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Pressure-gradient tailoring effects on the turbulent flame-vortex dynamics of bluff-body premixed flames

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ABSTRACT

This paper explores the effects of pressure-gradient tailoring on the turbulent flame and vorticity generation mechanisms of premixed flames. A turbulent premixed flame stabilized by a bluff-body in a high-speed combustor is used for the investigation. The combustor pressure gradient is altered using a variable-geometry test section. The turbulent flame-flow field is measured and characterized using simultaneous high-speed particle imaging velocimetry (PIV) and CH* chemiluminescence. A Lagrangian tracking technique is applied to analyze the details of the flame-vortex interactions from the experimental data. Lagrangian fluid elements are tracked as they evolve across the flame. The vorticity mechanisms are decomposed along the Lagrangian trajectories to determine their relative balance under various pressure gradient conditions. It is demonstrated that the induced pressure-gradient affects the relative magnitudes of combustion-generated dilatation and baroclinic torque, as well as the vortex stretching. An increase in the magnitudes of the vorticity mechanisms is shown with the largest gain in baroclinicity for the augmented pressure gradient relative to the attenuated.

1. Introduction

Flame-vortex interaction is among the most significant driving mechanisms of turbulent combustion [1–3]. Vortical structures of various types are prevalent in reacting flows, where they are formed via several key means: flame stabilization mechanisms, turbulent mixing, and flow injection processes [4,5]. The large-scale structure of the turbulent flame shear layers is accordingly composed of concentrated vorticity fields [4]. The interaction of this vorticity with the flame significantly impacts the turbulent combustion processes by the introduction of strain, curvature, and unsteadiness [3,6–8]. Such interactions have a considerable effect on the combustion heat release and the structure of turbulent flames [4]. The specific changes induced to the dynamics of the flame-vorticity interactions have been explored numerically through decomposition of the vorticity mechanisms, given by the vorticity equation [9,10]. These vorticity mechanisms contribute to vorticity generation and transport during the turbulent combustion processes [9–12]. Improved understanding of these mechanisms yields the opportunity to discern the key dynamics of flame-vortex interaction and consequently aid in the improvement of turbulent combustion technology [4].

The interaction dynamics of vorticity with the turbulent flame have been studied through many experimental and numerical methods [3,4,13–15]. The specific dynamics induced by flame-vortex interaction are dependent on the combustor configuration and flame stabilization mechanism used [4]. Among these, bluff-body flame stabilization is a favorable experimental configuration which is often used in fundamental studies of turbulent flame characteristics [16–24]. Furthermore, bluff-body flame holders are highly relevant to modern propulsion technology and are typically found in ramjet-type combustors and turbojet afterburners [25,26]. The characteristic flame-flow field induced by a bluff-body flame holder is generally well-understood for a wide range of configurations, thus permitting for direct isolation of flame-vorticity dynamics [27,28].

Flame-vortex dynamics can be effectively studied by investigating the particular vorticity contribution mechanisms. These mechanisms are defined by the terms of the vorticity equation. Among these, there has been specific interest in the dilatation and baroclinic torque mechanisms [9,29]. Dilatation is a combustion-induced mechanism resultant from heat release, which causes flow expansion [17]. A detailed numerical study conducted by Mehta and Soteriou demonstrated that dilation serves to attenuate the vorticity generated in the shear layer, causing suppression of the Bernard von Kármán (BVK) instability in reacting flows [29]. Furthermore, dilatation results in a symmetric flame and flow-field across the bluff-body centerline. Similar numerical research by

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Nomenclature

C_P	coefficient of static pressure
Da	Damköler number
ε	computational error
Φ	equivalence ratio
H	bluff-body height
η	Kolmogorov length scale
Ka	Karlovitz number
L_{11}	integral length scale
l_F	laminar flame thickness
λ_k	PIV measurement scale of Kolmogorov length scale
λ_m	PIV measurement scale
ν	kinematic viscosity
P	static pressure
ρ	density
ρ_R	density of reactants
ρ_P	density of products
Re	Reynolds number
Re_T	turbulent Reynolds number,
S_L	laminar flame speed
S_T	turbulent flame speed
T	temperature
t	time of Lagrangian tracking
t_o	time step of Lagrangian tracking,
U_o,	bulk velocity
u_{turb}	turbulence level
u	stream-wise velocity vector component
u'_{rms}	turbulence fluctuation of stream-wise velocity component
$\vec{V}$	velocity vector
v	cross-stream velocity vector component
v'_{rms}	turbulence fluctuation of cross-stream velocity component
$\vec{\omega}$	vorticity vector
ω	span-wise vorticity vector component
x	stream-wise position vector component
y	cross-stream position vector component

Erickson and Soteriou has indicated that the aforementioned impacts of dilatation are directly dependent on the density ratio of combustion [30]. Other researchers have sought to understand the second combustion-induced vorticity mechanism: baroclinic torque. Baroclinic torque results in vorticity generation along the flame, due to the misalignment of the pressure and density gradients [17]. Vorticity generated by baroclinic torque can serve to augment the existing vorticity in the domain or suppress it through superposition of vorticity of opposite sign [29]. The specific flame-flow field effects induced by baroclinicity were examined in detail by Geikie et al. for a bluff-body flame [31]. This study determined that baroclinic torque directly affects the flame structure, velocity fields, turbulence, and combustion heat release.

Historically, many research studies have focused on characterizing the combustion-induced vorticity mechanisms, including dilatation and baroclinic torque. Recently, however, the focus has expanded to consider all of the vorticity mechanisms. A series of recent numerical studies have considered these vorticity mechanisms by decomposition of conservation of vorticity and enstrophy. Chakraborty studied the vorticity vector alignment of planar premixed flames at low Karlovitz number conditions, $Ka = 0.54$, 13.17; the research was conducted through analysis of a direct numerical simulation (DNS) database [32]. The numerical study demonstrated a change in alignment of the vorticity vector with the most considerable principal strain rate as a result of combustion heat release. Despite this, the mean vortex stretching contribution remained positive regardless of vorticity alignment. A similar DNS study by Lipatnikov et al. analyzed the importance of dilatation, baroclinic torque and vortex stretching in weakly turbulent flames, characterized by $Ka << 1$ [33]. The analysis found that dilatation and baroclinic torque play important roles in both vorticity and enstrophy conservation. Furthermore, positive vortex stretching was observed for flames with large density ratios. Analogous research conducted by Hamlington et al. and Poludnenko et al., has indicated that the impact of turbulence intensity on the flame-vortex dynamics is significant. The investigations demonstrated that flames subjected to low-turbulence conditions have significant contributions from baroclinic torque and dilatation [34]. As turbulence was increased, the scaled magnitudes of both baroclinicity and dilatation were found to diminish substantially while the magnitude of vortex stretching increased. These results indicated that there is a fundamental change in the relative balance between the turbulent energy transport and combustion-induced mechanisms, including dilatation and baroclinicity, across the combustion regimes [9]. A related DNS study by Bobbit et al. focused on high Karlovitz number conditions with the additional inclusion of temperature-dependent viscosity [10]. It was observed that vortex stretching and viscous dissipation dominate the conservation of vorticity under these conditions. Furthermore, the relative magnitudes of baroclinicity and dilatation diminished with increasing turbulence.

In order to study the details of the flame-vortex dynamics, Lagrangian tracking methods have been developed. Uranakara et al. applied Lagrangian flame tracking to DNS data to quantify the effects of isotropic turbulence and chemistry on molecular transport and energy transport for hydrogen-air flames [35]. Lagrangian tracking methods have similarly been applied for fluid particle tracking. Numerical studies conducted by Yang et al. and Yeung et al. have implemented Lagrangian particle-tracking methods in DNS simulations [36,37]. These studies used Lagrangian fluid particle-tracking to analyze specific details of combustion and flame-vortex interaction. A series of numerical and experimental studies conducted by Day et al. applied Lagrangian particle-tracking methods to characterize the interaction of thermal/diffusive unstable flames with turbulence for low swirl laboratory flames [38,39]. More recently, a DNS study conducted by Hamlington et al. considered the effects of turbulence on unconfined stoichiometric hydrogen-air flames with $Ka = 150$ and 450 [40]. This research study sought to characterize the thermodynamic quantities, chemical composition, as well as fluid residence time and path length of the Lagrangian fluid elements as they evolved through the turbulent flame. A three-dimensional experimental study conducted by Steinberg et al. considered a pilot burner and used Lagrangian tracking to isolate the principal strain-rate source terms [12]. This work demonstrated that combustion serves to attenuate strain-rate related source terms, indicating attenuation of the turbulent strain-rate. Similarly, the vorticity-related source terms decreased within the flame due to attenuation of the reactant vorticity. The research concluded that the main driving mechanisms of these characteristics were the pressure and density gradient contributions [12].

The vast majority of research studies that advanced the knowledge of flame-vorticity dynamics have been implemented numerically. The results obtained in these studies have been instrumental in the quantification of the vorticity mechanisms for turbulent combustion. However, a substantial deficiency of experimental work in the area persists. Experimental data is crucial for the validation and expansion of the numerical results. The current study, therefore, seeks to expand the current knowledge through experimental characterization of the flame-vorticity dynamics of premixed bluff-body stabilized turbulent flames. A variable-geometry combustor is used to control the pressure gradient, thus allowing for augmentation and exploration of flame-generated vorticity