Combustion and Flame 158 (2011) 2384–2394

Contents lists available at ScienceDirect

Combustion and Flame

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

Sensitivity analysis of transfer functions of laminar flames

F. Duchaine [a,b,*], F. Boudy [c], D. Durox [c], T. Poinsot [a,b]

[a] Université de Toulouse, INPT, UPS, IMFT, Allée Camille Soula, F-31400 Toulouse, France
[b] CNRS, Institut de Mécanique des Fluides de Toulouse (IMFT), F-31400 Toulouse, France
[c] Laboratoire EM2C, CNRS and Ecole Centrale Paris, 92295 Chatenay-Malabry, France

ARTICLE INFO

Article history:
Received 8 November 2010
Received in revised form 12 May 2011
Accepted 14 May 2011
Available online 16 June 2011

Keywords:
Flame transfer function
Sensitivity analysis
Direct numerical simulation
Laminar flames

ABSTRACT

The sensitivity of laminar premixed methane/air flames responses to acoustic forcing is investigated using direct numerical simulation to determine which parameters control their flame transfer function. Five parameters are varied: (1) the flame speed s_L, (2) the expansion angle of the burnt gases α, (3) the inlet air temperature T_a, (4) the inlet duct temperature T_d and (5) the combustor wall temperature T_w. The delay of the flame transfer function is computed for the axisymetric flames of Boudy et al. [1] and the slot flames of Kornilov et al. [2]. Stationary flames are first computed and compared to experimental data in terms of flame shape and velocity fields. The flames are then forced at different frequencies. Direct numerical simulations reproduce the flame transfer functions correctly. The sensitivity analysis of the flame transfer function is done by changing parameters one by one and measuring their effect on the delay. This analysis reveals that the flame speed s_L and the inlet duct temperature T_d are the two parameters controlling the flame delay and that any precise computation of the flame transfer function delay must first have proper models for these two quantities.

1. Introduction

The prediction of acoustically coupled instabilities has become a major issue in combustion [3,4]. Numerous authors have proposed approaches to predict the resonant modes between acoustics and combustion [5–10]. In all theories, a crucial ingredient is the flame transfer function (FTF) first introduced by Crocco [11,12] and Tsien [13]. In its simplest form, the FTF $F(\omega)$ measures the response of the global unsteady reaction rate in the flame $(q'/\bar{q})$ to an inlet velocity perturbation $(u'/\bar{u})$ measured at a fixed reference point:

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

Although many of these studies were performed for complex geometry turbulent burners [14,10,15,16], they are usually limited and difficult to extrapolate to other regimes or other geometries because turbulent systems combine the difficulties of acoustic/flame coupling and turbulent flows. To isolate the mechanisms controlling FTF results, some groups have started investigating simpler laminar flames where the validity of acoustic/combustion theories can be tested in the absence of complex turbulent effects [17–20]. Studies dedicated to the FTF of laminar flames in multiple configurations [21,2,22,23,1] are now available, providing both experimental and numerical methods to obtain FTFs. In these cases, only acoustic perturbations imposed on perfectly premixed flames are investigated. Equivalence ratio fluctuations are out of the scope of the present study.

In all these configurations, the values obtained for the FTFs parameters are a gain n and a phase ϕ (or delay $\tau = \phi/\omega$), which depend on the forcing frequency ω and in certain cases on the forcing amplitude (see for example the recent developments on the flame describing function [21]). These parameters are critical to predict stability in acoustic solvers [11,24–26]. Small errors on the phase ϕ can lead to drastic changes in stability so that the question of uncertainties in measurement and simulation of FTF becomes an interesting issue. When computing the FTF of a flame, being able to evaluate the sensitivity of the results to modeling parameters is a critical question. For example, Kaess et al. [27] computed the FTF of a laminar flame and concluded that an accurate computation was impossible without the knowledge of the temperature of the stabilizing plate. More generally, many other input parameters of a FTF simulation may affect results and it is important to identify their relative importance. Experimentally, the same question arises: if FTF measurements depend critically on parameters which are not measured with accuracy, results will be useless. For example, the temperature of the plate on which flame are stabilized is rarely measured with precision but it could have a strong effect on the FTF.

* Corresponding author. Present address: CERFACS, France. Fax: +33 (0)5 61 19 30 00.

E-mail address: florent.duchaine@cerfacs.fr (F. Duchaine).

0010-2180/$ - see front matter © 2011 The Combustion Institute. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.combustflame.2011.05.013

A good solution to guess which parameters can modify FTFs is to start from theoretical models for the delay τ [17,19,14]. The global heat release rate $q(t)$ of a flame is written as [7,17]:

$$q(t) = \int_s \rho_u s_L \Delta q \, dA \quad (2)$$

where the integral is performed over the flame surface, ρ_u is the unburnt gas density, s_L the flame speed and Δq is the heat release per unit mass of mixture. From Eq. (2), fluctuations in the density ρ_u, the flame speed s_L, the heat of reaction Δq and in the flame surface A contribute to heat release oscillations $q'/\bar{q}$. Considering a perfectly premixed flow with a constant density and neglecting the effect of the stretch due to flame wrinkling on flame speed [28], the FTF can be expressed in terms of two dimensionless parameters ω^* and s_L^* [7,17,19,14]:

$$F(\omega) = \frac{q'/\bar{q}}{u'/\bar{u}} = F(\omega^*, s_L^*) = F\left(\frac{\omega H_f}{V_e}, \frac{s_L}{V_e}\right) \quad (3)$$

where V_e is the convective velocity at the burner inlet and H_f is the flame height. It is generally complex to express directly the fluctuation of the heat release as a function of the fluctuating velocity. Nevertheless, since it is observed that the phase ϕ increases regularly with ω^*, it is possible to describe ϕ as a time lag $\tau = \phi/\omega$. The simplest way to evaluate τ is to express it as the mean time necessary for a velocity perturbation to be convected from the exit plane to the effective position of concentrated heat release [17,14]:

$$\tau = \frac{H_f}{\beta V_e} \quad (4)$$

where β is a coefficient depending on the configuration. Values of β ranging from 1 to 3 are typically measured. Since the flame height depends on the flame speed s_L and on the convective velocity V_e, Eq. (4) suggests that τ changes only with s_L and V_e, hence that kinetic parameters (controlling s_L) but also temperatures of gas and walls (controlling V_e) must be important input data for τ.

In this paper, FTFs of laminar premixed flames were computed using direct numerical simulation (DNS) to evaluate the influence of five critical input parameters (Fig. 1): (1) the flame speed s_L, (2) the shape of the domain characterized by its expansion angle α, (3) the inlet air temperature T_a, (4) the inlet duct temperature T_d and (5) the combustor wall temperature T_w.

All these parameters have a direct effect on the FTF delay τ (or phase ϕ). The flame speed s_L obviously controls the flame length and therefore the delay of the flame to react to velocity changes. The shape of the domain determines the expansion of the burnt gases and the flow velocity, thereby also changing the FTF delay: here it is supposed to have a conical shape of angle α. Many experiments (and computations) are designed to perfectly match periodic arrays of flame [21,2] where α should be zero. Note that the confinement of the flames comes from the proximity of neighboring flames and not from a closed burner. In practice however, these flames are only partially confined: the gases produced by each individual flame can expand both in the axial and transverse directions. This can be accounted for in the DNS by using an expanding computation and values of α up to ten degrees are commonly observed experimentally. The inlet air temperature T_a affects both the gas velocity and the flame speed whereas the inlet duct temperature T_d changes the temperature and velocity profiles at the burner inlet. The combustor walls temperature T_w determines the lift-off of the flame and can also control the FTF delay. Obviously, other uncertainties and phenomena can affect the FTF as radiation heat losses, geometric imperfections, inlet velocity profiles (steady and forcing parts), flame to flame interactions, three-dimensional effects or position of the reference point for the velocity $u'/\bar{u}$ measurement. Nevertheless, the study is restricted to these five parameters which are difficult to determine precisely, have an important impact on FTF, and are easily manageable with a CFD solver.

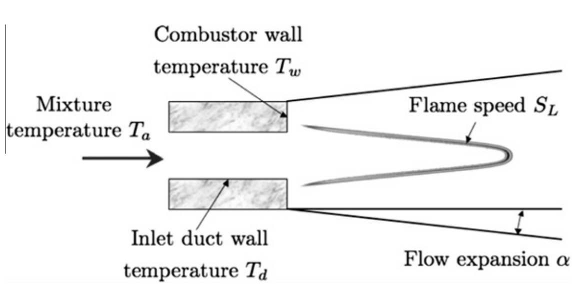

Fig. 1. Parameters controlling the FTF of a laminar premixed flame.

The objective of this work is to determine the sensitivity of the FTF to these five parameters. This identification will be done using simple differentiation methods (i.e. changing only one parameter and measuring its effect on the FTF delay). The exercise will be performed on two recent laminar flame experiments (Fig. 2) for which extensive sets of experimental results are available: the experiment of Boudy et al. [1] corresponds to 49 conical flames stabilized on a perforated plate while the configuration of Kornilov et al. [2] corresponds to an array of 12 slot flames.

The paper is organized as follows. First the Boudy et al. and Kornilov et al. experimental facilities are presented. The numerical methodology used to predict the FTFs is then described. Uncertainty sources in FTF phase determination are identified and the methodology for the sensitivity analysis is exposed. Finally, results on steady and forced flames are analyzed.

2. Experimental facilities

One method to study FTF is to take the flame out of its combustion chamber and pulsate it. This has two advantages: (1) optical diagnostics (usually radical emission) are easier and (2) the absence of the combustion chamber limits the occurrence of self-excited modes. It is generally assumed that the FTF does not change when the chamber is removed even though the confinement of the flame obviously changes. In this paper, two recent unconfined laminar experiments are used: the first one is referred in the following of the paper as the *Boudy case* [1] and the second one as the *Kornilov case* [2]. Both experiments use methane as fuel and operate at atmospheric conditions (p = 1 atm and T = 293 K) and the combustion zones are unconfined. For the cases used here, the equivalence ratio for the Boudy experiment is 1.03 while it is 0.8 for the Kornilov case. The range of frequencies for FTF measures is up to 1600 Hz for the Boudy case and 600 Hz for the Kornilov one. This section provides descriptions of these two experiments. Details concerning measurement techniques and experimental determination of FTF can be found in [1,2].

2.1. Boudy experiment setup

The experimental setup of Boudy et al. [1] is sketched in Fig. 2. The two main components of the burner are the feeding manifold and a perforated plate which delivers the premixed streams and anchors the flames. The perforated plate located at the top of the feeding manifold, anchors 49 small laminar conical flames. It has a thickness of 3 mm and a diameter of 30 mm. The plate is made of stainless steel, and comprises 49 holes of diameter $2r_p$ = 2 mm placed on a 3 mm square mesh. An inlet velocity of v_a = 1.09 ms^{-1} in the feeding manifold is used to stabilize the flames, leading to a bulk velocity in the holes of about V = 3.11 ms^{-1}. The temperature of the plate is evaluated experimentally as 450 ± 20 K for steady combustion.