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Influence of flame-holder temperature on the acoustic flame transfer functions of a laminar flame

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ABSTRACT

The occurrence of combustion instabilities in high-performance engines such as gas turbines is often affected by the thermal state of the engine. For example, strong bursts of pressure fluctuations may occur at cold start for operating conditions that are stable once the engine reaches thermal equilibrium. This observation raises the question of the influence of material temperature on the response of flames to acoustic perturbations. In this study, we assess the influence of the temperature of the flame holder for a laminar flame. Both experiments and numerical simulations show that the Flame Transfer Function (FTF) is strongly affected by the flame-holder temperature. The key factors driving the evolution of the FTF are the flame-root location as well as the modification of the flow, which affects its stability. In the case of the cooled flame-holder, the formation of a recirculation zone is identified as the main impact on the FTF.

1. Introduction

Experimentalists are aware that the wall temperatures of a combustion chamber affect the thermoacoustic combustion instabilities which can develop in the combustor [1–4]: a chamber does not exhibit the same noise and unstable modes when it starts (and walls are cold) or when it has run for a few minutes (and walls have reached a higher steady temperature). From the modeling point of view, however, most models assume adiabatic flames and do not include any interaction between walls and flames. This is clearly a weak aspect of most Large Eddy Simulation (LES) approaches for turbulent burners. Among all the walls found in a combustion chamber, flameholders play a very specific role: this is where flames are anchored and where they are the most sensitive to heat transfer. Any temperature change of the solid in the region where flames are stabilized can change not only its stabilization point (the place where it is anchored) but also its dynamics (its response to acoustic waves as well as its blow-off limits). The MIT group used DNS to study the stabilization of premixed flames on square flame holders [5–7] and showed that the location of the flame roots and the blow-off limits were strongly affected by the temperature of the flameholder. Kaess et al. [8] proved that the temperature of a laminar flame stabilized in a dump combustor controlled the flame response to acoustic waves. Duchaine et al. [9] used sensitivity analysis on a DNS to show that the acoustic response of flames stabilized by a backward facing step depended strongly on the wall temperatures. Mejia et al. [3] demonstrated experimentally that controlling the wall temperature of a 2D triangular laminar flame was sufficient to bring it in and out of thermoacoustic oscillations. These conclusions, obtained for laminar flames, have been confirmed for turbulent flames [10,11]. [10] showed that the thermal conductivity of the backward step blocks used to stabilize a turbulent flame, controlled the level of self-sustained instability.

The present work focuses on laminar flames and analyzes the acoustic response of V-flames stabilized on a two-dimensional cylinder which can be water cooled to fully control its temperature between 300 and 700 K. The setup corresponds to the one used by Miguel-Brebion et al. [12]: a laminar methane/air flame is stabilized on a cylinder where the temperature of this cylinder is controlled by water cooling. Miguel-Brebion et al. [12] described the different flame topologies and stabilization positions observed when the flame-holder temperature was changed. When it comes to describing the capacity of these flames to create self-excited instability modes, the most useful quantity to consider is the Flame Transfer Function (FTF) $\mathcal{F}(\omega)$ which measures the normalized variations of the global reaction rate $(q'/\bar{q})$ induced by a normalized inlet acoustic velocity pulsation (u'/u_b) [2,13,14]:

$$\mathcal{F}(\omega) = \frac{q'/\bar{q}}{u'/u_b} \tag{1}$$

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FTF's can be obtained experimentally or numerically: both methods will be used here. The present study focuses on measurements of FTF in the setup of Miguel-Brebion et al. [12] and shows that the FTF are extremely sensitive to the flameholder temperature which appears to be a first-order parameter controlling the FTF in terms of gain and phase. One of the new results obtained here is that this effects of the flame holder temperature is due not only to a modification of the flame root dynamics, close to the flame holder but also to a drastic change of the mean flow itself, far downstream as seen in [15], but in this case induced by the creation of a large recirculation zone when the flame holder is cooled.

The paper combines experimental measurements and direct numerical simulation (DNS) results to analyze the FTF's of a lean premixed laminar methane/air flame. Simulations are performed in dual mode: the flow is computed with DNS using a 19 species kinetic scheme for CH_4/air flames [16] while the temperature in the solid is computed with a heat transfer solver, coupled to the flow solver. The experiment uses a multi-microphone technique and hot wire measurements to quantify u' as well as unsteady CH* chemiluminescence and high speed imaginary to evaluate $\dot{q}'$.

The paper is organized as follows: the configuration is briefly described in Section 2. The experimental set-up used to measure the FTF's is described in Section 3. The DNS tools used to compute the FTF of the flames are described in Section 4. Finally a discussion of the results obtained experimentally and numerically is presented in Section 5.

2. Configuration

The experimental bench consist of a lean premixed methane–air V-flame stabilized in the wake of a steel cylindrical bluff body (diameter $d = 8$ mm). The burner has a constant cross section of $h = 34$ mm by $l = 94$ mm so that the flame remains two-dimensional, allowing faster DNS (Section 4). The Reynolds number based on the bluff-body diameter $Re_{cyl} \approx 500$ is low enough to ensure laminar flow. The reactants are premixed in a one-meter long injection tube and equally distributed to six injectors placed at the bottom of the injection chamber. The flow is laminarized by an array of small glass balls and one honeycomb panel and passes through the cooled plenum to ensure a constant fresh-gases temperature. Finally, it enters the combustion chamber where the bluff-body is located. The lateral sides of the combustion chamber are water cooled to impose the wall temperature. The plenum has three pressure plugs and one loudspeaker plug at each side. The combustion chamber has three optical accesses: one at the front to allow a direct view of the flame and one 3 mm slot on each for the laser sheet.

Two different bluff-bodies are used to stabilize the flame. The first, called CBB (Cooled Bluff-Body), is a steel water-cooled cylinder (Fig. 2, left). Drilled holes at the end of the feeding line allow the water to flow to the 6 mm outer line, where it is evacuated. The cooling system is designed to maintain temperatures around 285 K in the bluff-body walls. The second flame holder, called UBB (Uncooled Bluff-Body) is a full, solid, steel cylinder, with the same external diameter as the cooled one (Fig. 2, right). Its temperature is not controlled and depends on the flame shape. It can reach up to 700 K.

The operating condition is the same for all cases (Table 1). For this regime and this geometry of the chamber, there is no combustion instabilities (CI) so that the flame is steady. The burner power is 7 kW for an equivalence ratio $\Phi = 0.75$ and a bulk velocity $u_b = 1.07$ ms^{-1}. The flame holder temperature is measured with a K-type thermocouple: $T_{cyl}^{\mathrm{UBB}} = 670 \pm 40$ K. 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. The total flux taken from the flame is

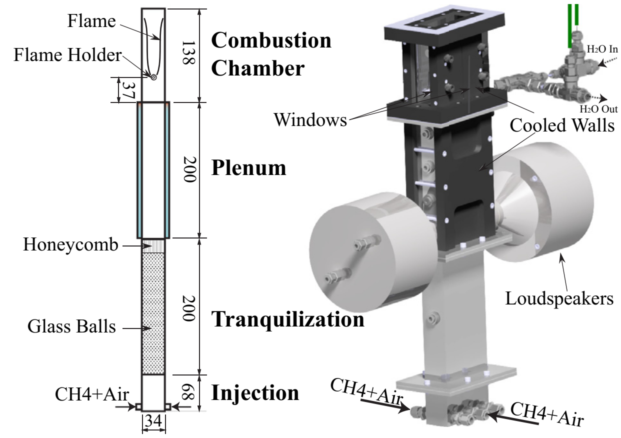

Fig. 1. Transverse cut (*left*) and isometric view (*right*) of the Intrig burner.

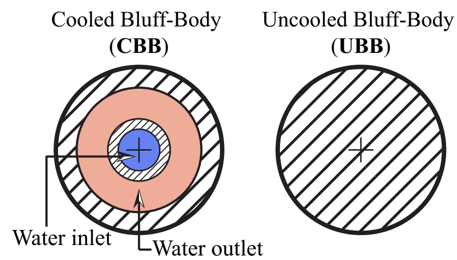

Fig. 2. Cooled bluff-body, CBB $T_w \approx 285$ K (*left*) and uncooled bluff-body, UBB $T_w \approx 700$ K (*right*).

Table 1
Operating conditions.

Name	Quantity	Value
Φ	Equivalence ratio	0.75
u_b	Bulk velocity	1.07 ms^{-1}
s_l	Laminar flame speed	0.24 ms^{-1}
T_u	Injection temperature	292 K
T_{adia}	Adiabatic flame temperature	1920 K

Table 2
Thermal properties of the flame-holder steel. The emissivity ϵ ranges from 0.2 for polished surfaces to 0.9 for oxidized surfaces.

Material	ρc_p [K^{-1}m^{-3}]	λ [W/m/K]	ϵ
35NCD16	3.5 10^6	32	0.9

$\Phi^{\mathrm{xp}}_{s\to w} = \dot{m} Cp \Delta T = 24$ W. The thermal properties of the steel used in both UBB and CBB cases are given in Table 2. In this configuration, Miguel-Brebion et al.. have shown that radiation form the flame holder is a key factor to predict the temperature of the UBB case. In the present experiments, bluff-bodies are oxidized so that an emissivity of $\epsilon = 0.9$ is retained.

3. Experimental strategy

The determination of the FTF (*cf.* Eq. 2) requires the knowledge of the heat release rate fluctuations. For a perfectly premixed mixture at a given equivalence ratio, the heat release rate $\dot{q}$ is proportional to the flame surface, $\mathcal{A}$, and to the light emission, I, from free radicals CH* [17–19], and it is possible to determine the transfer function from one of the following expressions:

$$\mathcal{F}(\omega) = \frac{\dot{q}'(t)/\bar{\dot{q}}}{u'(t)/u_b} = \frac{\mathcal{A}'(t)/\bar{\mathcal{A}}}{u'(t)/u_b} = \frac{I'(t)/\bar{I}}{u'(t)/u_b} \quad (2)$$