Combustion and Flame 194 (2018) 296–308

Contents lists available at ScienceDirect

Combustion and Flame

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

Analysis of the dynamic response of premixed flames through chemiluminescence cross-correlation maps

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ARTICLE INFO

Article history:
Received 8 December 2017
Revised 3 May 2018
Accepted 4 May 2018

Keywords:
Cross-correlation maps
Thermoacoustic instability
Chemiluminescence imaging
Flame transfer function

ABSTRACT

This work proposes a novel methodology to extract useful information on flame dynamics from instantaneous chemiluminescence images in terms of the ‘effective local response’, by means of the so-called cross-correlation maps (CCM). Theoretical considerations suggest that CCM presents some advantages with respect to other options: it allows filtering out some spurious heat release rate fluctuations, not related to the acoustic excitation (either natural or forced) and generates a map of the ‘effective gain’, which can be interpreted as the actual contribution of each flame parcel to the global dynamic response. The method has been applied to an experimental dataset collected for premixed V flames of methane and CO_2/methane blends, covering a wide range of operating conditions. The results are fully consistent with the physical interpretation proposed for the cross-correlation maps, and confirm their potential for diagnosing the effective contribution of the different flame regions to the global dynamic response, as quantified, for example, in terms of the flame transfer function. With further hypotheses (e.g., n-τ formulation), CCM can provide further information about some features of the dynamic flame response, such as the characteristic flame length related to convective time lag and, hence, to the phase of the FTF. Cross-correlation maps are also compared with the spatial distribution of the local Rayleigh index, revealing a qualitatively similar pattern but also some essential differences, related to the different nature of both magnitudes. CC maps reflect the intrinsic dynamic response of the flame, whereas the Rayleigh index is related to the spontaneous instability and, hence, depends on the coupling between flame and the rest of the system.

1. Introduction

Due to the very low values of pollutant emissions achieved, lean premixed combustion has prevailed among other solutions in the gas turbines field, and nowadays represents the leading technology for these plants [1]. However, lean flames are more prone to combustion dynamics [2], a phenomenon due to in-phase coupling between pressure fluctuation (p') and heat release oscillation (Q') in the combustion chamber [3]. The instability grows due to the acoustic energy supplied by the flame, in a way determined by its dynamic response. Hence, even though these are system instabilities, an adequate description of flame response is one of the main objectives in this field.

The flame transfer function (FTF) is normally used to characterize the linear, global flame response, in terms of Q' amplitude, to inputs which can affect heat release rate fluctuation (equivalence ratio, Φ', and/or inlet velocity, u' [4,5]), as a function of frequency. The paramount importance of this parameter in the study of thermoacoustics justifies the large number of works devoted to determine FTF and to investigate its characteristics in different configurations. For the most common case of perfectly premixed, V-shaped flames, many studies coincide in that their FTF presents a low-pass filter behavior in gain and an almost linear trend in phase [6–12].

The global response of the flame, as quantified by its FTF, is the result of the dynamic response of different flame regions, each contributing with widely different magnitudes and phases. Hence, the bulk Q' could actually reflect the dynamics of some flame portions, whereas other regions may even present negative contributions and, so, would tend to damp the response to an acoustic excitation. Since all these features are lost in the spatial

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https://doi.org/10.1016/j.combustflame.2018.05.005

Nomenclature

Latin

f	frequency
G	gain of flame transfer function
I	intensity of bandfiltered radiation
i	normalized radiation intensity
K	constant, as defined in Eq. (10)
L	characteristic convective length
N_{im}	number of images
N_{px}	number of pixels per image
n	gain of the $n-\tau$ model
p	pressure
Q	heat release rate
q	normalized heat release rate
T	integration time
t	time
u	injection velocity
V	mean convective velocity

Acronyms

CCM	cross correlation map
FFT	fast Fourier transform
FTF	flame transfer function
PMT	photomultiplier tube
PT	pressure transducer
RI	Rayleigh index

Greek

σ	standard deviation
τ	time delay of the $n-\tau$ model
φ	phase of flame transfer function
Φ	equivalence ratio
ω	angular frequency

Overscripts

$\overline{()}$	mean quantity
$\widehat{()}$	fast Fourier transform

Superscripts

$()'$	fluctuation

Subscripts

ex,f	relative to external acoustic forcing
x	denotes a local value of the variable at a generic location x

integration of Q', some kind of space-resolved diagnostic should be employed to analyze the local contribution of different flame zones to the global response. The proportionality between the chemiluminescence emission at certain wavelengths (e.g., CH* or OH* bands) and the instantaneous heat release rate [9,13–15] makes the analysis of bandfiltered images of the flame a most valuable tool in this respect, although the process needed to extract the relationship between global and local response is not so obvious.

Some information about the flame dynamic behavior can be obtained from time averaged maps of the heat released by the flame (analyzed either from line-of-sight integrated or Abel-deconvoluted images [9,10,16–18]), by extracting selected geometric characteristics of the flame, such as length, angle, aspect ratio (see, for example, [17,19]), which have been used as inputs to model the global response of laminar V flames [20,21] and turbulent, swirl-stabilized ones [22]. Local time averaged values, however, are not representative of the local dynamic response of the flame parcels. Alternatively, the standard deviation of the chemiluminescence intensity recorded at different locations could be used as a measure of local fluctuations [23–26]. It should be noted, however, that fluctuation maps could be influenced by spurious contributions such as spatial flame movements (e.g., wobbling), broadband fluctuations (e.g., due to turbulence) or noise, which do not actually contribute to the global thermoacoustic response of the flame, as represented by the FTF.

Phase-locked chemiluminescence images have been widely applied for the analysis of flame instabilities (e.g., [10,18,26–30]). This is a most valuable tool to reconstruct and interpret the dynamic flame behavior along an oscillation cycle. However, how to extract from phase-resolved maps statistically meaningful information on the effective contribution of different regions to the global Q' is not at all obvious. As a possibility, phase-locked images can be further processed to obtain the spatial distribution of the Rayleigh index (see, e.g., [31–34]). This is a most relevant magnitude in thermoacoustics, since it expresses the acoustic energy generated by the coupling of pressure and heat release oscillations [3]. Therefore, the RI map describes the role of different flame areas, in which acoustic energy can be either generated or damped (respectively due to in-phase or out-of-phase oscillation with respect to p'). Nevertheless, it is important to note that RI maps describe the coupling between the flame and the acoustics of the whole system and, hence, do not inform on the intrinsic response of the flame.

Alternatively, if chemiluminescence images are acquired at high frame rates, the frequency content of local heat release rate oscillations can be determined by performing the fast Fourier transform (FFT) on every pixel. Among other advantages, this procedure filters out spurious fluctuations not related to the acoustic excitation or to a specific oscillation mode. This approach has been applied in a few works [16,35], demonstrating the very good potential of local FFT to describe in detail the dynamics of the flame. However, as it will be discussed later, the effective role of different zones in building global Q' cannot be ascertained directly from these maps and further processing of FFT would be required, in particular to evaluate the actual synchrony between local oscillations and global flame response.

Therefore, the magnitude of local oscillations in a given flame region may not be indicative of its actual contribution to the global response of the flame, as quantified in terms of bulk Q' or FTF. In this work, the approach proposed to address such analysis is the evaluation of the '*effective local contribution*' of different portions of the flame to its global response and, to this end, a novel methodology based on '*cross-correlation maps*' (CCM) is proposed. In its simplest form, this approach only requires a series of instantaneous, low frame rate, bandfiltered flame images, which are converted into 2D maps directly related to the magnitude of the share of global response associated with different flame portions. A very preliminary version was presented in [36], showing its potential for the qualitative assessment of distributed dynamic response. That development was parallel to the method used in [37], based on the so-called '*heat release rate index maps*', which was successfully applied to diagnose the role of different flame zones in the global dynamic response.

In this article, the physical interpretation of CC maps is discussed and expressed in terms of the parameters of local and global FTF. The results of CCM analysis are illustrated here for a wide range of swirl-stabilized, perfectly premixed flames of methane and CO_2/methane blends. First, the experimental facility, instrumentation and conditions of the tests carried out are described. Section 3 summarizes the main features of the flames studied, in terms of FTF and various chemiluminescence maps. The rationale behind the cross-correlation method is explained in Section 4. The analysis and discussion of the results obtained is performed in Section 5, while the main conclusions are summarized in Section 6.