Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-46676

A REVIEW OF MECHANISMS CONTROLLING BLUFF-BODY STABILIZED FLAMES WITH CLOSELY-COUPLED FUEL INJECTION

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ABSTRACT

The processes controlling bluff-body stabilized combustion have been extensively studied over the years because such stabilization approaches are commonly used in many practical systems. Much of the current understanding of this problem was attained in experimental and analytical studies of premixed combustion systems where the complexities introduced by fuel atomization, vaporization and mixing could be neglected. Yet, practical considerations often require fuel injection just upstream of the bluff-body stabilized combustion region. Consequently, it's necessary to develop understanding of the fundamental processes in such non-premixed systems. Supplying fuel via the injection of discrete liquid fuel jets requires understanding of the complex physics of two-phase sprays and the transport to various regions within the combustor. This paper describes current understanding of the manner in which these processes affect flame stabilization in bluff-body combustion systems that employ close-coupled, liquid fuel injection. Specifically, the paper compares findings of premixed bluff-body flames with recent results obtained in studies using close-coupled fueling at Georgia Tech to support postulates of the processes controlling flame stabilization and flame structure. These findings are also used to propose a set of parameters that can be used to describe the combustion behavior and performance of such combustion systems.

INTRODUCTION AND BACKGROUND

Bluff-body flameholders are used to stabilize the combustion process in many practical propulsion and power generating systems such as gas turbines, industrial boilers, and ramjet and scramjet engines. The advantages of bluff-body flameholders over, e.g., swirl-stabilized configurations, are their relative simplicity, low cost and light weight. Bluff-body

NOMENCLATURE

d_0	=	fuel jet orifice diameter
L_{RZ}	=	length of recirculation zone
Le	=	Lewis number
J	=	momentum flux ratio of fuel jet to cross-flow
Re	=	Reynolds number
S_L	=	laminar flame speed
T_b/T_u	=	ratio of burned to unburned temperatures
u'_{FS}	=	free-stream turbulence level
U_e	=	velocity at edge of boundary layer
U_∞	=	bulk free-stream velocity
V_{jet}	=	velocity of liquid fuel jet
W	=	width of bluff-body
W_F	=	width of fuel pattern behind flameholder
W_S	=	width of fuel spray
We	=	Weber number
X_{FH}	=	distance from fuel injector to flameholder lip
Y_S	=	spacing between fuel injectors
κ	=	fluid strain rate
ε/k	=	ratio of turbulent dissipation to kinetic energy
Φ	=	equivalence ratio
σ_F	=	surface tension of fuel
θ_M	=	boundary layer momentum thickness
θ_T	=	thermal boundary layer thickness
τ_{EXT}	=	chemical extinction time scale

flameholders are typically used in higher Mach number applications like gas turbine afterburners or ramburners where liquid fuel is used and a low pressure drop is desired. Since mixing rates in these applications are considerably lower than a typical swirl-based system, the fuel is burned in relatively long flames downstream of near-field recirculation zones.

The fundamental processes controlling bluff-body stabilized combustion have been extensively studied over the years [1-5]. These experimental and analytical studies mostly addressed premixed combustion systems where the complexities associated with fuel atomization, vaporization and mixing could be neglected. Yet, many practical combustion systems, e.g., in aircraft engines, don't use premixed combustion but supply the fuel via discrete liquid jets injected a short distance upstream of the flame stabilization point. In fact, premixed systems have been avoided in modern gas turbines because high combustor inlet temperatures could cause potentially problematic autoignition [6], as is the case in ramjets and scramjets as well. Fuel injection schemes typically employ a system of simple orifice pressure atomizers that inject liquid fuel jets normal to the cross-flow direction and are sized to "optimally" distribute the fuel in the combustor volume. The dispersion of the fuel is now governed by complex atomization and mixing processes and the physics controlling bluff-body flame stabilization now depend upon the physics of complex two-phase reacting flows involving liquid and gaseous fuel species. Since fuel delivery rates typically vary significantly over the engine operating range, the flame stabilization process can depend strongly upon the operating condition, as well as the mode of liquid fuel injection and aerodynamic design of the bluff-body.

While studies of directly-fueled bluff-body [7] and cavity-type flameholders [8] show the importance of the interaction between the fuel injection system and the bluff-body aerodynamics, the fundamental processes that control these flame stabilization processes have not been adequately studied. To gain more understanding, this paper considers the physics of combustion process stabilization by a "simple", single bluff-body with directly-coupled liquid fuel injection using a number of circular fuel orifices located just upstream of the flameholder's trailing edge. This problem has been chosen for consideration in this paper because it includes features of bluff-body flame stabilization often used in gas turbine combustors and because this configuration has been recently investigated [6,9].

While previous experiments studying liquid fuel sprays have led to the development of correlations for fuel spray penetration and droplet diameter distribution, which allow engineers to estimate the position of the liquid fuel, accurate analytical predictions of fuel spray distribution are not yet possible. This is because of the complex physics that control the fuel jet breakup, atomization, evaporation, dispersion and subsequent mixing processes. Nevertheless, applications of advanced experimental diagnostics and modeling capabilities during the past twenty years have significantly improved the understanding of the interactions of a liquid fuel jet in a cross-flowing gas stream [10,11]. As the fuel jet penetrates into the cross-flow, interactions between the liquid jet and cross-flow flattens the liquid jet in the span-wise direction. This is followed by the formation of liquid ligaments and droplets, which may experience secondary droplets generation and ligament breakups that produce smaller droplets. In addition, the cross-flow exerts shearing forces upon the liquid jet that result in the formation of a cloud of small droplets that are stripped off the liquid fuel jet. The stripping mechanism creates a narrower range of small droplets, many of which are entrained into the wake flow behind the liquid jet near the bluff-body's wall. These complex atomization processes lead to the formation of a fuel spray consisting of a broad range of liquid droplet sizes which depend upon the ratio of the aerodynamic forces to the surface tension forces exerted upon the fuel jet, which is described by the Weber number (We). The distribution of liquid fuel droplets depends, therefore, on the properties of the fuel, the momentum of the liquid fuel jet, the characteristics of the gas stream, and the injector geometry. Furthermore, since the liquid fuel injection is inherently unsteady, involving a range of length and time scales, the resulting interactions between the fuel and gas phases may become very complex.

Previous studies of bluff-body flame stabilization in premixed combustion systems showed that the flame blowout limit could be correlated with a stability parameter depending on the flameholder's dimension, the free stream velocity, and the approach flow pressure and temperature [12,13]. The exponents used in these correlations account for combustion chemistry while the effects of fluid mixing are "absorbed" in an empirical constant. The early correlations developed for flame stability in premixed systems were essentially based upon the notion that the flame stabilization requires the presence of combustion in the recirculation zone (RZ). A recent review by Shanbhogue et al. [5] shows how the data is best described by use of a Damköhler number defined as a ratio of a fluid mechanical mixing time scale and a chemical time scale. While the chemical time for premixed systems may be "reasonably" prescribed based on the overall fuel-air ratio, description of the fluid mixing time is considerably more problematic. The assumption that mixing times are proportional to the ratio of a flameholder width to approach velocity seems to be a reasonable first approximation.

In contrast with premixed systems, where a characteristic chemical time for a Damköhler number can be defined, a corresponding single chemical time cannot be readily defined when liquid fuel jets are injected into the cross-flow prior to burning. This is because the so called "chemical" time needs to account for the times needed for atomization, vaporization and mixing processes, which may vary in space and time with close-coupled fueling. Additionally, one may have to account for the fact that some of these processes may occur "in parallel" rather than "in series" (i.e., they may occur simultaneously rather than sequentially). Furthermore, the local equivalence ratio in the resulting flame may vary with space and time. Consequently, the flame holding stability limits for non-premixed systems may not be describable by a single Damköhler number based on macro-scale parameters. In this case, predicting the stability of the combustion process may be only possible using multi-variable parametric analyses or numerical simulations of the process. In addition to the static stability, the dynamic characteristics of the bluff-body flame could be strongly influenced by spatial and temporal non-uniformities in local fueling.

This paper attempts to use knowledge of the processes that control bluff-body recirculation zone mixing and combustion, the behavior of two-phase liquid sprays (which govern fuel distribution) and far-field flame propagation to support hypotheses regarding the fundamental processes that control bluff-body stabilized combustion. A set of governing parameters is introduced that "contain" the physics that control this problem. This set of parameters should account for the properties of two-phase fueling, flameholder and injector geometries and aerodynamics, and operating conditions that are known to affect the performance of non-premixed, bluff-body stabilized combustion processes. Such a set of parameters could be used to describe the system's behavior and performance and/or guide the development of simulations and scaling of experimental results that are used in the design of full-scale bluff-body stabilized combustors.

This paper includes four sections of discussion. The first section describes the aerodynamic aspects of bluff-body flows, the second section discusses combustion characteristics for premixed flames, the third addresses combustion aspects for non-premixed flames, and the last section describes recent experimental results to support several postulates for bluff-body stabilized flames using close-coupled fuel injection.

RESULTS AND DISCUSSION

Description of Bluff-body Flow Processes

It is useful to describe the aerodynamics of a bluff-body's flow field by considering the time-averaged flow, as depicted in Figure 1, in spite of the fact that the actual flow is inherently unsteady. Typically, boundary layers first form on the top and bottom walls of the bluff-body whose characteristics depend on the length and shape of the bluff-body, the local pressure gradients, $\overrightarrow{\nabla P}$, and the free-stream turbulence, u'_{FS}. When the walls of the bluff-body are heated or cooled, a thermal boundary layer of thickness, θ_T, also forms on the bluff-body, in addition to the velocity boundary layer. The presence of a thermal boundary layer could affect the location of the separation point and vortex formation processes within the shear layers, as discussed below.

As the boundary layers separate from the downstream edge of the bluff-body, shear layers form downstream of the separation points around a recirculation zone (RZ) of length L_{RZ}. The normalized length of the RZ for high Reynolds numbers flows is typically of the order $L_{RZ}/W \sim 3$, where W is the bluff-body's width. This length depends upon the momentum exchange between the RZ and the free stream, which, in turn, depends upon the free stream turbulence level, pressure gradients, and the characteristics of the shear layers between the RZ and free stream. The energy-containing length scale for the shear layer flow is of the order of the momentum thickness, significantly less than the flameholder width, as depicted in Figure 1. The flow along the centerline within the RZ between the bluff-body and the location x= L_{RZ}, which is a stagnation point, is reversed and directed towards the bluff-body. Downstream of x= L_{RZ}, the flow transitions from a recirculating flow in the near-field wake behind the bluff-body to a wake flow in the far-field region of the bluff-body flow field. This transition region, where the RZ closes, in the range $2W <$x$< 4W$, is referred to here as the "Close Out Region" (COR). In this region, the streamlines converge and then diverge from the centerline, and strong gradients and fluid strain rates may be present in the flow. Downstream of the stagnation point and COR, the flow along the centerline moves away from the bluff-body and its velocity increases due to entrainment of high-momentum free stream flow.

The shear layers between the RZ and free stream are important features of the flow. These shear layers may experience Kelvin-Helmholtz (KH) instabilities at practical Reynolds numbers, which lead to the formation of coherent vortical structures in the flow. These vortex formation processes depend upon the boundary layer momentum thickness, θ_M, and the edge velocity, U_e, at the point where the flow separates from the bluff-body. The length scale of these vortices increases in proportion to $\mathrm{Re}^{1/2}$ as these vortices are convected downstream by the shear layers. At high Reynolds numbers, these shear layers may also experience instabilities that generate three-dimensional turbulent structures.

Another fundamental instability that may be encountered in isothermal bluff-body flows is the absolutely unstable, Bénard/von Kármán (BVK) instability, which occurs in the far-field wake region. The BVK instability is associated with transverse flow oscillations in the near-wake region that produce large coherent vortices that are alternately shed from top and bottom of the bluff body. The frequency of this instability generally scales with the ratio of the free-stream velocity to the bluff-body width and is characterized by a relatively constant non-dimensional frequency or Strouhal number of approximately 0.22. The ratio of the shear layer oscillation frequency to the BVK frequency for an isothermal flow around a bluff-body has been shown by Prasad [14] to scale as follows:

$$\frac{f_{SL}}{f_{BVK}} \approx \mathrm{Re}^{0.7}$$

and that these flow time scales are only in resonance for very low Reynolds number, ~ 260. Yet, the relationship and coupling of the shear layer and the BVK vortices is yet to be elucidated.

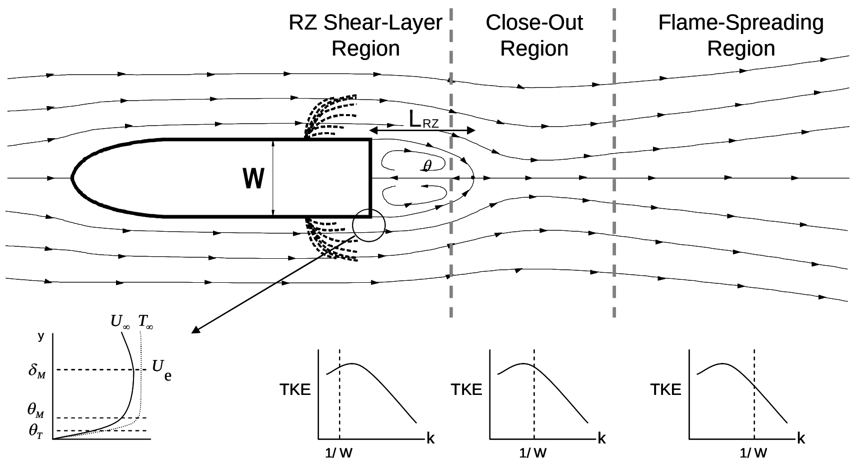

FIGURE 1: DESCRIPTION OF BLUFF-BODY FLOW FIELD, IDENTIFYING KEY REGIONS OF THE FLOW

Description of Premixed Bluff-body Combustion Processes

The "introduction" of combustion reactions into an isothermal bluff-body flow significantly changes the flow's characteristics. In a bluff-body stabilized flame, reactions in the near-wake shear layers produce a low velocity mixture of hot products, flamelets and radicals that are entrained into the RZ. Subsequently, these are back-mixed by the RZ to the shear layers just downstream of the point where the flow separates from the bluff-body, thereby igniting the unburned mixture entering the shear layers. This describes the classical bluff-body flame recirculation zone stabilization process.

When combustion process heat release is present, the length of the RZ has been found to approximately equal L_{RZ}/W =2.3-2.7 for ranges of Reynolds numbers of practical interest [1,5]. Reactions within the RZ can be sustained by a continuous supply of reactants and burning gas pockets from adjacent shear layers and/or backmixed from downstream near the stagnation point x=L_{RZ}; i.e., the region referred to above as the "Close Out Region" (COR) in Figure 1. Clearly, the mass exchanges between the RZ, shear layers and COR are controlled by molecular and turbulent transport processes and the dynamics of the vortical structures that are present in these three regions. Additionally, the gas expansion (i.e., flow dilatation) that is produced by combustion processes likely accelerates the flows in the shear layers, the COR and the far-field wake flow.

The reactions in the shear layers adjacent to the RZ are a critical element of the overall combustion process. The location of the reaction zone within the shear layers depends on heat and mass transport of reactants and products into and out of the shear layers, and may be affected by the Lewis number of the mixture based upon the molecular diffusivity of the fuel. Since mixing time scales in this region are relatively short, it's likely that chemical kinetic rates control the combustion process. A Damköhler number can be, thus, defined for this local flame region based upon a chemical time that can be related to the laminar flame speed, S_L, and a mixing time scale related to local turbulence characteristics of the shear layer. Measurements of the characteristics of the reaction zone and vorticity field in a premixed bluff-body stabilized flame by Chaudhuri et al. [15] indicate that the reaction zone occurs in the outer regions of the shear layers (i.e., adjacent to the external flow) when the equivalence ratio is nearly stoichiometric and the flame is stable. This flame region moves, however, towards the inner boundaries of the shear layers and even into the RZ as chemical kinetic rates decrease and blowout is approached.

The local equivalence ratio undoubtedly plays an important role in the stabilization process because it determines local composition and flame temperature, which affect chemical reaction rates. It also determines the ratio of the burned to unburned gas temperatures, T_b/T_u, which is a fundamental parameter that has been found to affect the dynamics of reacting shear layers [16,17] and, thus, the length of the RZ. Studies at lower Reynolds numbers [1] indicate that the average temperature in the RZ is close to the adiabatic flame temperature for most flameholder geometries, except near blowout, when the RZ temperature decreases. On the other hand, as the flow Reynolds number increases, the mixing time decreases and chemical reaction rates exert a stronger influence upon the RZ temperature whose magnitude can now depend upon the manner in which the flameholder geometry affects the flow and mixing characteristics.

Shanbhogue et al. [5] used various definitions of chemical and fluid mechanical time scales to correlate large blow off data sets obtained by various researchers and showed that the blow off limit may be correlated with a Damköhler number, albeit with a significant amount of data scatter. This study concludes that the blowout behavior scales with a Damköhler number independent of flameholder geometry. The usefulness of this conclusion depends, of course, on how the correlation would be used; i.e., the correlation may not be useful in engineering applications where accurate descriptions of the blow out limits are required (e.g., within 5-10%). Also, in combustor design, “real flow effects” associated with aerodynamics effecting local mixing between reactants and products must be accounted for. Reference 5 also shows that a chemical time based on the extinction strain rate, τ_{EXT}, which was derived from a chemical kinetics mechanism, may be used to correlate the data. The fluid mechanical time scale used in this study was assumed to be W/U_∞, which is not a mixing time scale. Nevertheless, the use of this (convective) time scale generally yielded satisfactory correlations, most likely because other length and velocity scales that describe mixing time scales are related to W and U_∞ in some manner.

Description of Non-Premixed Bluff-body Combustion

Non-premixed combustion process stabilization by a bluff-body also depends upon the method of fuel injection and the fuel injector geometry. To describe the differences between premixed and non-premixed combustion processes, we will first consider generic pathways of the streams of air, fuel and products in a bluff-body stabilized combustion process with the aid of Figure 2. As fuel jets are injected into the cross-flow, they atomize and mix with the air streams inside and outside the boundary layers next to the bluff-body. These interactions produce reactive mixtures in the boundary layers and free stream flows that burn in various regions of the combustor to form products that ultimately leave the system. In a well designed combustor, all the fuel passes though a reaction zone and is burned, resulting in high combustion efficiency. In practical systems, air is sometimes mixed in downstream of the flame to control the temperature distribution.

The prepared fuel mixture can burn in the separated shear layers, the near-wake RZ, the COR, or in the far-wake. Likely, a significant fraction of the fuel delivered to the boundary layers burns in the RZ shear layers to produce a low-velocity mixture of hot products, flamelets and radicals. A fraction of this mixture is entrained into the RZ where it reacts with boundary layer fuel interacting with the RZ. Clearly the combustion in the reaction zones associated with the RZ is strongly dependent on the back-mixing mechanism.

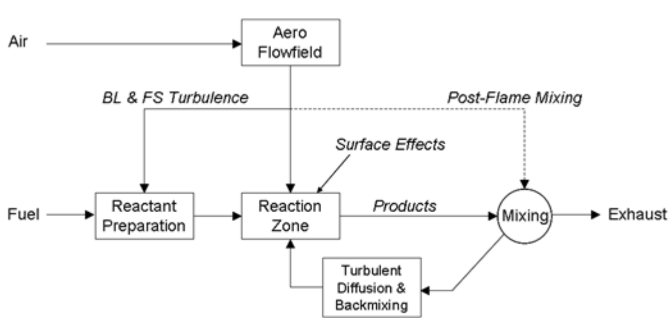

FIGURE 2: GENERIC FLOW PATHS FOR AIR AND FUEL IN A BLUFF-BODY STABILIZED COMBUSTION PROCESS

On the other hand, the fuel that is entrained into the faster moving free stream can be burned downstream of the near-wake region. Some of the free stream fuel and even boundary layer fuel is entrained into the COR, where it ignites due to mixing with the hot products and radicals moving through the RZ shear layers and reaction zones established in the low-velocity highly turbulent flow in the COR. The remaining free stream fuel passes the COR and reacts in the far-wake flame spread region reaction zone where the flame is anchored in a turbulent mixing layer and the fuel is ignited by mixing with hot products and radicals by turbulent diffusion from the center wake flow. It’s also noteworthy that in non-premixed systems, cooler air could be supplied directly to the combustion region where it can cool the mixture and reduce its equivalence ratio, possibly contributing to local extinction.

Combustion occurring in the COR likely affects combustion processes in both the RZ and far-wake regions. The hot products, flamelets and radicals generated in the COR are formed in a low-velocity flow region surrounding a “dynamic” stagnation point (i.e., a stagnation point whose location varies in time). The mixture of reactants, products and even clean air existing in the COR may convect/diffuse upstream into the RZ, where it contributes to the stabilization of the combustion processes in the RZ shear layers. Alternatively, this mixture may flow downstream and supply ignition sources and reactants that support the turbulent combustion in the far-field wake region. Therefore, the characteristics of combustion processes in the COR may play a critical role in the flame stabilization and completion of combustion in the far field.

Recent high-speed visualizations of such combustion processes have significantly improved the understanding of combustion processes in the RZ, COR and the far-wake regions. Figure 3 shows a schematic of the flame stabilization region that is based upon examination of these high-speed movies. It shows “back-mixing” of reacting gases and hot products from the COR into the RZ. Notably, the local heat release in the COR region is very high because of the low velocities in this “near stagnation” flow region, and the high mixing rates and rate of entrainment of fresh reactants from the free stream into this region by large scale turbulent structures. Figure 3 also indicates that reactants are supplied into the COR from both the shear layers and the free stream.

Again, the combustion process in the COR probably impacts the static stability of a bluff-body stabilized flame. Specifically, since the reaction rate depends on the local flow strain rate, which may be very high in the COR because of the very high flow curvature there, local extinction may first occur in this region. This, in turn, may cause extinction of the “entire” combustion process because the reacting flow generated in the COR supports/ignites combustion processes in the RZ upstream and far-wake flame downstream. The schematics in Figures 2 and 3 suggest that if local extinction of the combustion process occurs in the COR, then cool air and unburned reactants can back-mix into the RZ, resulting in flame blowout there. Such cold gases could also convect downstream and extinguish the far-field flame leading to complete blowout.

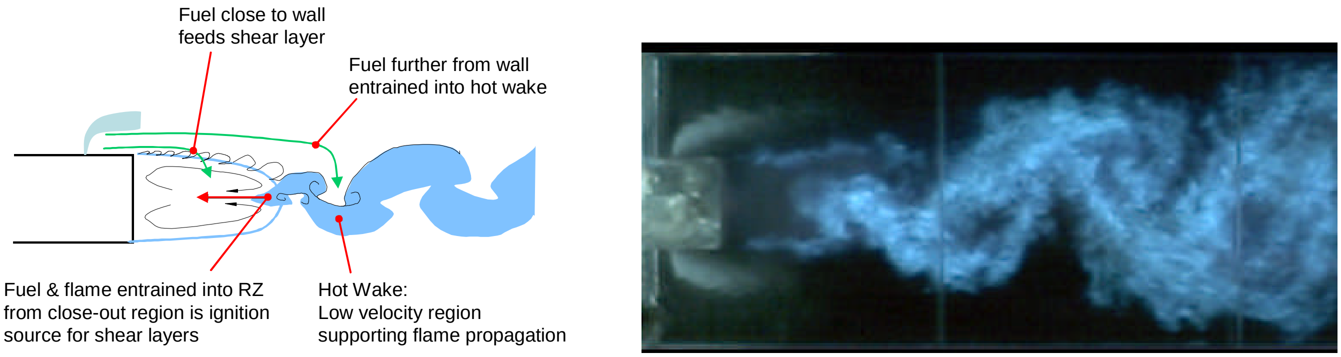

FIGURE 3: ILLUSTRATION AND PHOTOGRAPH OF THE DYNAMIC STRUCTURE OF A BLUFF-BODY FLAME USING CLOSE-COUPLED FUELING, SHOWING COMBUSTION IN THE SHEAR LAYER AS WELL AS REACTING GASES BEING ENTRAINED FROM THE CLOSEOUT REGION INTO THE RECIRCULATION ZONE

The turbulent flow in the far-field wake or flame-spreading region involves much larger scale turbulence and longer time scales compared to those encountered in the RZ region. In the far-field, Reynolds numbers are significantly higher, the magnitude of the vorticity is lower and turbulent length scales can be larger than the flameholder width as depicted in Figure 1. Under these conditions, the combustion process is dominated by turbulent flame propagation processes with no back-mixing; i.e., turbulent motions now control the transport of reactants and products into the reaction zone. The local turbulent mixing time scale is generally related to the local turbulent kinetic energy, ε/k, and the combustion time scale can be related to the local laminar flame speed, S_L.

The effects of combustion on the far-field dynamics (i.e., the asymmetric BVK instability) have recently been studied in more detail [9,16,17]. These studies revealed that, under certain flow conditions, large-scale vortices consisting of reactive mixtures can alternately shed from each side the bluff-body, ignite and "dominate" most of the flame structure as they are convected away from the bluff-body. An example of such a flame structure behind a 2D bluff-body that employed discrete liquid fuel jet injection is shown in Figure 3, which was "extracted" from a high-speed video of the flame [9]. These studies have also shown that the temperature ratio, T_b/T_u, strongly affects the BVK vortex dynamics. Specifically, BVK instabilities are suppressed when $T_b/T_u > 2$-3.

To understand the causes of this suppression, consider the vorticity transport equation, i.e., Equation (1) below, where the dilatation and baroclinic vorticity generation are described by the second and third terms on the right, respectively.

$$\frac{D\vec{\omega}}{Dt} = \underbrace{(\vec{\omega}\cdot\nabla)\vec{V}}_{\text{Vortex Stretching}} - \underbrace{(\nabla\cdot\vec{V})\vec{\omega}}_{\text{Dilatation}} + \underbrace{\frac{\nabla\rho\times\nabla p}{\rho^2}}_{\text{Baroclinic Production}} + \underbrace{\nu\nabla^2\vec{\omega}}_{\text{Viscous Diffusion}} \quad (1)$$

Both of these terms are proportional to the density gradient across the reaction zone, i.e. ρ_u/ρ_b. Dilatation is a vorticity sink, whereas the baroclinic term is a vorticity source term. In the case of a confined bluff-body stabilized flame, the baroclinic source term will generate vorticity of opposite sign to the bluff-body generated vorticity which exists in the boundary and shear layers. Thus, both dilatation and baroclinic torque act to decrease the amount of vorticity in the flow field. As the temperature (or density) ratio across the flame increases, these two terms will increase in magnitude and reduce the vorticity in the bluff-body flow field further. Consequently, bluff-body stabilized combustion processes resulting in sufficiently high temperature ratios (i.e., $T_b/T_u > 2$-3) will result in a suppression of the BVK instability due to these damping processes [5].

In combustors operating with high Mach and Reynolds numbers, which are of considerable practical interest, the relative strength of the vorticity generated in boundary layers next to the bluff-body is increased and the reaction zone (or flame) tends to align itself with the flow direction because the ratio U_∞/S_L increases. The baroclinic alignment is therefore more favorable, but the pressure gradient (primarily in the flow direction) is conversely reduced. Thus, it is not clear at this time if the relative importance of baroclinic vorticity increases or not with Reynolds number and further study is needed.

For engineering applications of bluff-body stabilized flames that require accurate knowledge of the stability limits, the effects of the multitude of processes that may affect the blow off limits (e.g., wall cooling, thermal and velocity boundary layers, recirculation zone processes, shear layers, mixing and BVK instabilities) will have to be understood, as it's highly unlikely that a single universal Damköhler number can be used to predict the blow off limits. Instead, it's expected that the combustion behavior for non-premixed flameholders must be characterized using multi-variable parametric analyses or numerical simulations of the process.

The above discussions suggest that the aerodynamics and combustion processes associated with bluff-body stabilized flames depend upon (or are controlled by) the set of governing

TABLE 1: LIST OF PARAMETERS GOVERNING BLUFF-BODY AERODYNAMICS AND COMBUSTION PROCESSES

Flameholder Aerodynamic and Combustion Parameters															
W	U_{∞}	U_e	Re	θ_M	T_u	θ_T	u'_{FS}	$\overrightarrow{\nabla P}$	Le	T_b/T_u	ϕ	S_L	ε/k	κ	τ_{EXT}

parameters listed in Table 1, in addition to the basic thermodynamic parameters of pressure, temperature and heat of reaction. The first ten parameters characterize the design and operating conditions of the combustor and the remaining six parameters are quantities that depend on the position in the flow field and could, in principle, be calculated or measured. In fact, it's recommended that the dependence of the stability limits upon these parameters be studied using, e.g., LES/CFD approaches to determine which parameters need to be accurately resolved to best characterize the stability limits.

Description of Close-Coupled Fuel Injection Processes

In practical bluff-body combustion systems, fuel is commonly supplied to the reaction zone by injecting a discrete number of liquid fuel jets into a cross-flow using simple round-orifice injectors. This approach produces, however, a complex fuel distribution in the combustor that is strongly dependent upon operating conditions and the combustor design. The penetration of a liquid jet injected into a cross-flowing gas stream scales approximately as $d_0J^{1/2}$ [11], where d_0 is the orifice diameter and J is the ratio of fuel jet momentum flux to gas stream momentum flux. The fuel jet is initially circular in cross-section and is progressively "flattened" in the span-wise direction due to the pressure gradient imposed upon the fuel jet. This creates a complex wake structure in the gas flow behind the injected liquid fuel jet that includes counter-rotating vortices along the sides of the fuel jet. Primary breakup of the main liquid column typically occurs at a distance of around 10 orifice diameters downstream of the fuel injection point, and measurements show that the dominant droplet generation mechanism shifts from a column breakup mode to the surface shear breakup mode as the momentum flux ratio increases [11]. Above a Weber number of approximately 50, the majority of the droplets are formed by a surface stripping mechanism. In this case, the droplet size decreases with increasing momentum flux ratio, and a general scaling for droplet diameter is given by the following relationship: $d \sim V_{jet}^{-1/2}$ [11].

Recent experimental studies have investigated the fuel droplet characteristics under combustor operating conditions simulating those encountered in modern gas turbines [18,19]. Figure 4 presents recent centerline measurements by Lubarsky et al. [19] that show the wake region behind a liquid fuel jet located 25.4 mm upstream of the flameholder edge in a single flameholder test with high inlet temperature conditions (i.e., d_0=0.711mm, T=815°C, We=970, J=10.5). Under these conditions, the aerodynamic wake behind the fuel jet is evident and persists up to the flameholder separation point. The presence of this wake likely influenced the amount and properties of the fuel delivered to the RZ shear layers downstream of the flameholder.

Representative PDPA measurements [19] of droplet diameter distributions in the normal and span-wise directions in the high temperature flow around the flameholder are shown in Figures 5 and 7, respectively. Figure 5 shows that at locations just downstream of the injection point (i.e., at x=7.6d_0), larger droplets exist at the outer periphery of the fuel jet. Figure 5 also shows that smaller drops, which were apparently generated by the stripping mechanism and entrained into the wake flow, are present behind the jet. This, in turn, supplies the boundary layer along the flameholder surface with a 'cloud" of small droplets. A photograph of this fuel "cloud" in the wake of the fuel jet is shown in Figure 6. Notably, Figure 5 shows that the droplet diameter distribution becomes nearly uniform at x~ 25.4 mm (i.e., x~35*d_o) downstream of the fuel jet, indicating that the larger drops are not present in the reaction zone beyond the edge of the flameholder when the fuel injectors are located at sufficient distances upstream of the reaction zone.

Figure 7 describes measurements of the variation of the droplet sizes in the span-wise direction. It indicates that the fuel spray width approximately equaled ±1cm (i.e., y/d_0~15) b the time the fuel has reached the lip of the flameholder, as no droplet could be detected by the PDPA beyond this range. From these data the dispersion rate of droplets can be estimated by considering the width of the detected fuel jet at the two axial locations and is approximately $W_S \sim 0.7X$ where X is the distance downstream from the injector. The degree of fuel dispersion is important when considering the uniformity of

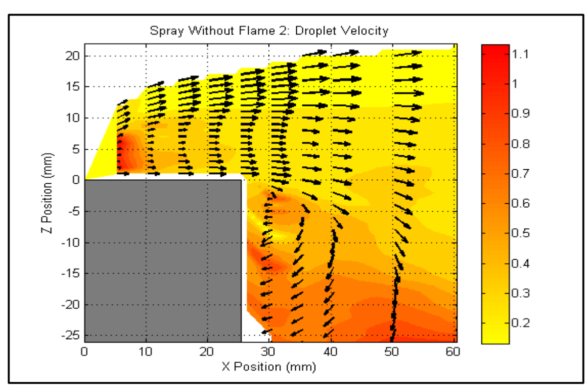

FIGURE 4: MEAN DROPLET VELOCITY VECTORS ON THE CENTER PLANE BEHIND A FUEL JET IN A HEATED CROSS-FLOW [19]

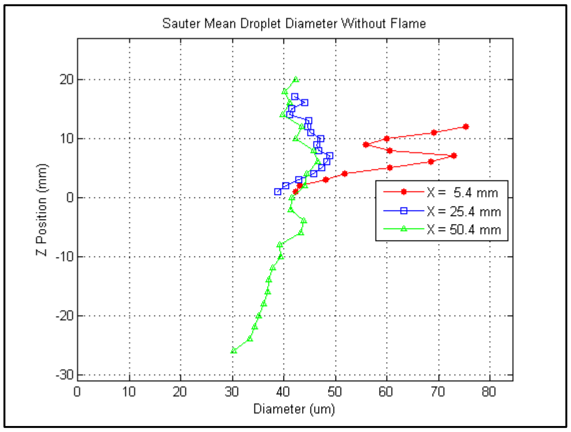

FIGURE 5: MEASURED DROPLET SIZES VERSUS VERTICAL DISTANCE FROM THE WALL FOR THREE AXIAL LOCATIONS IN A HOT CROSS-FLOW [19]

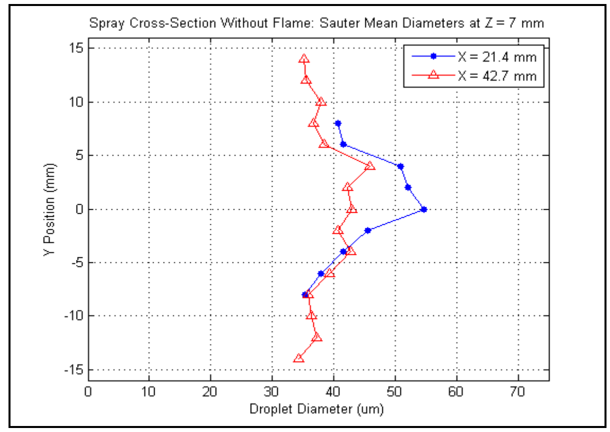

FIGURE 7: MEASURED DROPLET SIZES VERSUS SPAN-WISE DISTANCE FROM INJECTION POINT FOR TWO AXIAL LOCATIONS IN HOT CROSS-FLOW [19]

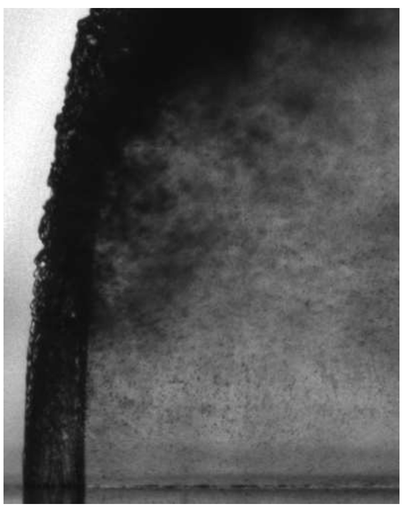

FIGURE 6: PHOTOGRAPH OF THE DROPLETS STRIPPED FROM A FUEL JET IN CROSS-FLOW EXISTING IN THE WAKE FLOW BEHIND THE JET

fueling the RZ shear layers when discrete liquid fuel jets are injected into the flow. Becker et al. [20] experimentally determined an empirical correlation for the half width of a liquid fuel jet injected into a cross-flow, showing that it scales as $W_S \sim d_0 J^{0.09}$. It can be shown that the fuel spray half-width in Figure 7 is in agreement with this correlation.

A key aspect of the close-coupled fuel injection problem is obtaining an understanding of where and how the fuel from the discrete fuel injectors interacts with the bluff-body's flow field and reaction zones. Recalling that the fuel jet penetration into the cross flow scales as $d_0 J^{1/2}$, it seems that the jet penetration could be described by the normalized penetration distance: $d_0 J^{1/2}/W$. To describe the fuel spray distribution in the span-wise direction, it's suggested that the non-dimensional ratio of the fuel spray width, W_S, at the axial location coinciding with the bluff-body lip, and the geometric spacing between fuel injectors, Y_S (i.e., W_S / Y_S), be used for this purpose as this parameter will provide a measure of the span-wise distribution and uniformity of the fuel entrained into the RZ shear layers. If W_S / Y_S is less than unity, uneven fueling of the shear layers just downstream of the flame holder trailing edge should be expected, which can potentially adversely affect flame stability.

Clearly, the physics controlling the formation and spreading of fuel sprays is very complex, involving parameters that describe the dynamics of the liquid and gas streams, and their interactions via free-surface instabilities. Since models that accurately predict the properties of sprays generated by complex fuels at high-temperature flow conditions are not currently available, the fuel distribution in engineering applications must be estimated using existing empirical correlations [20] and appropriate measurements at the conditions of interest. Table 2 suggests parameters that should be considered in the characterization of fuel sprays used to fuel bluff-body stabilized flames. The first four are geometric parameters, the next three are properties of the fuel, and the remaining parameters describe the fuel jet and air stream flows.

Experimental Studies of Bluff-Body Stabilized Flames Employing Close-Coupled Fuel Injection

The above discussion introduced several processes that are believed to control flame stabilization by bluff bodies that use close-coupled fueling. The combustion characteristics of such systems will be further discussed in this section using results acquired from a single-flameholder test rig developed and operated at Georgia Tech [9]. This test rig utilizes an air stream heated to approximately 800°C and supplied to a 7.6 x 15.2 cm rectangular test section whose exit opens to the atmosphere. The test section is ~ 1.5 m long and has a 0.9 m long section of quartz windows that provides optical access to the reaction

TABLE 2: LIST OF GOVERNING PARAMETERS FOR FUEL DISTRIBUTION USING CLOSE-COUPLED FUELLING

Fuel Spray Parameters												
d_0	L_0	Y_S/W	X_{FH}/W	ρ_F	μ_F	σ_F	V_{jet}	W_e	J	ε/k	$d_O J^{1/2}/W$	W_S/Y_S

zone downstream of the bluff-body. This optical access allows high-speed photography and chemiluminescence imaging of the flame region that have been used to study the characteristics of the combustion process heat release. The bluff-body was 4.75 cm wide and typically included four discrete 0.635mm simple-orifice fuel injectors integrated within the bluff-body 2.54 cm upstream of its trailing edge. Jet-A fuel was injected into the cross streams of hot, vitiated air via two fuel injectors, spaced 2.54 cm apart, on the top and bottom of the flameholder. Additional details can be found in reference [9].

Figure 8 shows long-exposure photographs of flames stabilized in this rig. Note also that fuel sprays emanating from the top and bottom of the bluff-body are visible on the far left of the photographs due to light scattering off the liquid sprays. The top image shows that at lower fuel air ratios (i.e., $\Phi_{global}<0.5$) the fuel spray remains close to the bluff-body wall and a bright recirculation zone is present downstream of the flameholder, indicating the presence of combustion and likely soot formation within the RZ. At higher fuel-air ratios (i.e., $\Phi_{global}>0.75$), the fuel jet penetrates further into the cross flow and the combustion process appears to resemble the flame structure encountered with premixed flames where the reaction is concentrated in the shear layers and the recirculation zone is dark, indicating that little or no reaction is present there [1,2].

These flame structure observations, which are typical of close-coupled fueling, describe some of the fundamental differences between premixed and non-premixed bluff-body stabilized flames. At low fuel jet penetration, a large fraction of the fuel spray is delivered to the near-wake shear layers, potentially forming rich fuel-air mixtures that can supply unburned fuel needed for reactions to occur in the RZ, as shown in the top image in Figure 8. At medium fuel jet penetration levels, a large fraction of the fuel spray may be entrained into the close-out region (COR in Figure 1), thus producing a robust combustion process that supplies high temperature products and radicals to the RZ and far-wake flame spreading region. This has been shown to produce a very stable flame with large local combustion process heat release. At large fuel jet penetration levels, the fuel spray may penetrate beyond the streamlines that affect the reaction zone in the near-wake shear layers, resulting in little fuel entrainment into this zone. Instead, most of the fuel is provided directly to the far-wake flame spreading region. Flame stabilization by the RZ is then strongly dependent on the fuel that is stripped from the fuel jet column and remains in the boundary layers feeding the separated shear layers of the RZ.

Spatial distributions of the time-averaged combustion heat release were determined using a three camera system equipped with narrow-band filters and a total exposure time of 0.1s [9]. Examples of false-color images of CH* emission intensity (422<λ<432 nm) are shown in Figure 9 [21] for three different global fuel-air ratios. These images show how the mean heat release distribution evolves as the fuel injection rate increases. Notably, combustion can be stabilized at overall equivalence ratios much lower than typical lean blow out limits of premixed systems (i.e., stable combustion was achieved at Φ as low as 0.2). This is possible because at low fuel flow rates, sufficient fuel is entrained into the recirculation zone to support stable

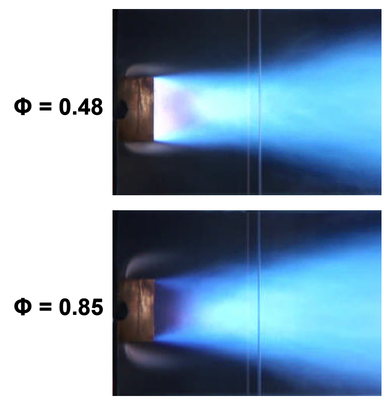

FIGURE 8: LONG EXPOSURE PHOTOGRAPHS OF FUEL SPRAY AND REACTION ZONE BEHIND BLUFF-BODY USING CLOSE-COUPLED FUEL INJECTION

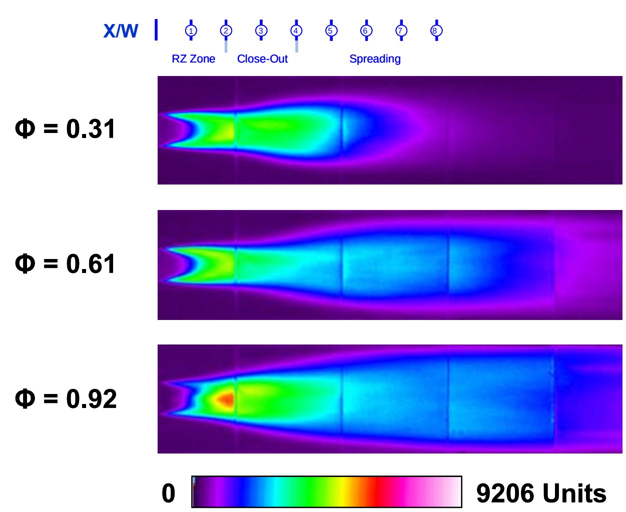

FIGURE 9: AVERAGE CH* IMAGES FOR THREE GLOBAL EQUIVALENCE RATIOS FOR BLUFF-BODY STABILIZED FLAMES UTILIZING CLOSE-COUPLED FUELLING [21]

combustion. Under this operating condition, combustion mostly occurs over a limited region downstream of the flameholder where the fuel is consumed. Consequently, high combustion efficiencies are expected for close-coupled bluff-body stabilized flames at low overall fuel-air ratios. As the fuel flow is increased to produce a global equivalence ratio of $\Phi>0.5$, the flame extends further downstream with the maximum heat release occurring notably in the COR.

As the fuel-air ratio is further increased towards globally stoichiometric operating conditions, a long and wide flame is created, extending many bluff-body widths downstream. At these high fuel flow rates, little heat release is observed in the near-wake RZ region. Instead, the maximum heat release occurs further downstream in the COR. It's also noteworthy that the reaction intensity in the shear layers surrounding the RZ becomes weaker as the fuel jets penetrate further away from the near-field region of the flow. Yet, sufficient amounts of fuel are still supplied to the near-wake shear layers by the small droplets stripped from the fuel jets. These fine droplets remain close to the bluff-body wall and are entrained into the RZ shear layers, where they react and anchor the flame to the bluff-body. If the fuel flow rate is further increased, insufficient amounts of fuel will be entrained into the near-wake and adjacent shear layers, and blow off will occur. Consequently, it's presumed that globally rich blow out in bluff-body stabilized combustion processes that use close-coupled fueling is caused by local lean blow out in the near-wake RZ shear layers.

The heat release distributions in Figure 9 show that the characteristics of the combustion process associated with close-coupled fuel injection significantly change as operating conditions vary. In contrast, the heat release distribution for premixed bluff-body stabilized combustion is typically more spatially uniform and invariant, although the overall intensity of the reaction changes as the equivalence ratio is varied.

Another unique feature of the combustion process using a close-coupled fueling system is noted when comparing flame images extracted from high-speed movies of combustors employing nearly premixed combustion and close-coupled fueling via discrete fuel jets with $W_S / Y_S \sim 0.7$, in Figure 10 [21]. For the nearly premixed case, high intensity flame luminescence is observed in the near-wake shear layers, indicating the presence of large combustion heat release there. In contrast, the light intensity emitted from the near wake region between the "bright" shear layers (likely due to thermal emission from combustion products) is low, suggesting that little heat release occurs inside the RZ. This image suggests that in this case, practically all of the fuel reaching the shear layers is likely consumed there with practically no fuel reaching and burning in the RZ. In contrast, when close-coupled fueling is used (lower image in Figure 10), the reaction zone is observed to be distributed throughout the wake flow field and is not constrained to the shear layers adjacent to the RZ or in the wake. This indicates that a fraction of the fuel "bypasses" the reaction zones in the shear layers and reacts within the RZ and downstream wake flow. Furthermore, a large fraction of the

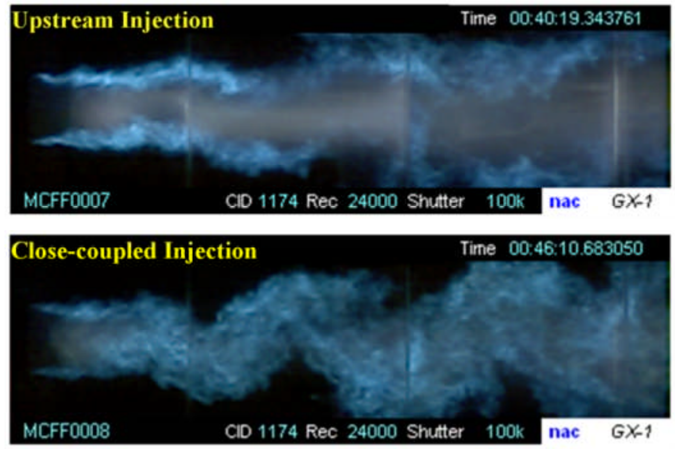

FIGURE 10: INSTANTANEOUS IMAGES OF THE BLUFF-BODY FLAME FOR NEARLY PREMIXED (UPPER) AND CLOSE-COUPLED (LOWER) FUELING AT Φ=0.61 [21]

fuel burns throughout the system of BVK vortices downstream, as evident by the sinuous structure of the flame in Figure 10.

Images of the C_2*/CH* ratio, which has been shown to be an indicator of the fuel-air ratio in premixed [22] and liquid-fueled hydrocarbon flames [9,23], were also acquired [21]. For the nearly premixed case, the average C_2*/CH* value of the entire reaction zone was found to linearly increase as the global equivalence ratio of the combustor increased, as might be expected. In contrast, this ratio was nearly constant for all fuel-air ratios for the close-coupled fuel injection configuration. Furthermore, this constant value was found to be nearly equal to the value obtained for premixed combustion when the global equivalence ratio of the combustor was stoichiometric. These results strongly suggest that the combustion is occurring, on average, in stoichiometric flamelets (or thin reaction zones) when close-coupled fueling is used. This observation is consistent with our understanding of liquid fuel spray diffusion combustion. One plausible hypothesis is that the liquid fuel jets produce clouds of droplets that are dispersed throughout the combustor and mostly burn in stoichiometric diffusion flames.

This postulate will be now explored with the aid of the drawing on the left in Figure 11, which shows a span-wise cross-section of the recirculation zone downstream of a bluff-body that uses discrete fueling. The solid line represents the time-average contour where fluxes of fuel vapor and air are presumably supplied in stoichiometric proportions, with a rich condition inside the contour and lean conditions outside. At low fuel flow rates, when a significant fraction of the fuel spray is entrained into the RZ, one can expect the stoichiometric surface to exist in the recirculation zone, although it is likely "broadened" by molecular and turbulent mixing processes within the RZ. Defining the span-wise width of the "fuel region" (or the stoichiometric contour) as W_F, it is likely that $W_F > W_S$ in the RZ. The PLIF measurements behind a discretely fueled bluff-body by Gould et al. [7] using a low

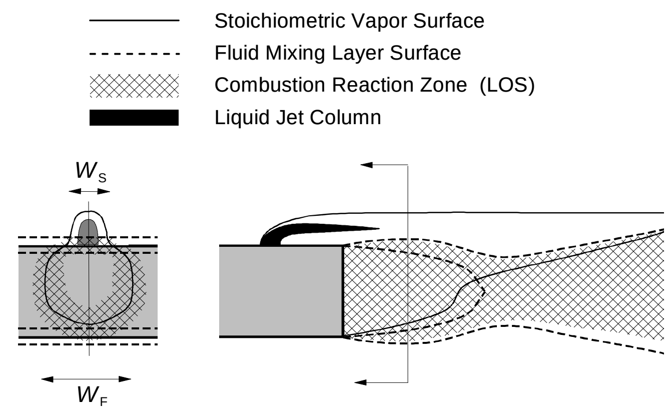

FIGURE 11: SCHEMATIC OF POSSIBLE REACTION ZONE STRUCTURE WITH CLOSE-COUPLED FUELING

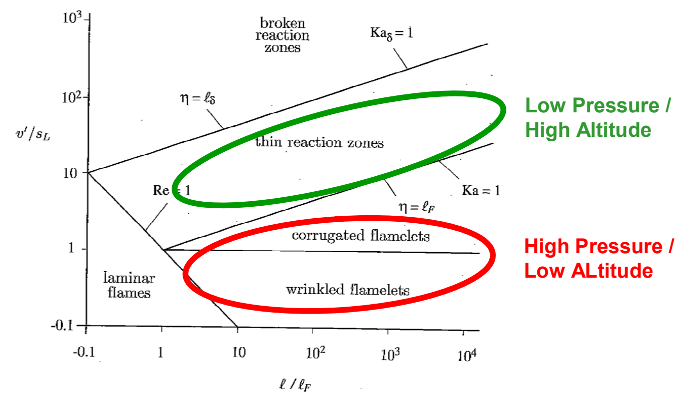

FIGURE 12: MODES OF TURBULENT COMBUSTION LIKELY TO PREVAIL AT DIFFERENT ENGINE OPERATING CONDTIONS.

penetrating gaseous fuel supports this view and indicates that the fuel concentration footprint within the RZ is roughly $W_F \sim W$ as might be expected.

Following diffusion flame theory [24], the reaction zone would be centered about the stoichiometric contour, as illustrated by the hatched lines in Figure 11. In this manner, for low penetrating fuel jets, it is possible that stoichiometric reaction zones occur inside the recirculation zone itself and in the downstream wake flow. The illustration on the right side of Figure 11 describes the reaction zone and stoichiometric diffusion flame surface in a plane centered with the axis of the fuel jet. The "broad" reaction zone illustrated in the figure is what would be observed from a time-averaged, line-of-sight (LOS) perspective, such as the images in Figure 10.

The spatial distributions of the combustion processes strongly depend on the properties and spacing of the liquid fuel jets and other factors such as local turbulent mixing and equivalence ratio throughout the flame. For low penetrating fuel jets, a large portion of fuel will be entrained into the RZ, and a stoichiometric reacting surface can occur. For highly penetrating fuel jets, it is possible to have a situation in which no stoichiometric region will exist within the RZ and adjacent shear layers. Instead, combustion would occur mostly as in a premixed system in which the reaction rate is limited by mixing of unburned reactants from the free stream and hot products in the RZ or in the turbulent far-wake region.

The above discussion implies that for flameholders using discrete fueling, the characteristics of the combustion process strongly depend on how the fuel is delivered to the reaction zones. It suggests that when the fuel burns in the RZ in stoichiometric flamelets, the combustion process is very stable because the chemical time scales are short for stoichiometric burning. More detailed measurements are needed, however, to validate this combustion process description. Specifically, it's necessary to determine the spatial dependence of the velocity fields, equivalence ratio and reaction rates in the RZ, shear layers, COR and far-wake region in high Reynolds number combustors to determine where local regions of stoichiometric flamelets are present. Considering the ranges of length and velocity scales, and of chemical kinetic times and flame speeds that likely exist in the high-speed high-temperature flows in aircraft engines, it is possible that the fuel is burned in different turbulent combustion processes that range from wrinkled flamelets to distributed reactions, c.f., Figure 12.

The dynamics of the flame are also different for close-coupled fueled and premixed systems. Cross et al. [21] have used FFT analyses of high-speed movies of the combustion process to show that the amplitudes of BVK instabilities are significantly larger for bluff bodies using closely-coupled fueling than for systems using premixed fueling. Figure 13 compares the flame oscillation amplitudes at the BVK instability frequency for the two fueling methods at nearly identical operating conditions (i.e., global fuel-air ratio, gas velocity and temperature). The results clearly show that the BVK oscillation amplitude is much larger, particularly in the far-field region, when discrete fueling is used. Recalling that a large fraction of the fuel burns in the shear layers adjacent to the RZ in premixed systems, it appears that the large temperature ratio produced by the reactions suppressed BVK vortex generation in the near-wake region and subsequent far-field region. When close-coupled fueling is used, relatively cool, unburned gas can reach the RZ (see Figure 11) and COR because of the presence of distinct reaction zones connected to the fuel sprays separated by unburned gases. Therefore, the stabilizing effects of heat release are reduced compared with the premixed case, in which the fuel and air are uniformly mixed across the entire span of the combustor. The results of this study showed that the BVK oscillation amplitude in the far field was correlated with the heat release magnitude occurring in the near-field RZ shear layers, such that the heat release was increased for the premixed case thereby suppressing the initial BVK oscillations and their subsequent growth.

The analyses of the high-speed videos also provided information about longitudinal, thermo-acoustic combustion instabilities occurring with close-coupled fueling. Figure 14 shows high-speed flame images at four relative phases during a

210 Hz longitudinal instability when close-coupled fueling was used. The images clearly show that the flame characteristics and intensity vary during the cycle. For example, at Φ=270°, the overall flame intensity is very high throughout and the width of the flame zone is large, indicating a relatively high combustion heat release rate. In contrast, at Φ=90°, the overall flame intensity and the width of the flame zone is substantially reduced, indicating a reduced combustion heat release rate The fact that these combustion modulation characteristics appear to occur over the entire flow field suggests that the combustion process characteristics are influenced by the presence of the long-wavelength, axial, acoustic pressure and velocity oscillations, indicating direct coupling between pressure and the reaction rate oscillations. This modulation in reaction rate and the corresponding volumetric expansion causes the recirculation zone size to modulate, which undoubtedly contributes to the feedback mechanism that drives the thermo- acoustic instability. It's possible that the coupling of the pressure and reaction rate oscillations when close-coupled fueling is used is enhanced because the reactions are occurring near stoichiometric conditions in this case.

The high-speed videos also showed that BVK oscillations were always present to some degree for close-coupled fueling, but that a coupling to the 210 Hz longitudinal instability was not observed (i.e., the two instabilities appeared to exist independent of one another) [9]. Both the BVK shedding frequency and the 210 Hz combustion instability could be detected in the high-speed movies of flame luminescence. However, dynamic pressure measurements at multiple axial locations in the combustor did not detect the presence of the high-frequency, transverse BVK oscillations due to a lack of resonance in the rig at such high frequencies. The longitudinal mode was always detectable by dynamic pressure sensors.

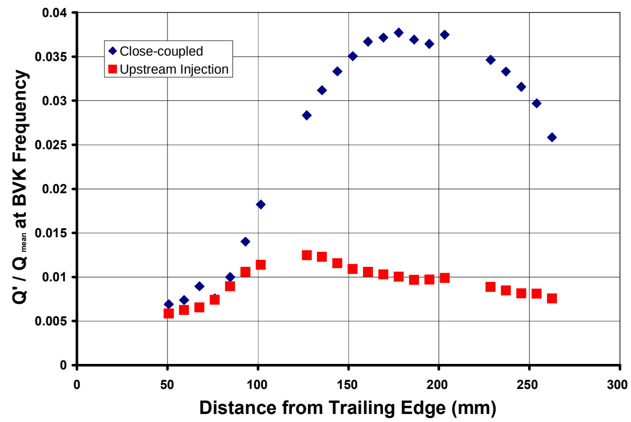

FIGURE 13: AXIAL DISTRIBUTIONS OF BVK FLAME OSCILLATION AMPLITUDES AT Φ=0.61 FOR CLOSE-COUPLED AND WELL-MIXED FUELING [21]

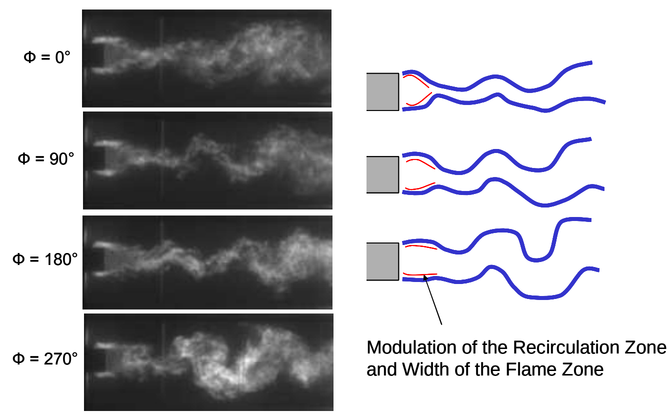

FIGURE 14: HIGH-SPEED IMAGES OF FLAME LUMINOSITY AT DIFFERENT PHASES OF A 210 HZ LONGITUDINAL ACOUSTIC INSTABILITY

CONCLUSIONS

The physics associated with bluff-body stabilized combustion processes have been reviewed with particular attention given to combustion systems employing close-coupled liquid fuel injection. The aerodynamics associated with the bluff-body flow were discussed, and the importance of the "close-out region" (where the recirculation zone ends and the flow transitions into a wake flow) in the flame stabilization process was highlighted. A list of governing parameters expected to describe the characteristics of the flow field and combustion processes was developed. The complex physics of a liquid jet in cross-flow was also considered, with particular attention given to the physical processes controlling fuel jet penetration, span-wise dispersion and consequent interaction with the reaction zone behind the bluff-body. A set of governing parameters expected to describe the interactions between the fuel jet spray, cross-flowing gas stream and aerodynamics of the bluff-body flow field was developed.

Recent experimental observations on the time-averaged and instantaneous characteristics of the combustion process heat release were reviewed to support postulates for the flame structure and governing physics unique to bluff-body stabilized flames using close-coupled fueling. Results suggest that the reaction takes place in very stable, stoichiometric flamelets distributed throughout a relatively large reaction zone (analogous to diffusion flame theory) that can exist throughout the wake flow behind the bluff-body and are not constrained to the outer mixing layers. Flame dynamics were also discussed, including flame oscillations due to von Kármán vortex shedding. The von Kármán flame oscillations are shown to be significantly higher in amplitude for close-coupled fueling compared to premixed fueling conditions. This was attributed to the entrainment of relatively cool, unburned air into the recirculation zone and close-out region when the fuel was injected in the form of discrete jets, reducing the gas expansion and vorticity suppression mechanisms in the near-wake region of the flame, and leading to increased BVK oscillations in the far-field regions.

It is anticipated that the hypothesized processes and governing parameters described in this paper can be used to analyze and scale the complex physical processes associated with bluff-body stabilized combustion using liquid jets in cross-flow fueling. Future experimental and computational studies of this problem will serve to further advance the understanding of bluff-body combustion with close-coupled fueling common to many practical combustion systems.

ACKNOWLEDGMENTS

This work was funded through the Pratt & Whitney Center of Excellence partnership established with Georgia Tech.

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