Stabilization of ultra-lean hydrogen enriched inverted flames behind a bluff–body and the phenomenon of anomalous blow–off

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ABSTRACT

This paper presents a fundamental study of ultra-lean flames stabilized behind a thin, highly conducting metallic rectangular bluff body acting as a flame holder. Using high fidelity numerical simulations, we reproduce a phenomenon observed experimentally, showing that in this configuration steady hydrogen–methane flames can exist at equivalence ratios below the flammability limit associated with planar un-strained flames with the same hydrogen–methane proportion. These ultra–lean hydrogen–enriched mixtures exhibit a distinct stabilization mechanism compared to pure methane flames: they stabilize in the form of inverted closed V or U flames farther away from the flame holder as the inflow reactants velocity is reduced, leading eventually to blow-off for sufficiently small velocities. Conversely, as the reactants flow rate is increased, the flames anchor closer to the flame holder, and surprisingly no blow-off is observed at high velocities. This response is shown to be linked to the presence of hydrogen in the fuel mixture and its large diffusivity, which results in locally richer mixtures in the strained, curved flame base.

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1. Introduction

Flame anchoring (or static stabilization) using a solid obstacle as a flame holder is a recurrent subject of interest in combustion science, both as a fundamental research problem and because it is one of the practical means of effectively obtaining a stable premixed flame in a high velocity reactant flow over a wide range of inflow rates. The solid body immersed in the flow creates a low velocity recirculation zone where the flame can anchor even when the burning velocity is very small compared to the mean flow velocity. The recirculating flow produces a flux of hot products towards the reactants that contribute to their preheating, therefore favoring ignition conditions. Additionally, the solid body can contribute to flame stabilization by providing means by which some of the heat produced in the combustion zone is conducted through the solid back to preheat the reactants. Aerodynamic strain and curvature, together with possible effects of differential diffusion and heat transport determine the local flame propagation speed and its shape.

The relative relevance of these different stabilization mechanisms depends on the problem parameters, e.g., the flow velocity, fuel composition, bluff–body shape and material, etc. Stabilization, in some cases, can be achieved without thermal interaction with the flame holder (adiabatic stabilization [1–3]), while in others stability criteria depend on the thermal properties of the bluff-body [4]. As discussed in [4] and later studies [5–7], this depends on the mixture burning characteristics and flow rate as well as on the thermal properties of the solid. Thus, including conjugate heat exchange between the gas and the bluff–body is warranted unless it is clear a priori that this interaction is negligible.

Until recently, experiments have been the primary source of information on the study of bluff-body stabilized flames. Starting with the pioneering work of Lewis and von Elbe [8,9], who performed experiments of inverted flames stabilized behind a central body and linked the blow-off to the velocity gradient at the nozzle reaching a critical value, many researchers have tried to explain the mechanisms that affect flame stabilization and blow-off in these flames, adding other factors such as flame curvature [2,3] and heat exchange with the flame holder [1–3,10]. A review on the dynamics of blow-off of turbulent flames stabilized behind a bluff-body can be found in [11].

Numerical studies where the combustion field, its heat exchange with the solid body and the internal temperature distribution inside the latter can be coupled have been scarce until recent years. Advances in computational power and parallel computing as well as specific time–coupling strategies [12,13] have allowed

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direct numerical simulations of this kind of problems using detailed chemistry and transport properties of complex fuels and including the conjugate heat exchange with the solid [4–7,14,15].

Most of the studies mentioned above have focused on mechanisms of methane flames stabilization behind solid bodies. A recent interesting experimental study [16] (also studied numerically in [17]), has, however, shown a different stabilization mechanism of hydrogen-enriched flames. That work examined methane-air and methane-hydrogen-air flames anchored behind a long, highly conducting metallic cylindrical rod with a small diameter (1 to 3 mm), placed along the axis of a circular channel. It showed that pure methane flames behave according to the well-know mechanism, anchoring farther away from the solid rod as the flow rate is raised and eventually blowing off at a high enough flow rate. On the other hand, when the burning mixture contains a sufficient amount of hydrogen, the trend is reversed: increasing the flow rate results in the flame anchoring closer to the metallic rod and reducing the flow rate leads to flames stabilized farther from the flame holder and can eventually lead to blow-off. This blow-off by decreasing the inflow velocity, termed "anomalous blow-off" in [16], was found when hydrogen content was equal or larger than 20%. For these mixtures "normal blow-off", that is, flame extinction as the flow rate is raised, at high flow rates was also reported. Moreover, the study showed that in this configuration hydrogen-containing flames could be stabilized for mixtures well below the flammability limit, permitting ultra-lean combustion.

The authors relate this anomalous behavior to the effect of differential diffusion on the burning speed of a stretched methane-hydrogen flame. According to theory (see e.g., [18,19]), the influence of flame stretch on the flame burning speed is twofold: one is the contribution of pure stretch, which always decreases the flame speed (for positive stretch) and the second is the contribution of the combined differential diffusion (unequal heat and mass diffusivity) and stretch, whose effect on the flame speed depends on the mixture Lewis number. For mixtures with Lewis number smaller than one, differential diffusion results in more intense burning when positive stretch is increased. Mixtures with Lewis number larger than one show the opposite behavior, with the flame speed decreasing with increasing stretch. While it is difficult to define a global Lewis number for a mixture of methane-hydrogen, it is clear that for a sufficient fraction of hydrogen it should be smaller than one and the flame speed should increase with stretch.

Anomalous anchoring and blow-off was explained as follows: for sufficient hydrogen content the Lewis number is smaller than one and the burning intensity increases with flame stretch; therefore as the inflow velocity and consequently the flame stretch are raised the flame burns faster and moves closer to the flame holder. Moreover, to burn $Le < 1$ fuel mixtures below their flammability limit, a minimum stretch rate is needed to increase the burning velocity and make the mixture flammable. What remains unclear is that for the same hydrogen content (and Le number) a mixture can also be blown off for very large stretch rates, as the experiments suggest (normal blow-off). The experimental study in [16] reported only measurements of the flame position change and the flame holder temperature, no measurements of the flame stretch rate or burning speed were available, hence validation of the hypothesis described above was not feasible. Moreover, the analysis in [17] was mainly devoted to the study of flame stability and not to explaining the anomalous blow-off mechanism.

The aim of the present work is to contribute to the study of this problem using detailed numerical simulations, from which more detailed information can be extracted. First, we attempt to reproduce the blow–off phenomenon. For simplicity we selected to perform the simulations in a planar (2D) set-up, with a fixed-size, shorter flame holder and for mixtures with a single value of

methane-hydrogen ratio. After experimenting with different bluff-body sizes and reactant mixtures we selected a flame holder with height d equal to 5 mm and length equal to $3d$, and a mixture with $H_2 - CH_4$ ratio 40–60%. For this hydrogen fraction, ultra-lean flames and anomalous blow-off were reported in experiments (albeit in the experiment the solid body is cylindrical and these effects were observed for diameters ≥ 2 mm). Next, by varying the equivalence ratio of the mixture and/or the reactants flow rate we determined the limits for flame stabilization, finding that blow-off occurs as the velocity was reduced, for ultra–lean mixtures with $\phi = 0.35$. This study utilizes direct numerical simulation (DNS) of chemically reacting flows in the presence of a heat conducting solid developed by Kedia et al. [20]. As discussed in our previous publications, our model includes conjugate heat transfer between the fluid and the solid, which is treated using an immersed boundary approach, a block-structured adaptive mesh refinement strategy to adapt to local flame resolution needs and detailed chemical kinetics and species transport.

In Section 2 we describe briefly the conservation equations and the numerical method; Section 3 introduces the particular set-up used to model the present problem; in Section 4 we describe the steady flame solutions, and characterize the heat exchange with the flame holder, the flame stretch rate and the effect of the large hydrogen diffusivity in flame stabilization. Finally, Section 5 summarizes the main conclusions of our study.

2. Numerical model

Under the low-Mach number approximation, the conservation equations for mass, momentum, energy and species are:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}), \tag{1a}$$

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

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

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

where $\mathbf{v}$ is the velocity vector, ρ the density, T the temperature, Y_k the k species mass fraction, p the hydrodynamic pressure and N_s the number of involved chemical species. This system of equations is supplemented with the equation of state for an ideal gas:

$$p_0 = \frac{\rho \mathcal{R} T}{\overline{W}}, \tag{2}$$

where p_0 is the thermodynamic pressure, considered spatially uniform in the low-Mach number limit, and also constant in time in the present, open-domain configuration; $\mathcal{R}$ stands for the universal gas constant, and $\overline{W}$ corresponds to the mixture molecular weight: $\frac{1}{\overline{W}} = \sum_{k=1}^{k=N_s} \frac{Y_k}{W_k}$, with W_k the molecular weight of species k.

The convection, diffusion and reaction terms in Eq.(1) are:

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

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

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