Combustion and Flame 172 (2016) 153–161

Contents lists available at ScienceDirect

Combustion and Flame

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

# Joint experimental and numerical study of the influence of flame holder temperature on the stabilization of a laminar methane flame on a cylinder

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ARTICLE INFO

*Article history:*
Received 15 March 2016
Revised 10 May 2016
Accepted 24 June 2016

*Keywords:*
DNS
Conjugate heat transfer
Analytical chemistry
Radiative transfer
Stabilization
Premixed flame

ABSTRACT

The mechanisms controlling laminar flame anchoring on a cylindrical bluff-body are investigated using DNS and experiments. Two configurations are examined: water-cooled and uncooled steel cylinders. Comparisons between experimental measurements and DNS show good agreement for the flame root locations in the two configurations. In the cooled case, the flame holder is maintained at about 300 K and the flame is stabilized in the wake of the cylinder, in the recirculation zone formed by the products of combustion. In the uncooled case, the bluff-body reaches a steady temperature of about 700 K in both experiment and DNS and the flame is stabilized closer to it. The fully coupled DNS of the flame and the temperature field in the bluff-body also shows that capturing the correct radiative heat transfer from the bluff-body is a key ingredient to reproduce experimental results.

## 1. Introduction

The burnt gas temperatures reached in combustion chambers usually exceeds the maximum temperatures which can be sustained by most materials, especially metals used in engines. Therefore, cooling these walls as well as all chamber elements in contact with the flame is mandatory for combustion chamber designers. While cooling is obviously needed to preserve walls, its effects on the flames themselves has received less attention and is usually neglected in many CFD approaches. Flame/wall interaction, for example, is a field of combustion which has not been investigated yet with sufficient care [1–6]. In most cases, authors measure or compute the maximum wall heat fluxes induced by the flame but do not investigate the effects of the wall on the flame itself.

In the field of simulation, most models [7–11] assume adiabatic flows. For premixed flames, the famous BML (Bray Moss Libby) approach, for example, which is the workhorse of many theories for turbulent premixed flames [12,13] assumes that a single variable (the progress variable $c$) is sufficient to describe the flow: this is true only when the flow is adiabatic. In the same way, many usual methods for chemistry tabulation such as FPV [14], FPI [15] or FGM [16] assume that chemistry can be described using only two variables, the mixture fraction $z$ and the progress variable $c$, which implies that the flames must be adiabatic.[1] Considering that wall heat fluxes in most chambers correspond to approximately 5–40% of the chamber total power, assuming adiabaticity is clearly not compatible with the high-precision methods which are sought today. Note that computing the interaction between the flame and the wall requires to compute both the flow and the temperature within the walls simultaneously: the LES code must be coupled with a heat transfer code within the combustor walls. This task is not simple [19,20] because time scales are usually very different (a few milliseconds in the flow and a few minutes in the walls).

Among all walls present in a chamber, flame holders play a special role because they control the most sensitive zone of the chamber: the place where the flames are anchored. Any temperature change of the flame holder will induce a change of position for the flame roots and therefore a change in stability and efficiency. The coupling mechanisms between heat transfer within flameholder and flame stabilization have not been analyzed in detail yet. In a series of recent papers [21–23], the MIT group has numerically studied the stabilization of premixed flames on square flame holders and shown that the location of the flame roots but

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[1] Non adiabatic effects can be included in (Z,c) tabulation as done by Marracino et al. [17] or Fiorina et al. [18] but this increases the complexity of the tabulation significantly.

http://dx.doi.org/10.1016/j.combustflame.2016.06.025
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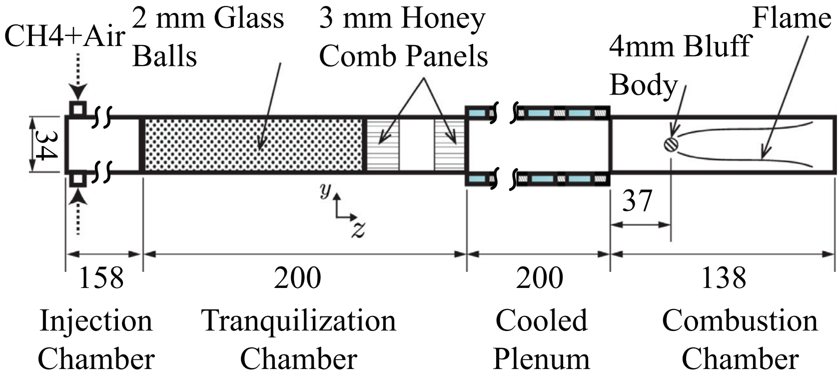

**Fig. 1.** Transverse cut of the burner.

also the blow-off limits were strongly affected by the temperature of the flame holder.

The present study focuses on a similar question: which differences in flame anchoring are observed when the temperature of the flame holder varies from a low (typically 300 K) to a high value (700 K). To obtain such a large variation in temperature, a premixed laminar methane/air flame is stabilized on a cylindrical flame holder. Two flame holders are used, with exactly the same external shape. The first one has an internal water cooling system, leading to a surface temperature close to 300 K. The second one is a full, solid cylinder which is uncooled, leading to a surface temperature close to 700 K.

Both experiments and DNS are used to analyze the differences in flame structure near the flame holder. Simulations are performed in dual mode: the flow is computed with DNS using a 13 species kinetic scheme for $CH_4$/air flames [24] while the temperature in the solid is computed with a heat transfer solver, coupled to the flow solver. The simulations, performed for cooled and uncooled flame holders, reveal drastic differences in flame root location and flow topologies. They also show that radiative heat transfer must be taken into account to predict the flame topology for the uncooled case.

Section 2 presents the experimental setup. The tools used for the coupled flow/solid simulation are described in Section 3. Results for the cooled flame holder are discussed in Section 4 before presenting the uncooled case in Section 5. Finally Section 6 discusses the influence of radiative heat fluxes on the flame stabilization when the flame holder is uncooled.

## 2. Experimental configuration

The experimental rig is shown in Fig. 1: a lean premixed methane-air V-flame is stabilized over steel cylindrical bluff body (radius of $r = 4$ *mm*). The burner has a constant cross section of $h = 34$ by $l = 94$ mm so that the flame remains two-dimensional. Individual mass flow meters are used to control air and methane flow rates. Fuel and oxidizer are premixed before entering the injection chamber though six holes. Glass wool, small glass balls and two honeycombs panels are used to laminarize the flow. The flow passes through a water-cooled plenum to ensure a constant fresh-gases temperature. Hot wire measurements downstream of the plenum show that the flow is laminar: the fluctuation level remains below 1% everywhere in the chamber. After the plenum, the flow enters the combustion chamber where the flame holder is located. Two different bluff-bodies have been used to stabilize the flame. The first one is a cooled steel cylinder (Fig. 2, left) maintained at 285 K by a 37 g $s^{-1}$ mass flow rate of cooling water. The second flame holder is a solid steel cylinder, which has exactly the same external geometry as the cooled one (Fig. 2, right). In the following, these cases will be denoted as CBB (Cooled Bluff-Body) and UBB (Uncooled Bluff-Body) respectively. Finally, the combustion chamber has a quartz window in the front, and one on each lateral side wall, for visualization.

**Table 1**
Operating conditions for the CBB and UBB cases.

| Name | Quantity | Value |
|---|---|---|
| $\Phi$ | Equivalence ratio | 0.75 |
| $u_b$ | Bulk velocity | 1.07 m $s^{-1}$ |
| $s_l$ | Laminar flame speed | 0.24 m $s^{-1}$ |
| $T_u$ | Injection temperature | 292 K |
| $T_{adia}$ | Adiabatic flame temperature | 1920 K |

The operating conditions are given in Table 1. In these conditions, the flame is steady for all cases and the power of the burner is 7 kW for $\Phi = 0.75$ and $u_b = 1.07\,\mathrm{m\,s^{-1}}$. In both cases, dimensionless flow parameters are identical. The Reynolds number based on the bluff-body diameter $Re_{bb} \approx 520$ is low and the flow remains laminar. Without combustion, a Kármán vortex street is obtained at $f = 40$ Hz in the wake of the cylinder. For reacting mixtures, the flow becomes fully steady for all cases tested here. Similarly, the ratio between the laminar flame velocity and the bulk speed $s_l/u_b \approx 0.22$ is sufficiently low to avoid flashback events.

Flames are imaged on an intensified PCO-Sensicam camera equipped with a $CH^*$ narrow band-pass filter and a *f*/16,180 mm telecentric lens [25] (Fig. 2).

In the UBB case, the full cylinder is attached at only one side of the combustion chamber. On the other side, there is a gap of approximately 3 mm between the cylinder and the quartz window. This gap drops to 1 mm at steady state because of thermal expansion. The flame holder temperature has been measured with a K-type thermocouple: $T_{cyl}^{UBB} = 670 \pm 40$ K. A temperature difference of about 70 K has been measured between the two extremities of the cylinder. This corresponds to a gradient of $\partial T/\partial x \approx 750\ \mathrm{K\,m^{-1}}$. The corresponding heat transfer is below 2 W so that axial heat flux is not taken into account in the DNS. This allows to run both the DNS and the heat transfer code on 2D meshes.

In the CBB case, the temperature elevation of the water used for cooling is equal to $\Delta T = 0.15 \pm 0.05$ K so that the cooling water temperature can be assumed to be constant. It leads to a total flux taken from the flame $\Phi^{xp}_{s \to w} = \dot{m} C_p \Delta T = 24$ W.

The thermal properties of the steel used in both UBB and CBB cases are recalled in Table 2. The emissivity of the bluff body is directly linked to its surface state. In the present experiments, the bluff-bodies are oxidized so that an emissivity of $\epsilon = 0.9$ is retained. The effects of $\epsilon$ are discussed using DNS in Section 6.