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Lean blowoff behavior of asymmetrically-fueled bluff body-stabilized flames

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ABSTRACT

Bluff-body stabilized flames were studied in an enclosed, asymmetrically-fueled duct with a two-dimensional triangular flame holder. Acetone laser-induced fluorescence was used to characterize the fuel distribution for both uniform and non-uniform fuel profiles. Flame dynamics were captured with high-speed chemiluminescence imaging during stable operation and near blow off conditions for three cases with varying fuel–air gradients across the flame holder. Particle imaging velocimetry was used to measure the velocity field. It was discovered that for a given velocity, increased fuel profile asymmetry caused an increase in the blowoff equivalence ratio, produced greater vortex shedding coherence, and for lower velocities resulted in dynamic coupling between the heat release and the duct acoustics. High-speed imaging of the acoustically uncoupled cases revealed the same flame blowoff process as previously observed in uniformly fueled cases. The blow off process in the acoustically coupled cases was dominated by acoustically influenced velocity straining the flame adjacent to the wake stagnation zone causing local extinction and rapid entrainment of reactants into the recirculation zone. From the Mie scattering images gathered for PIV, density transition contours were extracted and used as flame contours to calculate local aerodynamic strain rates and curvature. Statistics revealed conditional relationships between the local strain, wake geometry and fluid mechanics.

1. Introduction

Laboratory burners are often designed to produce strictly premixed or non-premixed flames. In contrast, typical combustion applications rarely use premixed combustion due to limitations imposed by mixing length and time scales, and concerns with autoignition [1]. Neither is fuel burned at completely non-premixed conditions due to long flame lengths, lower extinction limits, and higher pollutant emissions. Therefore, fuel transport and local fuel concentration under practical, non-uniform fueling conditions must be considered to ensure stable, efficient combustion.

The creation of a recirculation zone by flow divergence induced by some mechanical or aerodynamic means is a typical design strategy in turbulent flows to stabilize flames. The recirculation zone steadily entrains hot combustion products from the adjacent shear layers and carries them upstream to ignite cool reactants [2]. Recirculation zones can be formed with swirled jets, sudden expansion, and obstructions in the flow field generically referred to as bluff bodies. A bluff body, placed in the flow, produces a recirculating wake structure that allows combustion to anchor and then propagate into the free stream.

Though the design and implementation of bluff body combustors are affected by fuel distribution and wake behavior that influence stable flame anchoring, they have found a wide range of applications because of their relatively low-pressure drop and simple geometry. Depending on the design of the burner, fuel non-uniformity may either expand or contract the operational envelope. Locally rich or near stoichiometric combustion that anchors and propagates flames to the rest of the combustor may be used to expand operability. Static and dynamic stability issues with bluff body flame holders have been a persistent problem, driving investigators to examine repeatedly this same problem in a number of different settings and with a wide array of tools. As a result, there is vast literature with experimental, analytical, and computational studies on this subject. However, most past research on bluff-body flame stability has considered primarily purely premixed or non-premixed conditions. For aircraft augmentors, changes in combustor designs have allowed ever-hotter combustor inlet conditions, increasing the risk of autoignition, resulting in fuel being injected much closer to the flame holder driving more

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non-uniform fuel distributions at the flame holder location [1]. In the present paper, we examine experimentally the effects of non-uniform fuel distribution on bluff-body flame stability and flame dynamics.

1.1. Background

The earliest bluff body flame investigations were performed to characterize operability boundaries for a given burner design as well as the underlying flameholding and blowoff behavior [2–5]. For fully premixed bluff body stabilized flames, a number of recent investigations have revealed some of the fundamental behaviors, including the details of the coupling of the wake aerodynamics and flame behavior and the final stages of blowoff. A review by Lieuwen et al. [6] compiled and explained bluff body wake behavior in isothermal and reacting conditions, with detailed descriptions of the wake instabilities. A review and analysis by Shanbhogue et al. [7] and later investigations by [8,9] and by the present authors [10,11] have revealed details of the blowoff process for premixed bluff body stabilized flames.

Of particular relevance to this investigation are transitions between symmetric Kelvin–Helmholtz (KH) shear layer roll-up found in stable flames and asymmetric Bénard–von Kármán (BVK) vortex shedding observed preceding flame blowoff [6]. This behavior has been linked analytically, experimentally, and numerically to the dilatative and baroclinic vorticity production common to reacting flows, which both appear as source terms in the vorticity transport equation:

$$\frac{\partial \vec{\omega}}{\partial t} + (\vec{u} \circ \nabla)\vec{\omega} = (\vec{\omega} \circ \nabla)\vec{u} - \vec{\omega}(\nabla \circ \vec{u}) + \frac{\nabla \rho \times \nabla p}{\rho^2} + v\nabla^2\vec{\omega} \qquad (1)$$

Of note is the attenuation of the Bénard–von Kármán instability by dilatation and the attenuation of the Kelvin Helmholtz instability by baroclinic vorticity production [12–15]. Dilatative and baroclinic vorticity production, respectively, are expressed and scaled by the terms

$$\vec{\omega}(\nabla \circ \vec{u}) \sim \frac{U_S}{\tau_f \delta}\left(\frac{\rho_u}{\rho_b} - 1\right) \qquad (2)$$

$$\frac{\nabla \rho \times \nabla p}{\rho^2} \sim \left[\frac{U_S}{\delta}\left(\frac{\rho_u}{\rho_b} - 1\right)\right]^2 \sin\alpha \qquad (3)$$

where U_s is the unburned upstream velocity, δ is the shear layer thickness [16], ρ_u is the unburned density, ρ_b is the burned density, τ_f is a characteristic flame propagation time scale [14], and α is the flame angle.

In reacting shear layers, both the dilatation and baroclinic vorticity production exert rotational momentum in the opposite direction to that produced by the shear layer between the recirculation zone and bulk flow, effectively attenuating the shear layer velocity gradient. As the heat release rate is decreased from stoichiometric, the associated gradient attenuation decreases and the associated shear layer instabilities are stronger. This produces greater strain on the flame and eventually leads to flame extinction and blowoff [10,17,18]. When non-uniform fuel distributions are present in a burner, non-uniform heat release across the flame surface and variations in the coupled shear layer dynamics can be expected, but the impact of these heat release distributions has not been thoroughly explored.

1.2. Non-uniform fuel effects

From Eqs. (2) and (3), non-uniform fuel distributions, and the resulting non-uniform heat release, will influence the dynamics of the wake shear layers. The non-uniform fuel distribution results in combustion that may be characterized by two possible situations [19]:

1. *Stratified combustion* may be characterized as combustion at conditions where the fuel has been mixed sufficiently such that there are leaner and richer regions, with respect to the temporal or spatial mean, within the flammability limits of the fuel and air mixture, such that diffusion flames are not present.
2. *Staggered or staged combustion* may occur where fuel-lean and fuel-rich regions, including concentrations outside of the flammability limits, are formed. Therefore, both premixed and non-premixed flames form at different locations in the flow field. This includes combustor designs with multiple fuel and/or air injection locations, where one set of flames may pilot another.

A number of investigations have studied the influence of spatial and temporal fuel non-uniformities on flame behavior. A study by Kang and Kyritsis [20] showed that flames propagate in the direction of stratification into lean mixtures outside the flammability limit. For mixtures within the flammability limits, flame speeds up to twice that of homogeneous mixtures were observed because the flames were piloted by heat transfer from flames nearer stoichiometric conditions. They also determined that the local equivalence ratio gradient was not sufficient to describe the variation in the laminar flame speed. In an experimental study by Pasquier et al. [21] of flame propagation in a spatially-stratified turbulent fuel–air mixture, it was shown that local burning velocities were increased or decreased with large-scale fuel stratification. Flame speeds in leaner regions were increased by their proximity to richer flames, while the flame speeds in the richer flames were decreased by proximity to leaner flames, reflecting the heat transfer dependencies of premixed flame propagation.

A direct numerical simulation (DNS) study by Poinsot et al. [22] showed that fuel–air non-uniformities induce flame stretch and wrinkling, especially in cases where the local velocity field non-uniformity scales are less than the variations in laminar flame propagation due to the fuel non-uniformity [19,23]. This may have either positive or negative results on the overall combustion efficiency of a system, as shown by various studies [24,25].

In most of the aforementioned studies relating to stratified or partially premixed flames, the numerical or experimental studies were focused on laminar canonical burners or numerical configurations applicable to spark ignition engines. The study by Robin et al. [19] was of a bluff body flame holder, symmetrically fueled, but unenclosed. The present investigation is focused on asymmetrically fueled flow in an enclosed duct to simulate the behavior found in a bluff body combustor such as an aircraft augmentor and characterizes the effect of non-uniform fuel and resulting heat release on the wake.

2. Experimental apparatus

Measurements were made in a rectangular duct capable of either unvitiated or vitiated upstream conditions. Previous measurements in this facility for premixed conditions have been reported [10,11], wherein the present study focuses on stratified fueling. Since the design and flow conditions are described in detail in Refs. [10,14] only a brief overview is given here. A cross-section of the experimental duct, flameholder, and fuel injectors are schematically shown in Fig. 1. The bluff body was an equilateral triangular bar, 9.62 mm on each side. The duct was 76.2 mm wide and 38.1 mm high, such that the blockage was 25% and the cross-stream aspect ratio of the bluff body of 7.9. Fused silica windows 19.1 mm thick were used on the top, bottom, and front sides of the test section for optical access and directing laser sheets across