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Impact of the bluff-body material on the flame leading edge structure and flame–flow interaction of premixed CH_4/air flames

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ABSTRACT

In this paper we investigate the interaction between the flame structure, the flow field and the coupled heat transfer with the flame holder of a laminar lean premixed CH_4/air flame stabilized on a heat conducting bluff body in a channel. The study is conducted with a 2-D direct numerical simulation with detailed chemistry and species transport and with no artificial flame anchoring boundary conditions. Capturing the multiple time scales, length scales and flame-wall thermal interaction was done using a low Mach number operator-split projection algorithm, coupled with a block-structured adaptive mesh refinement and an immersed boundary method for the solid body. The flame structure displays profiles of the main species and atomic ratios similar to previously published experimental measurements on an annular bluff body configuration for both laminar and turbulent flow, demonstrating generality of the resolved flame leading edge structure for flames that stabilize on a sudden expansion. The flame structure near the bluff body and further downstream shows dependence on the thermal properties of the bluff body. We analyze the influence of flow strain and heat losses on the flame, and show that the flame stretch increases sharply at the flame leading edge, and this high stretch rate, together with heat losses, dictate the flame anchoring location. By analyzing the impact of the flame on the flow field we reveal that the strong dependence of vorticity dilatation on the flame location leads to high impact of the flame anchoring location on the flow and flame stretch downstream. This study sheds light on the impact of heat losses to the flame holder on the flame–flow feedback mechanism in lean premixed flames.

1. Introduction

Bluff body flame holders are commonly used in industrial combustors and propulsion systems. In practical combustors the reactants velocity is orders of magnitude higher than the burning velocity, thus the recirculation zone generated at the wake of a bluff body provides a low velocity region where the flame can stabilize. A comprehensive review of the fluid mechanics of bluff body stabilized flames was given in [1]. Most of the experimental studies on bluff body stabilized flames focused on the blow off limits [2], blow off dynamics [3], and flame response to acoustic forcing [4]. Various modeling approaches have been used to analyze different phenomenon in bluff-body stabilized premixed flames. Soteriou et al. [5] used an unsteady two-dimensional vortex element method to show the shifting of the vortex structure from the asymmetric Von-Karman regime in non-reacting flow to a symmetric vortex shedding field in reacting flow. Giacomazzi et al. [6] used LES to show that 2D simulations over predict the length of the recirculation zone. Ketelheun et al. [7] incorporated heat losses into the tabulated chemistry for LES of lean premixed combustion and showed the importance of heat losses on a flame stabilized on a bluff body. Nevertheless, in the vortex element method and LES the flame scales are not resolved, therefore those models are not appropriate for investigating the detailed flame structure.

The structure of the flame was also experimentally investigated, but until recently it was done only far (at a distance of a few diameters of the bluff body) downstream from the body itself [8], due to technological constrains. Recently, Barlow et al. [9] showed the flame structure at the vicinity of the bluff body. They performed Raman–Rayleigh–LIF diagnostics of premixed CH_4/air flames stabilized on a bluff body, and presented temperature and major species profiles, highlighting the important role of preferential diffusion. Barlow et al. proposed that H_2 and H_2O diffuse preferentially ahead of the CO and CO_2 towards the reactants and subsequently convect downstream, while retaining higher CO and CO_2 concentrations in the recirculation zone. The results show the presence of preferential diffusion at low reactants flow velocities, where the flow is expected to be laminar, with an amplified effect with increasing Reynolds number, and saturation as Reynolds number reaches sufficiently high values in turbulent flow regime [10].

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Those experiments further support the significance of molecular transport processes even in highly turbulent flames, as reviewed by Lipatnikov and Chomiak [11], and further emphasized by Driscoll [12] who reviewed evidence of flamelet structure in highly turbulent premixed flames. More recent experimental data showed that the effect of preferential diffusion, displayed as change in the atom ratios (C/H and C/O), increases closer to the body [13]. Additionally, it was found that the scalars profile resembles that of a strained flame. Euler et al. [14] performed temperature measurements with laser-induced phosphorescence of the same bluff body combustor that Barlow et al. [9] investigated, aiming to provide modelers the solid boundary condition for simulations.

DNS analysis on a similar geometry of that of Barlow et al. [9] was conducted by Katta and Roquemore [15], assuming axisymmetric laminar flow and a detailed chemical mechanism (GRI-3 [16]). The computations were able to reproduce the high C/H atomic ratio increase near the bluff body and the increase in the preferential diffusion with reactant flow velocity. Lee et al. [17] also used DNS to model lean premixed H_2/air flames stabilized on a bluff body in a narrow channel. The simulations showed that as the reactants velocity approaches the blow off limit, the flame dynamic exhibit a sequence of extinctions and re-ignitions. Since adiabatic boundary condition at the bluff body was assumed in all modeling approaches outlined above the flame anchoring position was artificially attached to the body surface. Heat losses to the body quench a flame touching the surface, thus in reality the flame anchor at some location in the flow field. Other investigations of premixed flames with DNS employed other artificial flame anchoring conditions such as a high temperature hot-spot [18] or isothermal boundary conditions [19].

A novel approach for DNS method for chemically reacting flow over a heat conducting solid and their conjugate heat transfer was presented by Kedia et al. [20]. The method incorporates an immersed heat conducting solid, a block structured adaptive mesh refinement framework, a low Mach number operator-split projection algorithm, and detailed chemical kinetics. This model was used for investigating flame anchoring [21], blow off [22], and response to harmonic flow forcing [23] in a bluff body stabilized flame. Calculations revealed [21] that the flame anchors itself inside the recirculation zone at a location with suitable ignition conditions of temperature and composition. The conjugate heat transfer with the bluff body and the preferential diffusion were found to have important influence on the temperature and composition at the vicinity of the bluff body, and thus influence the flame anchoring location. Kedia and Ghoniem [21] also observed that with a bluff body that has higher heat conductivity the recirculation zone length increased, but a mechanistic explanation was not provided. Moreover, the high stretch rate at the flame leading edge and its impact on the flame and flow structure was not recognized.

The current study was further motivated by experimental investigation of Hong et al. [24] with PIV and chemiluminescence measurements of lean premixed flames in a backward facing step combustor with different flame holder materials. The measurements showed that a ceramic step increased the stability operating conditions in comparison to a steel step. The significance of the flame holder interaction with the flame leading edge was also highlighted in the experimental investigation of Mejia et al. [25] in a slot burner. They have demonstrated the impact the flame holder temperature on the flame leading edge motions and the flame transfer function, which leads to transition from unstable to stable operation as the temperature of the flame holder increases. This suggests a possibility to influence the flame–flow interaction by altering the thermal properties of the bluff body.

In the current study we use the numerical approach presented by Kedia et al. [20] in order to shed light on the flame structure and flame–flow interaction. First, we examine the species, temperature and enthalpy fields near the leading edge and show that the flame leading edge structure and location are primarily controlled by high stretch rates and heat losses. The high stretch rates at the flame leading edge and their significant impact on the structure and location of the flame were not addressed in recent detailed numerical simulations of the flame anchoring conditions [21] and flame structure [15] in bluff body stabilized flames. The flame species vs. temperature phase plot has good correspondence with the trends and conclusions from the measurements of Magnotti and Barlow [13], and also demonstrates the accumulation of CO_2 in the recirculation zone due do preferential diffusion effects. By analyzing the flame response to a step in the inlet velocity we show that the accumulation of CO_2 in the recirculation zone has negligible influence on the heat release and flow structure. Examining the vorticity field reveals to what extent the changes in the flame location effect the damping of vorticity. Finally, we present a feedback mechanism between the flame location and flow structure that is impacted by the heat losses to the bluff body, which explains the significant impact of the bluff body thermal properties on the flow and flame structure.

2. Model

The model is based on a 2-D direct numerical simulation with detailed chemistry and species transport, and with no artificial flame anchoring boundary conditions. Capturing the multiple time scales, length scales and flame-wall thermal interaction was done using a low Mach number operator-split projection algorithm, coupled with a block-structured adaptive mesh refinement (SAMR) and an immersed boundary method for the solid body. Full details of the DNS model were presented and validated by Safta et al. [26], and further developed by Kedia et al. [20]. In the present paper we only present the governing equations and outline the numerical methodology.

2.1. Governing equations and numerical methodology

At the low-Mach limit, the continuity, momentum and scalar equations are written in the compact form as:

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

$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{1}{\rho}\nabla p + C_U + D_U \tag{2}$$

$$\frac{\partial T}{\partial t} = C_T + D_{T,cond.} + D_{T,diff.} + S_T \tag{3}$$

$$\frac{\partial Y_k}{\partial t} = C_{Y_k} + D_{Y_k} + S_{Y_k},\ \ k = 1, 2, \ldots, N_s \tag{4}$$

where $\mathbf{u}$ is the velocity vector, ρ the density, T the temperature, Y_k the mass fraction of species k, p is the hydrodynamic pressure, N_s is the number of chemical species, and the operator $\frac{D}{Dt}$ represents the material derivative. The convection, diffusion and source terms in (2)–(4) are given by:

$$C_U = -(\mathbf{v}\cdot\nabla)\mathbf{v},\ D_U = \frac{1}{\rho}\nabla\cdot\tau \tag{5}$$

$$C_T = -(\mathbf{v}\cdot\nabla)T,\ D_{T,cond.} = \frac{1}{\rho c_p}\nabla\cdot(\lambda\nabla T),$$
$$D_{T,diff.} = -\left(\sum_{k=1}^{N_s} c_{p,k} Y_k \mathbf{V_k}\right)\cdot\nabla T \tag{6}$$

$$C_{Y_k} = -(\mathbf{v}\cdot\nabla)Y_k,\ D_{Y_k} = -\frac{1}{\rho}\nabla(\rho Y_k \mathbf{V_k}) \tag{7}$$