Combustion and Flame 161 (2014) 2327–2339

Contents lists available at ScienceDirect

Combustion and Flame

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

The anchoring mechanism of a bluff-body stabilized laminar premixed flame

Kushal S. Kedia, Ahmed F. Ghoniem *

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 4 October 2013
Received in revised form 22 December 2013
Accepted 8 February 2014
Available online 5 March 2014

Keywords:
Premixed flame anchoring
Bluff-body
Flame structure
Conjugate heat exchange
Preferential diffusion
Laminar

ABSTRACT

The objective of this work is to investigate the mechanism of the laminar premixed flame anchoring near a heat-conducting bluff-body. We use unsteady, fully resolved, two-dimensional simulations with detailed chemical kinetics and species transport for methane–air combustion. No artificial flame anchoring boundary conditions were imposed. Simulations show a shear-layer stabilized flame just downstream of the bluff-body, with a recirculation zone formed by the products of combustion. A steel bluff-body resulted in a slightly larger recirculation zone than a ceramic bluff-body; the size of which grew as the equivalence ratio was decreased. A significant departure from the conventional two-zone flame-structure is shown in the anchoring region. In this region, the reaction zone is associated with a large negative energy convection (directed from products to reactants) resulting in a negative flame-displacement speed. It is shown that the premixed flame anchors at an immediate downstream location near the bluff-body where favorable ignition conditions are established; a region associated with (1) a sufficiently high temperature impacted by the conjugate heat exchange between the heat-conducting bluff-body and the hot reacting flow and (2) a locally maximum stoichiometry characterized by the preferential diffusion effects.

1. Introduction

In practical combustors, the inlet velocity of the premixed reactants are typically much higher than the unstretched adiabatic laminar flame speed of the mixture. Bluff-bodies are often used to furnish the necessary mechanism for flame stabilization and continuous burning in such combustors. They provide a low-velocity region for the aerodynamic anchoring of the flame. There is often significant flame-wall interactions due to the conjugate heat exchange between the hot products and the nearby heat-conducting flame-holder. Furthermore, in these systems the length scales vary from the meter-scale combustor geometric details to the thin sub-millimeter scale flame fronts. The time scales span the slow conjugate heat exchange processes and the rapid radicals' diffusion and reaction phenomena. In our recent work in [1], we developed a numerical method to accurately capture these wide spectra of spatial and temporal scales using an operator-split projection algorithm (for the multi-time-scales) coupled with a block-structured adaptive mesh refinement (SAMR) framework (for the multi-length-scales) and immersed boundary formalism (to incorporate the flame-wall interactions). When coupled with a detailed chemical kinetics mechanism, fully-resolved simulations using this tool can provide valuable insight into the complex underlying physical mechanisms of fundamental processes like flame stabilization, extinction and blow-off.

Blow-off of bluff-body stabilized premixed flames has been widely investigated in the literature, primarily using experiments. Shanbhogue et al. [2] comprehensively review these investigations. However, there does not exist any literature (experimental or numerical) describing the mechanism of bluff-body flame anchoring or the simultaneous dynamic and heat transfer interactions between the reacting flow and the bluff-body, to the best of our knowledge. Experimental investigations face severe limitations such as optical diagnostics issues, harsh combustion environment and lack of detailed species-field data near flame-holder walls. Numerical simulations have not yet been performed in the literature incorporating detailed chemical kinetics and accurate description of the flame-wall interactions due to the large computational expense. In fact, artificial flame anchoring conditions are often used in direct numerical simulations (DNS) such as a high temperature hot-spot [3], isothermal flame-holders [4] or hot combustion products co-flowing with reactants at the inlet used in the slot-burner simulations in [5]. As a result, most DNS investigations

* Corresponding author.
E-mail address: ghoniem@mit.edu (A.F. Ghoniem).

http://dx.doi.org/10.1016/j.combustflame.2014.02.005
0010-2180/

are limited to the flow-field far away from the anchoring region. In our recently developed numerical method [1], no artificial flame anchoring boundary conditions were imposed. We allowed the flame to naturally choose an anchoring location by accurately solving for the flame-wall conjugate heat exchange. We also elucidated the laminar stabilization and blow-off mechanism of perforated-plate stabilized premixed flames and highlighted the coupled role of curvature and conjugate heat exchange with the plate in [6].

Soteriou and co-workers [7,8] studied the physics of the bluff-body stabilized premixed flame at high Reynolds number using an unsteady two-dimensional vortex element method. They analyzed the role of baroclinic vorticity generation, wall-generated vorticity and the dilatation due to the combustion heat release in shifting the asymmetric non-reacting flow in the von-Karman regime to a symmetric shedding field. An adiabatic boundary condition at the bluff-body was imposed in these simulations thereby forcing an artificial flame anchoring condition. Furthermore, the influence of the multi-species transport on flame anchoring cannot be investigated with their tool due to the kinematic flame-sheet modeling of the reacting flow.

In this paper, our objective is to use our high fidelity numerical tool to study the hitherto unexplored flame anchoring mechanism on a bluff-body and investigate the impact of conjugate heat exchange and preferential diffusion on it. We will also show the existence of an unconventional flame structure in the anchoring region. We focus on laminar flames only, thereby decoupling the additional complexities of flow unsteadiness and vortex shedding associated with turbulent flames. We summarize the governing equations in Section 2 and the numerical method in Section 3. We present our numerical simulations in Section 4 and the conclusions in Section 5.

2. Governing equations

In this section, we briefly summarize the governing equations that are numerically integrated. At the low-Mach number limit, the continuity, momentum and scalar equations are written in compact form as

$$\nabla\cdot\mathbf{v} = -\frac{1}{\rho}\frac{D\rho}{Dt} \tag{1a}$$

$$\frac{\partial\mathbf{v}}{\partial t} = -\frac{1}{\rho}\nabla p + C_U + D_U \tag{1b}$$

$$\frac{\partial T}{\partial t} = C_T + D_T + S_T \tag{1c}$$

$$\frac{\partial Y_k}{\partial t} = C_{Y_k} + D_{Y_k} + S_{Y_k} \quad k = 1,2,\ldots,N_s \tag{1d}$$

where $\mathbf{v}$ is the velocity vector, ρ the density, T the temperature, Y_k the mass fraction of species k, p is the hydrodynamic pressure, and N_s is the number of chemical species. The $\frac{D}{Dt}$ operator represents the material derivative, $\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla$. The system of governing equations is closed with the equation of state for an ideal gas

$$P_0 = \frac{\rho\Re T}{\overline{W}} = \rho\Re T\sum_{k=1}^{N_s}\frac{Y_k}{W_k} = \text{const} \tag{2}$$

where P_0 is the thermodynamic pressure, $\Re$ is the universal gas constant, W_k is the molecular weight of species k, and $\overline{W}$ is the molecular weight of the mixture. The thermodynamic pressure is spatially uniform in the low-Mach number limit. Further, restricting our focus to flows in open domains, P_0 is constant. Radiation is ignored.

The convection and diffusion terms in (1) are given by

$$C_U = -(\mathbf{v}\cdot\nabla)\mathbf{v}, \quad D_U = \frac{1}{\rho}\nabla\cdot\tau \tag{3a}$$

$$C_T = -(\mathbf{v}\cdot\nabla)T, \quad D_T = \frac{1}{\rho c_p}\nabla\cdot(\lambda\nabla T) - \left(\sum_{k=1}^{N_s} c_{p,k}Y_k\mathbf{V}_k\right)\cdot\nabla T \tag{3b}$$

$$C_{Y_k} = -(\mathbf{v}\cdot\nabla)Y_k, \quad D_{Y_k} = -\frac{1}{\rho}\nabla(\rho Y_k\mathbf{V}_k) \tag{3c}$$

and the source terms by

$$S_T = -\frac{1}{\rho c_p}\sum_{k=1}^{N_s} h_k\dot{\omega}_k, \quad S_{Y_k} = \frac{\dot{\omega}_k}{\rho} \tag{4}$$

where τ is the stress tensor given by $\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{v}\right)$, μ is the dynamic viscosity, and λ is the mixture thermal conductivity. Further,

$$\mathbf{V}_k = -\frac{D_{k,m}}{Y_k}\left(\nabla Y_k + \frac{Y_k}{\overline{W}}\nabla\overline{W}\right) \tag{5}$$

is the diffusion velocity of species k, where $D_{k,m}$ is the mixture-averaged diffusivity of species k. Finally, c_p and $c_{p,k}$ are the specific heats at constant pressure for the mixture and species k, respectively, and h_k and $\dot{\omega}_k$ are the specific enthalpy and molar production rate, respectively, of species k. The equation of state (2) is used to derive an expression for the right hand side of the continuity Eq. (1a)

$$\frac{DP_0}{Dt} = 0 \rightarrow \frac{1}{\rho}\frac{D\rho}{Dt} = -\frac{1}{T}\frac{DT}{Dt} - \sum_{k=1}^{N_s}\frac{\overline{W}}{W_k}\frac{DY_k}{Dt} \tag{6}$$

$$= -\frac{1}{T}(D_T + S_T) - \sum_{k=1}^{N_s}\frac{\overline{W}}{W_k}(D_{Y_k} + S_{Y_k}) \tag{7}$$

The Soret and Dufour effects are not included in the transport model, also assumed in many previous investigations [9] (and references within). Further, these effects were shown to be less important in [10] for pure methane–air lean premixed flames. A mixture-averaged formulation is used to compute the transport properties of the gas mixture. The domain boundary conditions are presented in [11].

There is thermal contact between the immersed solid body and the surrounding fluid. This conjugate heat exchange between the solid and the fluid is incorporated by simultaneously integrating the equations governing the reacting flow with the transient heat conduction equation inside the solid:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho_{fh}c_{fh}}\nabla\cdot(\lambda_{fh}\nabla T) \tag{8}$$

where ρ_{fh} is the density, λ_{fh} is the thermal conductivity and c_{fh} is the heat capacity of the solid. Additionally, the no species-penetration condition, continuity of the temperature field and the heat-flux conservation are imposed at the solid–fluid boundary at each time step using the buffer zone method introduced in [1].

3. Numerical methodology

In this section, we briefly summarize the numerical methodology used to integrate the governing equations. The sequential stages of the numerical algorithm are described in [1]. In that paper, we introduced a buffer zone immersed boundary method and coupled it with a block-structured adaptive mesh refinement (SAMR) framework and a low-Mach number operator-split projection algorithm. We thoroughly validated the numerical method using benchmark simulations documented in the literature. We also demonstrated its overall second-order spatio-temporal convergence.