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Analysis of chemiluminescence, density and heat release rate fluctuations in acoustically perturbed laminar premixed flames

J. Li [a,b], D. Durox [a,b], F. Richecoeur [a,b], T. Schuller [a,b,*]

[a] CNRS, UPR 288 Laboratoire d'Energétique Moléculaire et Macroscopique, Combustion (EM2C), Grande Voie des Vignes, Châtenay-Malabry 92295, France
[b] Centrale-Supélec, Grande Voie des Vignes, Châtenay-Malabry 92295, France

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ABSTRACT

Laser interferometric vibrometry (LIV) has recently been proposed as an alternative mean to obtain time-resolved density and heat release rate measurements at relatively low cost and experimental effort. This technique is sensitive to fluctuations of the refractive index of gases resulting from density and composition changes along the laser beam intersecting the reacting flow. It yields a line-of-sight integrated signal of the probed flow from which density and heat release rate disturbances may be inferred. The link between these signals with chemiluminescence is examined in the present study by first considering a theoretical analysis to determine the relationships between the LIV, density and heat release rate perturbation signals in a multi-species reactive mixture of gases. For air combustion systems interacting with sound waves, low frequency density perturbations in the flame zone, result mainly from heat release rate fluctuations below a certain frequency threshold. An experimental analysis is then conducted with confined conical laminar premixed flames submitted to harmonic flow modulations. Measurements are presented for methane–air mixtures at different equivalence ratios $0.8 \le \phi \le 1.2$ and thermal powers. It is shown that fluctuations of the chemiluminescence signal examined in different wavelength bands, including the OH^*, CH^* or the entire visible emission bands, always capture the same dynamics. This indicates that heat release rate fluctuations can be deduced without specific filters for the laminar premixed methane–air flames investigated. It is then shown that heat release rate measurements deduced from LIV and chemiluminescence data match well. A proportional relation is found that does not depend on the measurement position, modulation frequency and modulation level for fixed injection conditions. This linear relation slightly depends on the mean flow operating conditions partly due to the difficulty to interpret chemiluminescence emission for rich flames.

1. Introduction

Monitoring and controlling density and heat release rate disturbances is an important issue in practical combustion chambers because these perturbations generate direct and indirect combustion noise [1]. They may also trigger self-sustained thermoacoustic instabilities causing potential severe damages and early aging of components of the combustor. It is therefore important to control these disturbances and have reliable time-resolved diagnostics to measure these quantities.

There are different possibilities to determine heat release rate perturbations that were recently reviewed in [2,3]. The main ones are briefly described. Recording the natural emission from the flame is the simplest diagnostic yielding time-resolved estimates of heat release rate fluctuations [4,5]. Effects of the turbulence intensity, strain rate, flame front curvature, mixture composition, temperature and pressure need however to be included to obtain quantitative heat release rate data [6–14]. These studies stress out the need of alternative techniques to measure heat release rate disturbances. Measurements are then often limited to flame images for qualitative analysis except in a few studies where the signal is calibrated using specific post-processing procedures to map the heat release rate on two-dimensional images [15,16]. Another limitation is that the chemiluminescence emission yields a signal integrated in the line-of-sight and it is difficult to obtain spatially resolved data without additional hypothesis on the system symmetry.

One possibility to improve spatial resolution is to use Laser Induced Fluorescence (LIF) by stimulating certain electronic transitions of specific species present within a laser sheet intersecting the flow. Time resolved data are more difficult to obtain due to the limited repetition rates and limited energies delivered per pulse from the lasers,

* Corresponding author at: CNRS, UPR 288 Laboratoire d'Energétique Moléculaire et Macroscopique, Combustion (EM2C), Grande Voie des Vignes, 92295 Châtenay-Malabry, France.
E-mail address: thierry.schuller@ecp.fr (T. Schuller).

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although OH and CH concentration measurements at a few kHz were recently reported in flames to characterize transient phenomena in turbulent reacting flows (see for example [17–19]). Quantitative spatially resolved heat release rate measurements deduced from LIF signals are still challenging [20]. This has motivated a series of studies based on LIF measurements of different species concentrations to estimate the local distribution of heat release rate in flow configurations of increasing complexity [10,21–24]. Simultaneous measurements in unsteady flows remain however difficult and require high power well-tuned laser beams at different wavelengths and specific optics.

A novel approach yielding line-of-sight integrated data was recently examined by exploiting the link between heat release rate fluctuations and density disturbances in acoustically perturbed laminar premixed flames [3] and turbulent swirling flames [25,26]. The following relation is exploited:

$$\frac{\partial \rho'}{\partial t} \simeq -\frac{\gamma-1}{c^2}\dot{q}' \tag{1}$$

where ρ' and $\dot{q}'$ denote density and heat release rate (per unit volume) perturbations, respectively, c corresponds to the speed of sound and γ indicates the specific heat capacity ratio of gases. Similar expressions were already used in simulations of combustion noise radiated by turbulent diffusion flames [27–29]. It constitutes an interesting alternative to measure heat release rate fluctuations because different techniques may be envisaged to detect density fluctuations. Eq. (1) provides then a simple way to reconstruct heat release rate disturbances provided that the speed of sound and the heat capacity ratio are known with sufficient accuracy if quantitative data are needed. One of the main advantage of this reconstruction is that Eq. (1) does not depend on the combustion mode. It is well known that the current diagnostics based on the interpretation of the LIF or chemiluminescence signals to infer heat release rate are often limited to perfectly premixed systems. Heat release rate disturbances in non-perfectly premixed systems when mixture inhomogeneities have to be taken into account are more difficult to measure.

Several approximations were made in [3] to derive Eq. (1) that was obtained in a single species flow context. Measurements in [3] were also carried out for a rich unconfined M-flame, at a fixed flowrate and at a fixed equivalence ratio $\phi = 1.19$. The flame was submitted to harmonic flow disturbances at two forcing frequencies $f = 51$ Hz and $f = 102$ Hz and at a single forcing level. The motion of the unsteady plume of burnt gases surrounding the unconfined perturbed flame precluded a clear identification of the density perturbations detected, because this motion has to be taken into account in the signal processing. This problem has recently been modeled by Li et al. [30] for perturbed unconfined conical flames, but in general the link between the flame motion and the motion of the interface between the burnt gases and ambient air is not known. Only a qualitative agreement between low frequency heat release rate and density fluctuation signals was obtained, but it was not possible to reproduce the correct heat release rate oscillation level. Differences between the rate of change of density fluctuations and heat release rate perturbations were also observed at high frequencies.

In a recent analysis of the response of turbulent premixed swirling flames to acoustic forcing [25,26], differences between heat release rate disturbances deduced from chemiluminescence emission measurements and exploitation of Eq. (1) were also found due to a series of contributions to density fluctuations which were not linked to heat release rate perturbations. To avoid the complexity inherent to turbulent flows, acoustically perturbed laminar premixed flames are considered in this study. The difficulties identified in [3] are reconsidered here first theoretically to determine the validity limits of Eq. (1) in Section 2 for a reactive mixture of gases, and then secondly experimentally with an improved experimental setup allowing quantitative measurements of density fluctuations and detailed analysis of the chemiluminescence signal. The laser interferometric technique used to detect density fluctuations is presented in Section 3. The experimental setup is described in Section 4 together with the different diagnostics. An analysis of the flame chemiluminescence signal with different interference filters is conducted in Section 5. It is shown that in the configurations investigated the signal collected by a camera with a glass lens is a good tracer of heat release rate fluctuations without interference filter when the equivalence ratio is lower than $\phi \leq 1.2$. Measurements of density fluctuations integrated along the line-of-sight determined with the laser interferometric technique are presented in section 6. Heat release rate fluctuations determined with the different techniques are then compared for the different flow operating and perturbation conditions explored. Conclusions regarding the validation of the proposed technique for measuring time-resolved heat release rate disturbances are finally presented.

2. Theoretical analysis

2.1. Density disturbances in a reacting flow

Considering a single species flow of a perfect gas, the link between density ρ and pressure p is given by [31]:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{1}{c^2}\frac{\mathrm{d}p}{\mathrm{d}t} - \frac{\rho}{c_p}\frac{\mathrm{d}s}{\mathrm{d}t} \tag{2}$$

where c denotes the speed of sound, c_p is the heat capacity at constant pressure and s stands for entropy that contributes to density changes which are not linked with the sound wave.

For a reactive mixture of gases obeying to the perfect gas law $p = \rho r T$, a transport equation linking density ρ, pressure p and the volumetric rate of heat released by combustion $\dot{q}$ may be derived as shown in Appendix:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{1}{c^2}\frac{\mathrm{d}p}{\mathrm{d}t} - \frac{\rho}{r}\frac{\mathrm{d}r}{\mathrm{d}t} - \frac{\gamma-1}{c^2}[\nabla\cdot(\lambda\nabla T) + \tau : \nabla\mathbf{v} + \dot{q}] \tag{3}$$

where γ denotes the ratio of the specific heats of the gaseous mixture and $r = R/W$ is the coefficient appearing in the mixture perfect gas law, R being the universal gas constant and W is the mixture molar mass. The terms in the brackets correspond to the thermal conductivity λ, the viscous stress tensor $\boldsymbol{\tau}$ and the flow velocity $\mathbf{v}$. This transport equation may be found in slightly different forms in [28,31,32] with other approximations. Body forces, such as gravity forces, can be neglected in most practical combustion chambers because the flames are submitted to large pressure gradients. Radiative heat fluxes are also often neglected [33]. Changes of density due to interactions with body forces, radiative heat transfer, Soret and Dufour effects were thus neglected in Eq. (3).

Combustion is generally a non iso-molar transformation, but except in oxy-combustion systems [34], changes of the mixture molar mass $W = \sum_k Y_k W_k$, where Y_k denotes the mass fraction of species k and W_k its molar mass, remain weak during the transformation in air combustion systems because of the strong dilution of the reactants and products by nitrogen. One may then neglect changes of r in Eq. (3) when the oxidant is air. It is difficult to further simplify Eq. (3) for instantaneous flow quantities transported by the mean flow.

Considering now perturbations (a') of the flow variables (a) around a steady state ($\overline{a}$) in a combustor operating in a continuous mode, one finds to the leading order:

$$\frac{\partial \rho'}{\partial t} = \frac{1}{c^2}\frac{\partial p'}{\partial t} - \frac{\gamma-1}{c^2}[\nabla\cdot(\lambda\nabla T') + \dot{q}'] \tag{4}$$

if the flow Mach number remains small. This expression shows that in multi-species reacting flows, density disturbances ρ' result mainly from pressure perturbations p', density changes associated to temperature fluctuations T' and perturbations of the rate of heat released by combustion $\dot{q}'$. The first term in the brackets in Eq. (4) corresponds