.5 - 428.1 \) ms in Fig. 4.6 and \( t = 1982.6 - 1984.0 \) ms in Fig. 4.7).
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4.2.2 Factors Affecting Blowoff Limits

Based on the experimental observations in the flow fields and the flame dynamics prior to blowoff, it is hypothesized that the lean operability is governed by three competing factors, namely the frequency of cross nozzle flame transport, the recirculation zone strength, and the fluid mechanical strain rate inherent to the combustor configuration. The first two factors promote flame stabilization, while the fluid strain may induce local extinctions if it exceeds the extinction strain rate. This section will discuss the role of each factor on the blowoff limits.

To quantify the relationships between $S_{eff}$ and the frequency of observed flame cross nozzle transportation, the OH fields were first divided into two or five regions depending on the number of operating nozzles as demonstrated in Fig. 4.8.

Consecutive measurement time sequences were considered as one individual event when a flame fragment originated from a particular nozzle crossed the boundary and traversed across the nozzles similar to the process observed in Fig. 4.6 (i.e. $t = 385.0 - 385.5$ ms) and Fig. 4.7 (i.e. $t = 1982.8 - 1983.6$ ms). The frequency of the cross-nozzle flame transport at any instance during the measurement period was determined by counting the number of events detected within the rolling window from $t$ to $t - 150$ ms.
Figure 4.8: Representative OH field with all the flames stably attached, where the regions used to determine the flame cross-nozzle transport is marked in black boxes.

Figure 4.9: Number of flame cross-nozzle transportation events within the rolling window from $t$ to $t - 150$ ms.

normalized by the rolling window size as demonstrated in Fig. 4.9. The green lines in Fig. 4.9 indicated the frequency of the cross-nozzle flame transport events observed within the rolling windows in the corresponding case. Similar to the observations reported by Barre et al. [63], at small $S_{eft}$, flame fragments were subjected to less variability and this kind of flame cross-nozzle transportation occurred more frequently.

While the cross-nozzle flame interaction is plausible to explain the enhanced lean operating envelope when the number of operating nozzles increased from one to two, one may consequently expect the combustor operability continued to improve when the inter-nozzle spacing was reduced further in the five-nozzle configuration, since flame fragments
could be transported into neighbouring nozzles more easily. However, adjusting the $S_{eft}$ would change the flow field, and hence the hydrodynamics, which may explain the superior lean performance observed in the combustor with two operating nozzles.

The fluid strain may contribute to the flame blowoff by inducing local flame extinction in the high strain region. Figures 4.10a-4.10c show two representative instantaneous snapshots of the magnitude of in-plane fluid strain ($S = \sqrt{S_{ij}S_{ij}}$) overlaid with the flame locations for cases ISR1, ITR1, and IFR1, respectively. The instantaneous tangential

---

**Figure 4.10**: Magnitude of in-plane fluid strain rate ($S$) overlaid with the flame topology (black line).
strain rate on the flame can be calculated from the velocity gradients obtained from the S-PIV measurements and the flame topology using Eqn. 2.3. Figure 4.11 show the probability density function (pdf) of tangential strain ($a_t$) experienced by the flame front in two different downstream regions for cases ISR1, ITR1, and IFR1. The $a_t$ pdfs for cases ISR1 and ITR1 were similar, with the flames in case ITR1 experiencing slightly higher compressive strain rates. In contrast, case IFR1 experienced significantly higher magnitude tangential strain-rates. It is hypothesized that the increased extinction associated with higher strain rate in the five-nozzle configuration was more significant than any stabilization benefit through inter-nozzle transport of burning flame segments.

To check whether this hypothesis is sufficient to explain the deterioration in lean operability limits for the five-nozzle configuration, the mean strain fields at the blowoff conditions are compared for each $S_{eft}$ (cases ISR2, ITR2, and IFR2). One may expect the mean strain fields at blowoff conditions would be similar, however, this is not the case. The average $S$ for cases ISR2 and ITR2 were significantly higher than IFR2. That indicates just because cases ISR1 and ITR1 experienced a smaller magnitude of $a_t$ relative to case IFR1 at condition with $V_{bulk} = 13.7$ m/s, does not mean the strain resulting in the blowoff would be the same for combustor with different $S_{eft}$. 

\[ 0.2 \leq y/D_n \leq 0.6 \]
\[ 1.2 \leq y/D_n \leq 1.8 \]

**Figure 4.11:** The pdf of tangential strain rate ($a_t$) experienced by the flame fronts in two different downstream locations for different operating configurations with $V_{bulk} = 13.7$ m/s.
Figure 4.12: Mean magnitude of in-plane fluid strain ($S$) at blowoff conditions with different number of operating nozzles.
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Table 4.2: Evaluation of different parameters at intermittent blowoff conditions with different number of operating nozzles.

<table>
<thead>
<tr>
<th>Case</th>
<th>( V_{\text{bulk}} ) [m/s]</th>
<th>( L_{\text{crz}} ) [( 10^{-2} ) m]</th>
<th>( S^0_L ) [m]</th>
<th>( \delta_f ) [( 10^{-4} ) m]</th>
<th>( Da )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISR2</td>
<td>30.8</td>
<td>4.6</td>
<td>0.16</td>
<td>7.8</td>
<td>0.30</td>
</tr>
<tr>
<td>ITR2</td>
<td>41.1</td>
<td>5.8</td>
<td>0.16</td>
<td>7.8</td>
<td>0.29</td>
</tr>
<tr>
<td>IFR2</td>
<td>16.4</td>
<td>2.7</td>
<td>0.16</td>
<td>7.8</td>
<td>0.33</td>
</tr>
</tbody>
</table>

The differences in the critical strain that resulted in the blowoff of the nozzle suggests the recirculation strength also played an important role. It is noted that the recirculation strength for cases with two-operating nozzles are the strongest, which can potentially extend the blowoff limits by recycling heat and combustion radicals [44].

In blowoff analysis, it is common to describe the blowoff limits in terms of a Damköhler number, which relates the time scales of chemistry and turbulence in the combustion zone. The application of this dimensionless number enables one to relate the stability limit in a laboratory-scale combustor to that required for a full-scale system. To demonstrate the importance of the recirculation strength, the following form of Damköhler number [93] is adopted:

\[
Da = \frac{L_{\text{crz}}/V_{\text{bulk}}}{\delta_f/S^0_L} \tag{4.1}
\]

where the \( L_{\text{crz}} \) is the time averaged length of the CRZ for the blown nozzle.

Table 4.2 shows the \( Da \) calculated with Eqn. (4.1). It is noted that the measurement field-of-view was not large enough to cover the whole CRZ region for case ISR2; the \( L_{\text{crz}} \) was estimated by the rate of decay for the reversed velocity (become less negative) along the center \( x/D_n = 0 \) at the downstream region of the CRZ, which is around \( 177 \text{ s}^{-1} \). The resultant \( Da \) for all cases lie between 0.29 to 0.33.

The general picture of how different factors influencing the blowoff limits are summarized here. As the fluid strain rate increased with \( V_{\text{bulk}} \), the probability of local extinction increased [51]. Blowoff occurred when the re-ignition by the entrainment of unburnt reactants into the CRZ and cross-nozzle flame transport were not fast enough relative to the local flame extinction. It is noted that for combustor with a small \( S_{\text{eft}} \), the inherit fluid strain is higher and the CRZs are weaker. Hence, it is more prone to blowoff compared
to the combustor with a larger $S_{\text{eft}}$.

4.3 Effect of Non-uniform Reactant Distribution on Lean Blowoff

Up to this point, the discussion about the factors controlling the blowoff limits in combustor with the isolated reactant feeding configuration is based on the assumptions that the fuel and air are ideally premixed and evenly supplied to each operating nozzle. However, the reactant feeding system in practical gas turbine engines is much more complicated [2]; as a result it is quite common that reactants are not evenly distributed across the combustor. Both the velocity and equivalence ratio of the flames may vary across the combustor rig. All of these can potentially affect the lean blowoff limits of the combustor. To isolate the effect caused by uneven reactant mass flow rate distribution and equivalence ratio stratification on the lean stability limit, two scenarios were considered separately.

In the first scenario, the equivalence ratio to all nozzles was maintained at $\phi = 0.65$ but the total air and fuel flow rates ($\dot{m}_{A,i}, \dot{m}_{F,i}$) to each nozzle was varied. Figure 4.13 illustrates how the uneven reactants flow rate distribution was achieved.

One of the main questions is whether the presence of uneven reactants distribution can improve or deteriorate the combustor’s lean blowoff limits. As mentioned in the previous sections, $N_3$ was the most prone to liftoff among all the nozzles due to the net swirl in the combustor. We have considered an operating condition at which $N_3$ intermittently lifted from its nozzle (Fig. 4.14a). By re-distributing the reactant mass flow rate across each nozzle ($\alpha_A \neq 0$ and $\alpha_F \neq 0$), all five flames became stably attached to the nozzles even though $\dot{m}_{A,T}$ and $\dot{m}_{F,T}$ remained constant as demonstrated in Fig. 4.14b-4.14c. Further increasing the variations of reactants flow rates across the rig, the fluid strain associated to $N_1$ increased, and eventually resulted in liftoff of $N_1$ at $\alpha = 20.8\%$.

Figure 4.15 shows the $V_y$ fields normalized by the $V_{\text{bulk}}$ of $N_2$ ($V_{\text{bulk},2}$) for cases IFR2, IFR3, and IFR5. It is observed that the swirling jets of $N_3$ expanded towards the adjacent
nozzles as $\alpha_A$ increased, due to higher momentum, while the swirling strength of $N_2$ \(\left\langle V_y, cr_z, 2 \right\rangle\) reduced by 9.3% (from -6.4 m/s to -5.8 m/s) as $\alpha_A$ increased from 0% to 20.8%. This indicates the flows are coupled together, changes in the inlet condition of one nozzle will affect the adjacent nozzles due to momentum transfer as suggested by Fanaca et al. [62].

Figure 4.16 demonstrates how the stratified combustion was achieved in the second scenario, in which the fuel flow rates ($\dot{m}_{F,i}$) to each nozzle was held constant and the air mass flow rate ($\dot{m}_{A,i}$) was varied resulting in variations of equivalence ratio across the nozzles.

Figure 4.17 shows that at an operating condition that is far away from the liftoff of any nozzle, all the flames remained stably attached to the nozzle until $\alpha_A$ reached 8%. On the other hand, if the system was originally operating at a condition where $N_3$ was intermittently lifted, a small amount of stratification $\alpha_A = 1.3\%$ was enough to stabilize
**Figure 4.14:** Average OH*-CL signal showing the combustor response at conditions with $\dot{m}_{A,2} = 144 SLPM$ and different $\alpha_A$s: case IFR2 (a), case IFR3 (b), case IFR4 (c), and case IFR5 (d).

It is interesting to observe that the combustor performance is more sensitive to the changes in $\phi$ rather than changes in the reactant mass flow rate. Again, we are interested to see if we can arrive at a common $Da$ correlation such that one would be able to predict how much variation in mass flow rate and equivalence ratio the system can handle before reaching the blowoff condition. Since the $L_{crz}$ did not vary much for cases with the same $S_{eft}$, the Damköhler number of each nozzle can be estimated as

$$Da_i = \frac{(D_n/V_{bulk,i})}{(\delta_{f,i}/S_{L,i}^0)}$$  \hspace{1cm} (4.2)
Chapter 4. Individual Plenum Configuration

(a) $\alpha_A = 0\%$

(b) $\alpha_A = 13.9\%$

(c) $\alpha_A = 20.8\%$

Figure 4.15: $\nabla_y$ flow fields with different $\alpha_A$s: case IFR2 (a), case IFR3 (b), and case IFR5 (c).

where the $V_{bulk,i}$ is the bulk velocity, $S_{L,i}^0$ is the laminar flame speed, $\delta_{f,i}$ is the laminar flame thickness for the corresponding nozzle, calculated at conditions at which blowoff occurred for one of the nozzles. Table 4.3 shows the resulting values at multiple conditions.

As noticed from the stability characteristics, the $1/Da_i$ varied across the nozzles for combustor with $S_{eff} = 1.34D_n$, ranging from 0.13 to 0.20. The presence of uneven reactant distribution does not change the blowoff limits for individual nozzle obtained from the conditions with uniform reactants distribution. For instance, $Da_1$ for cases
Figure 4.16: Schematic drawing demonstrating the stratification driven by uneven air flow rate distribution across the rig.

\[ \dot{m}_{A,T} = 5 \times \dot{m}_{A,2} \]
\[ \dot{m}_{F,T} = 5 \times \dot{m}_{F,2} \]
\[ \Delta \phi_s = 0 \]

\[ \dot{m}_{A,T} = 5 \times \dot{m}_{A,2} \]
\[ \dot{m}_{F,T} = 5 \times \dot{m}_{F,2} \]
\[ \Delta \phi_s \neq 0 \]

\[ \dot{m}_{A,2}(1 + \alpha_A), \dot{m}_{F,2} \quad \dot{m}_{A,2}(1 - \alpha_A), \dot{m}_{F,2} \]

Figure 4.17: Average OH*-CL signal showing the combustor response at conditions with \( \dot{m}_{A,2} = 100 \text{SLPM} \) and different \( \alpha_A \): case IFR6 (a), case IFR7 (b), and case IFR8 (c).

IFR3, IFR7, IFR10, and IFR12 collapsed to a single point. Given that the total reactant mass flow rates for cases IFR3 and IFR8 are the same, and \( 1/Da_1 \) for IFR3 and IFR7 agree with each other, this suggests that the overall combustor’s lean operability can be
improved by allowing the reactants to distribute itself as long as the $Da_i$ are kept above their corresponding critical values.

### 4.4 Comparison of Connected and Isolated Plenum Configurations

The observed differences in the flame dynamics as the combustor operating condition approached to the lean blowoff limits between the systems with connected (Chapter 3) and isolated plenum suggests that upstream coupling is a significant factor in blowoff of the connected plenum system, its role will be discussed in this section.

In the subsequent analysis, simultaneous OH*-CL and PIV were performed in the...
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(a) Individual plenum (case IFI1)  
(b) Connected plenum (case CI1)

Figure 4.19: Representative instantaneous $V_y$ fields inside the plenum for cases with different plenum configurations (cases IFI1 and CI1). The regions used to calculate the $V_{y,B,i}$ marked in black boxes, while the white regions in (a) correspond to the area blocked by the combustor enclosure.

combustion chamber and plenum, respectively, to measure the flame behaviour and the flow field inside the plenum. The inflow velocities upstream of the three center nozzles ($N_1 - N_3$) were quantified by calculating the average transverse and axial velocities inside the three probe boxes ($\langle V_{x,B,i}\rangle$, $\langle V_{y,B,i}\rangle$) as shown in Fig. 4.19 for both plenum configurations. It is noted that the $V_{bulk}$ for both cases are slightly different. For the purpose of comparison, only the fluctuations of both velocity components inside the probe boxes, $\langle V_{x,B,i} \rangle_F = \langle V_{x,B,i} \rangle - \langle V_{x,B,i} \rangle$ and $\langle V_{y,B,i} \rangle_F = \langle V_{y,B,i} \rangle - \langle V_{y,B,i} \rangle$, were considered. Figure 4.20 shows the variations of $\langle V_{y,B,i} \rangle_F$ typically observed in both plenum configurations. It is noted that the white regions in Fig. 4.19a correspond to the regions blocked by the plenum dividers.

A total of 10000 snapshots for each case were used to compute statistics. The pdf's of the $\langle V_{x,B,i} \rangle_F$ and $\langle V_{y,B,i} \rangle_F$ measured in both configurations are depicted in Fig. 4.21 in which the $\sigma_{I,x,i}$, $\sigma_{I,y,i}$, $\sigma_{C,x,i}$, $\sigma_{C,y,i}$ are the standard deviations of the $\langle V_{x,B,i} \rangle_F$ and $\langle V_{y,B,i} \rangle_F$ in both configurations, respectively.

The distributions of $\langle V_{x,B,i} \rangle_F$ and $\langle V_{y,B,i} \rangle_F$ in the connected plenum configuration (case CI1) are wider for all two velocity components. In general, $\sigma_{C,x,i}$ and $\sigma_{C,y,i}$ are about 4 and 3 times the $\sigma_{I,x,i}$ and $\sigma_{I,y,i}$, respectively. This suggests the flow was more chaotic when the flow in the region upstream of each nozzle was allowed to interact with each other. At the same time, this observation implies the coupling in flame transitions
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(a) Individual plenum configuration (case IFI1)

(b) Connected plenum configuration (case CI1)

Figure 4.20: Representative $\langle V_{y,B,i} \rangle_F$ observed in the different plenum configurations.

Figure 4.21: The pdfs of $\langle V_{x,B,i} \rangle_F$ and $\langle V_{y,B,i} \rangle_F$ measured in individual (case IFI1) and connected plenum configurations (case CI1), where $\sigma_{I,x,i}$, $\sigma_{I,y,i}$, $\sigma_{C,x,i}$, $\sigma_{C,y,i}$ are the standard deviations of the $\langle V_{x,B,i} \rangle_F$ and $\langle V_{y,B,i} \rangle_F$ in individual and connected plenum configurations, respectively.
observed in the connected plenum configuration maybe related to the flow interaction within the plenum region.

The \( \langle V_{y,B,i} \rangle \) with different flame attachment states were examined to further understand how the flow in the region upstream of each nozzle responded to the changes in flame dynamics inside the combustion chamber in case CR7. Similar to the analysis mentioned in Section 3.3, the state of flame \( i \) at any instant during the measurements were determined by the total OH*-CL signal intensity in region \( i \), normalized by each region’s maximum over the time sequence (\( \Omega_{CL,i} \)). The time sequence was divided into two distinct states, namely all five flames stably attached (shaded in red in Fig. 4.22a) and three central flames blown-off (shaded in red in Fig. 4.22a). Based on \( \Omega_{CL,i} \), the \( \langle V_{y,B,i} \rangle \) measured at the attached and blown off states are \( \langle V_{y,B,i} \rangle_a \) and \( \langle V_{y,B,i} \rangle_b \) as shown in Fig. 4.22b, respectively.

Three independent trials of measurements were performed for case CR7, which provided a total of 35161 snapshots to compute the distribution. Figure 4.23 shows distributions of the \( \langle V_{y,B,i} \rangle \) over the time instants where all five flames were stably attached (54%), and the three central flames were blown-off (46%) for all three trials. The mean of the probe velocity distributions at the attached and blown-off states are \( \mu_{y,i|a} \) and \( \mu_{y,i|b} \).

It is observed that when the three central flames were blown off, \( \mu_{y,1|b} \) and \( \mu_{y,3|b} \) increased, while \( \mu_{y,2|b} \) decreased. From this trend, one would expect the blowoff of \( N_3 \) should be followed by the blowoff of \( N_1 \), which corresponds to the OOI transition mentioned in Section 3.3. However, given that the probabilities of OIO and OOI are close to each other, as shown in Fig. 3.6a, this suggests the coupled blowoff observed in the connected plenum configuration (which resembles to the practical system) is attributed to the the complex interaction of both cross-nozzle interaction within the plenum, and the local balance of the cold reactants and heat release within the combustion chamber as demonstrated in the flow diagram shown in Fig. 4.24.

The blowoff of one nozzle was followed by changes in the strength of the recirculation zone and jet penetration of the other nozzles, which can be due to a complex interaction of several competing factors. The blown out nozzle allows higher density cold reactants entering the combustor chamber, which can potentially lower the overall combustor tem-
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Figure 4.22: Representative $\Omega_{CL,i}$ and the corresponding $\langle V_{y,B,i} \rangle$ observed for different nozzles in case CR7: $N_1$ (black), $N_2$ (red), and $N_3$ (blue).

Temperature. At the same time, the adjacent attached nozzles provides additional means of re-stabilizing a (partially) extinguished flame through serving as pilots for the reactants issuing from the blown-out nozzle and cross-nozzle flame convection, which can lead to loss of heat from the attached flames and weaken the recirculation strength. In addition, the change in flame attachment state leads to upstream flow redistribution across the combustor. Both complex heat transfer occurring in the chamber and upstream
cross-nozzle interactions are equally important in the multi-nozzle flame blowoff process. Similarly, the reattachment of one nozzle leads to upstream flow redistribution, and at the same time it can serve as a pilot for the reattachment adjacent nozzles. However, it is noted that the in chamber cross-nozzle interaction plays a more important role in reattachment transitions, as reattachment of one nozzle is more likely to be followed by the reattachment of the nozzle next to it.

Figure 4.23: The pdf of $\langle V_{y,B,i} \rangle$ during different flames attachment states in case CR7: all five flames attached (red), and three central flames blown-off (blue).
Figure 4.24: Proposed mechanism for the coupled lean blowoff in typical multi-nozzle system.
Chapter 5

Conclusion and Future Work

5.1 Conclusion

This thesis investigated the transition between different flame stabilization modes in a gas turbine model combustor comprised of several interacting nozzles, which is representative of advanced designs for next generation engines. The objective was to understand the effects of different geometric and operating parameters on the combustor stability near the lean operability limit. The combustor consists of an array of five axial swirlers with inter-nozzle spacing of 1.34 times of the $D_n$, and the center of each swirler is comprised of a bluff-body with a flat trailing edge. Two different reactants feeding configurations were designed to isolate the effects of different aspects of the system on the combustor’s fuel lean performance. The first configuration closely resembled the feeding system in practical combustors, in which reactants to each nozzle were fed through a common plenum, and the flow was allowed to naturally distribute between the nozzles. In the second configuration, each nozzle had an independent plenum that was fed from a dedicated set of electromechanical mass flow controllers. The transient processes of flame blowoff and reattachment inside the combustor were examined experimentally using 5-10 kHz repetition rate OH-PLIF and S-PIV. The main observations and conclusions of this study are as follows:

1) In the multi-nozzle combustor, the blowoff process for an individual flame was initiated in a similar manner to isolated bluff-body stabilized flames, in which a sequence of
local extinctions occurred at axial locations several nozzle diameters downstream of the combustor entrance and resulted in flame fragmentation. However, the presence of multiple interacting flames in the combustor could mitigate this affect through entrainment of flame segments from an adjacent nozzles by convection or the region downstream of the merged flame tips. These processes are expected to increase flame stability relative to a single nozzle combustor. Nevertheless, local extinction could eventually dominate and lead to blowoff of an individual flame in a manner similar to single nozzle combustors.

2) The effect of inter-nozzle spacing ($S_{eft}$), by changing the nozzles receiving reactants, on combustor stability characteristics was investigated in the individual plenum configuration. In contrast to the previous studies [69, 70], the combustor’s lean operability did not have a monotonic relationship with $S_{eft}$. It was found that the two-nozzle configuration was more stable than the one-nozzle configuration, which was more stable than the five-nozzle configuration. While the cross-nozzle flame transport through convection is plausible to explain the enhanced lean operating envelope when the number of operating nozzles increased from one to two, the increase in strain field and reduction in recirculation strength played a more dominant role in the stability limits as the number of operating nozzles from two to five. The $Da$ correlation with the ratio of averaged length of recirculation zone to the $V_{bulk}$ as the fluid time scale for combustor with different effective nozzle spacings agreed well with each other.

3) The effect of variation in reactant mass flow rate and equivalence ratio across the combustor rig on the lean blowoff limits was investigated in the individual plenum configuration. Two different sets of tests were performed, one in which the equivalence ratio to all nozzles was constant but the total flow rate to each nozzle was varied, and one in which the fuel flow rates to each nozzle was held constant and the air mass flow rate was varied resulting in different equivalence ratio across the nozzles. It is found that the presence of uneven reactant distribution and equivalence ratio stratification do not change the blowoff limits for individual nozzle obtained from the conditions with uniform reactants distribution, as the $Da$ correlation for each nozzle in different scenarios
collapsed into a single point. In addition, the experimental results demonstrate that the overall combustor’s lean operability can be improved by allowing the reactants to distribute itself among all the nozzles, as long as the flow condition for individual nozzle was larger than the critical $D_{a_i}$.

4) In the connected plenum configuration, it was found that the blowoff of one nozzle was followed by decreases in strength of the recirculation zone and jet penetration of the other nozzles; blowoff of a single nozzle was followed shortly by blowoff of the other nozzles. Nozzles $N_3$ preferentially blew off first, but no preference was found for the ordering of blowoff of the subsequent nozzles. After all flames were blown-off, the flame stabilized downstream of the inflowing jets and recirculation zones. The reattachment process involved a flame segment entering the recirculation zone of a particular nozzle, moving upstream, and eventually reigniting the attached flame. Steady stabilization of an attached flame was preceded by intermittent reattachment. Shortly following the reattachment of one flame, the flames for the other nozzles reattached in a similar manner. $N_3$ preferentially reattached first, the reattachment of one nozzle was followed by increases in strength of the recirculation zone and jet penetration of the other nozzles. While flame segments from the reattached nozzle could be entrained into the recirculation zones of other nozzles, the reattached flame can served as a pilot to enhance reattachment of middle nozzle.

5) Such temporal coincidence of the blowoff and reattachment transitions were not observed in the individual plenum configuration, which suggests the upstream coupling could not be neglected. It is hypothesized that changes in downstream conditions as a result of flame attachment states transition would lead to flow re-distribution inside the plenum and promote the blowoff/reattachment of other nozzles. The statistical analysis performed in both reactants feeding configurations shows that the upstream velocity distribution was wider in the connected plenum, indicating the presence of flow interaction within the plenum region. In addition, it is found that the blowoff/reattachment of any nozzle leads to upstream flow redistribution in the connected plenum configuration, in
which the upstream velocities increased for the outer nozzles, but decreased for the inner one. Given the slight preference regarding the sequencing of the transitions between nozzles, these demonstrate that the in chamber and upstream cross-nozzle interactions are equally important in flame blowoff transitions inside a practical combustor. On the other hand, it is found that the in chamber cross-nozzle interaction plays a more important role in reattachment transitions.

6) These findings have significant implications for gas turbine combustor designs that utilize interacting nozzles, particularly in terms of the complex cross-nozzle interaction processes within the plenum region that would need to be simulated in order to accurately predict stability limits and the interpretation of stability data from single-nozzle experiments.

5.2 Future Works

With the current proposed findings, a better understanding of the flame dynamics and the flow condition in the upstream region near blowoff is required. It can be achieved by performing S-PIV in the combustion chamber and premixer region simultaneously.

In addition, it would be of interest to measure the temperature field inside the combustion chamber. Since the reattachment of a particular nozzle is more likely to be followed by the adjacent ones, this means the thermal heat transfer is playing an important role in reattachment transition. Measuring the changes in temperature in the regions downstream of the adjacent nozzles after reattachment of a particular nozzle will allow a better examination of the linkage between heat transfer and the CRZs.
Bibliography


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