Fuel 194 (2017) 239–256

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Lagrangian mechanisms of flame extinction for lean turbulent premixed flames

Marissa K. Geikie, Kareem A. Ahmed *

Propulsion and Energy Research Laboratory, Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, FL, USA

ARTICLE INFO

Article history:
Received 24 August 2016
Received in revised form 1 December 2016
Accepted 15 December 2016
Available online 13 January 2017

Keywords:
Bluff-body premixed flames
Flame extinction
Strained flames
Lagrangian vortex modeling

ABSTRACT

Flame extinction is a critical impediment invariably limiting the performance of modern turbulent combustion technology. Combustion systems operating at lean conditions are highly susceptible to dynamic flame stability induced by local flame extinction. This stimulates flame blow-out and inevitably termination of the combustion process. The present study focuses on understanding the driving mechanisms which lead to flame extinction. A Lagrangian flame-vortex model is developed and used to study the flame extinction mechanisms. The model dynamically simulates the turbulent reacting flow exploiting a Lagrangian vortex element scheme and detailed strained kinetics. This systematic modeling strategy effectively encapsulates the dynamics of premixed turbulent flames in terms of stability and extinction. Two extinction modes of flame blow-out are analyzed using the model, the first of which is induced by decreasing equivalence ratio primarily resulting in diminishing strain rate limit of the flame. The alternate mode is focused on inflow-velocity induced extinction which is caused principally by increased hydrodynamic strain in the flow-flame field. The mechanics of both modes are examined utilizing the model's unique Lagrangian tracking capability for extinction-inducing fluid element clusters. This technique enables isolation and detailed analyses of flame and fluid properties leading to blow-out, demonstrating the crucial driving mechanisms of flame extinction.

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1. Introduction

Enhanced understanding of the flame extinction mechanisms is critical for the advancement of lean turbulent combustion technology [1]. Despite the associated benefits, lean reactions are susceptible to dynamic stability due to local reaction extinction leading to flame blow-out. Flame stability and extinction is a major challenge for propulsion and energy systems. An improved understanding and prediction of flame extinction and dynamic flame stability will lead to innovative solutions for turbulent combustion-reliant systems for increased efficiency, broadened safe operating domain, and reduced emission of harmful pollutants [2].

Flames holders are extensively utilized in aerospace propulsion and energy combustion systems for flame stabilization and turbulent mixing [3]. The flame holder in the form of a bluff-body induces flow separation establishing a recirculation zone [4,5] where the recirculating products sustain a stabilized flame through turbulent transport with the freestream reactants [6]. Dynamic stability of this mechanism is limited to a specific operating envelope [6] outside which flames are particularly susceptible to the fluid dynamics and hydrodynamic strain. At strain rates exceeding the threshold of flame limit, blow-out occurs [3,7–9]. Repeated local blow-out and re-ignition events have been demonstrated by Chaudhuri et al. [3,7] and Tuttle et al. [10,11] to consistently precipitate global flame extinction. These series of events occurs predominantly in the recirculation region where fresh reactant entrainment motivates re-ignition [1,6,7]. However, global extinction inevitably occurs following the entrainment of excess reactants, which effectively dilutes the mixture and interrupts the flame ignition mechanism [4,6].

Considerable efforts have focused on isolating the mechanisms which drive flame blow-out. Investigations conducted by Nair [1,12] and Shanbhogue [6,13] have concluded that blow-out is primarily caused by excess flame strain, resulting from a process comprised of two notable stages. First, local extinctions due to the aforementioned mechanisms induce the development of flame holes. As a result, downstream flame holes motivate transition to Bérnard von Kármán (BVK) shedding. This conclusion is also supported numerically by Kiel et al. [14,15]. Computational work by Mehta et al. [16] and Erikson et al. [13] have shown that

* Corresponding author.
E-mail addresses: mkgeikie@knights.ucf.edu (M.K. Geikie), kareem.Ahmed@ucf.edu (K.A. Ahmed).

http://dx.doi.org/10.1016/j.fuel.2016.12.097
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diminishing baroclinic torque production, characteristic of lean flames, similarly promotes the transition to BVK vortex shedding. This shedding causes significant excess strain in the flow-field, which has been shown to inevitably result in global flame extinction [6,13,16].

Similar studies have sought to determine where global blowout is predominantly induced. Using Large Eddy Simulation (LES), Knaus et al. [17,18] concluded that extinction is most probable directly downstream from the flame anchor location, along the recirculation region edge [17]. The work computed a mean Damköler field for the extinction criteria which ultimately neglected to capture the dynamic effects of the flame-flow instabilities. Related experimental investigations by Chaudhuri et al. [3,7] and Tuttle et al. [10,11] determined global flame extinction to be most apparent along the recirculation and reattachment regions. High speed laser diagnostic results indicated the magnitude of span-wise vorticity was maximum in this domain. The data furthermore demonstrated maximum flow-field and flame strain rates in the recirculation region [10]. These experimental measurements of Chaudhuri et al. [3,7] and Tuttle et al. [10,11] were concurrently used for comparison with related numerical research. Sankaran et al. [5,19] used a Lagrangian vortex model [20,21] for a similar bluff-body flame configuration. The study resulted in evaluation of local flame strain and flame extinction using the Karlovitz number [8]. The Karlovitz number was based on the hydrodynamic strain, laminar flame speed, laminar flame thickness and required calibration factors [5,19]. The results showed flame extinction developing in vortex roll-up regions and consequently flame blow-out. Although the global flame extinction was captured, the local dynamics of flame extinction were fundamentally different from the experimental data shown by Chaudhuri et al. [3,7] and Tuttle et al. [10,11].

This research improves upon the current understanding [5,17–20] of flame extinction physics for lean premixed turbulent combustion. Two modes of lean flame extinction are isolated for analysis: equivalence ratio and velocity induced extinction. The methodology uses a Lagrangian flame-vortex model to isolate the fundamental local and global driving mechanisms of flame extinction. The model has been adapted from related research [16] and extended to include flame extinction modeling via dynamic flame property and strain rate calculations. The model spatially and temporally couples the fluid dynamics and chemical kinetics using a Lagrangian transport vortex element method coupled with strained flame kinetics. Local flame strain rate limit is computed using the opposed jet flame detailed kinetics mechanism [22,23]; actual local flame hydrodynamic strain rate is calculated directly [8,9]. Flame extinction is subsequently inferred by comparison of the flame strain rate limit to local strain conditions; when the latter is in excess of the limit, flame extinction occurs. The temporal mechanisms resulting in flame extinction are then analyzed using this model's unique Lagrangian tracking capability. The focus of the analysis is the influence of flow-field and flame interaction leading to blow-out, with specific emphasis on fluid dynamics and strain rates.

2. Numerical method

The current model simulates premixed turbulent bluff-body stabilized combustion with a two-dimensional assumption. Since the Reynolds number is within a low turbulence regime and channel width is much larger than the bluff-body dimensions, two-dimensionality is an adequate assumption as demonstrated by Kedia [24,25], Mehta [16] and Nair [1]. This assumption has been verified using Reynolds-averaged Naiver-Stokes (RANS) and Discrete Eddy Simulation (DES) models. The results confirm that the span-wise velocity component is small; the maximum magnitude is less than 7% of the inflow, confined to a limited region of the domain. Further validations of key flow-flame characteristics are executed to ensure the reacting flowfield of the bluff-body is accurately captured using this Lagrangian model. The inflow conditions are uniform as shown in Fig. 1; there is a finite density and viscosity gradient across the flame which is captured using the two-dimensional flame sheet model. The turbulent flow model is devised as the Lagrangian discretization of the unsteady vorticity in the form of discrete elements. Flame and fluid elements are propagated using the Lagrangian equations of motion and vortex elements are added along the bluff-body surface to satisfy the no-slip boundary condition.

The computational domain is 12H, where H is the bluff-body height [26,27]. This extended domain is chosen to allow for direct comparison of current numerical results with relevant experimental and numerical data. Furthermore, this domain captures the entirety of baroclinic torque effects along the flame region, which is a critical consideration for extinction analyses [16]. The time step used for this work is of order 10^{-4} s [21].

2.1. Vorticity equation

The turbulent flow model is formulated on the basis of the unsteady vorticity convection equation,

$$\underbrace{\frac{D\vec{\omega}}{Dt}}_{Vorticity\ Convection} = \underbrace{\vec{\omega}\cdot\vec{\nabla}\vec{v}}_{Vorticity\ Stretching} - \underbrace{\vec{\omega}\vec{\nabla}\cdot\vec{v}}_{Dilatation} + \underbrace{\upsilon\nabla^2\vec{\omega}}_{Vorticity\ Diffusion} + \underbrace{\frac{1}{\rho^2}(\vec{\nabla}\rho\times\vec{\nabla}p)}_{Baroclinic\ Torque} \quad (1)$$

which has been simplified to this form for inviscid interior flow. This assumption is prevalent in similar numerical formulations which demonstrate the effects to be negligible [20,28]. Furthermore, vorticity stretching is neglected since the model is two-dimensional and vorticity is treated as a scalar [19]. The discrete elements are convected by means of unsteady vorticity Lagrangian discretization. The dilatation term attenuates vorticity due to the gas expansion. Diffusion further spreads vorticity due to molecular transport. Baroclinic torque is responsible for the emergence and generation of vorticity [19,20]. A detailed derivation of Eq. (1) can be found in related Refs. [19,20].

Eq. (1) is solved numerically, evaluated by superposition of fundamental terms, each of which is solved independently and sequentially in fractional steps [20]. The modeled reacting flow field subsequently combines all term solutions to the vorticity equation.

2.2. Boundary conditions

Boundary layers developing along the bluff-body surfaces are the primary source of vorticity generation. The boundary layer is modeled by the addition of vortex elements along the surface, emulating the no-slip boundary condition. Elements are added at the surface of the bluff-body prior to each computational step. In terms of real flow physics, this corresponds to a generation frequency of 1500 Hz. The resultant average spacing is 0.05H ± 0.015H for a typical steady-state simulation which satisfies the overlap requirement for accuracy of vortex methods [27,29,30].

The no-penetration boundary condition is similarly imposed on the bluff-body, restricting elements from entering the surfaces at the end of each computational step. This condition is implemented using the method of images, i.e., reflecting elements within the solid boundaries back to the computational domain [21].

As vortex elements exit the domain, they are inevitably deleted to preserve computational efficiency. The choice of deletion

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