Experimental Thermal and Fluid Science 53 (2014) 93–103

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Effect of local flame properties on chemiluminescence-based stoichiometry measurement

Tatiana García-Armingol [a], Yannis Hardalupas [b], A.M.K.P. Taylor [b], Javier Ballester [c,*]

[a] Laboratory of Research on Fluid Dynamics and Combustion Technologies (LIFTEC), CSIC – University of Zaragoza, Spain
[b] Mechanical Engineering Department, Imperial College, London, United Kingdom
[c] Fluid Mechanics Group/LIFTEC, CSIC – University of Zaragoza, Spain

ARTICLE INFO

Article history:
Received 11 July 2013
Received in revised form 4 October 2013
Accepted 10 November 2013
Available online 18 November 2013

Keywords:
Chemiluminescence
Premixed flame
Stoichiometry
Local equivalence ratio sensing

ABSTRACT

Spontaneous chemiluminescence emission has been suggested as one of the most promising options for flame stoichiometry monitoring, with particularly interesting application for lean premixed combustors. Most published works are focused on global and time-averaged flame stoichiometry; however, the results reported in previous studies it can be concluded that chemiluminescence measurement could be also valid for local or instantaneous equivalence ratio monitoring. This could enable the development of novel diagnostic techniques with interesting applications in many combustion situations, like the study of thermo-acoustic instabilities. This was the main motivation for this study, focused on analyzing the feasibility of chemiluminescence for space- and/or time-resolved stoichiometry measurements. The results revealed unexpected results, not reported in previous studies, with a non-negligible variation of the relation between chemiluminescence and equivalence ratio that seems to be related to changes in local flame properties such as temperature or composition. This finding has important practical consequences since the chemiluminescence vs. equivalence ratio curves should be carefully verified for each application.

1. Introduction

One of the challenges of the combustion industry is the development of appropriate methods for supervision and optimization of the combustion processes with the aim of improving their efficiency, reliability and flexibility for using different kinds of fuels. The importance of sensors for flame monitoring as a key pre-requisite in the development of advanced combustion control strategies has been widely discussed in previous works [1,2]. Methods based on optical sensors have been shown as a good alternative for the supervision of industrial flames because they have many advantages like being instantaneous, cheap, non-intrusive and suitable for harsh environments.

The measurement of the spontaneous emission of electromagnetic radiation due to excited species generated in chemical reactions (*chemiluminescence*) has been commonly used to evaluate flame properties, especially for estimating fuel–air ratio. Spectral bands commonly selected for flame monitoring correspond to one or several of the main light emitters in hydrocarbon flames: OH^*, CH^*, C_2^* (with peaks at 309, 431 and 516 nm, respectively) and CO_2^* (continuum emission in the band 300–600 nm).

Many authors have studied numerically [3–7] and experimentally [3,4,7–16] the existence of relationships between the light emission and the properties of the flame, such as fuel–air ratio or heat release. In general, these studies are based on the global radiation emitted by the whole flame and all of them conclude that chemiluminescence is strongly correlated with the equivalence ratio (ϕ), pointing out to potential application for the development of flame stoichiometry sensors. Moreover, most of them suggest using ratios between signals corresponding to light collected at different wavelengths, instead of the single signals, in order to avoid some of the interferences caused by geometrical or optical parameters of the measurement setup. Particularly, the ratio OH^*/CH^* has been demonstrated to be independent of strain rate or turbulence intensities [5,9,11,15,17,18] and for that reason it is commonly proposed as a reliable parameter to monitor a wide range of practical flames. It should be noted that most of the previous studies, such as [5,10,14,16] were performed on laminar premixed flames (Bunsen or counterflow burners). However, since it was found that the OH^*/CH^* ratio does not depend on strain rate and assuming that practical turbulent flames are usually in the flamelet regime, the conclusions can be expected to be also applicable to real combustors. In fact, results obtained in turbulent flames [7–10,19] are in good agreement with the findings in small-scale laminar flames regarding the existence of a clear relationship between chemiluminescence and air–fuel ratio.

---

* Corresponding author. Address: Fluid Mechanics Group, School of Engineering and Architecture, María de Luna, 3, 50018-Zaragoza, Spain. Tel.: +34 976 762 153; fax: +34 976 761 882.

E-mail address: ballester@unizar.es (J. Ballester).

0894-1777/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.expthermflusci.2013.11.009

The fast response of radiation sensors is an important advantage that can be exploited to develop stoichiometry sensors with high temporal resolution; also, local equivalence ratio could be estimated by means of an adequate optical setup. These ideas might be applied to perform a detailed characterization of equivalence ratio in studies on thermo-acoustic instabilities, where pressure oscillations can induce variations in fuel or air flow rates and, therefore, temporal fluctuations in the equivalence ratio of the air–fuel mixture. This general idea was tested by the authors in swirl-stabilized, turbulent, premixed methane flames. The approach consisted in applying a calibration curve previously determined empirically to estimate instantaneous and local values of ϕ from chemiluminescence measurements, so as to evaluate fluctuations at the dump plane or the resulting axial ϕ wave due to convective transport.

In order to evaluate the accuracy of the method and whether the oscillations observed in OH^*/CH^* ratio could be fully interpreted in terms of ϕ fluctuations, it was applied in cases where the fuel–air mixture was injected through choked orifices. Using a choked injection has the advantage of making equivalence ratio insensitive to pressure fluctuations and therefore, equivalence ratio should be constant in time and space. Consequently, in these conditions, chemiluminescence ratios (e.g. OH^*/CH^*) calculated from time and/or space-resolved signals could be also expected to be constant. However, OH^*/CH^* displayed non-negligible variations along the time or between different flame zones, which suggested that, in a given flame, chemiluminescence signals depend not only on the fuel–air ratio but also on other conditions of the reacting mixture.

These observations can be relevant in general terms regarding the properties of chemiluminescence in flames and can also determine the possibilities and limitations of techniques based on the use of radiation signals for flame diagnostics. Although Nori and Seitzman [4] already detected a potential effect of temperature on chemiluminescence curves by the study of preheating, no previous reference to a systematic analysis of the effect of local conditions on chemiluminescence ratios was found in the literature, and the initial study was extended to investigate the potential causes. Different hypotheses were considered that could explain this apparently anomalous behavior of chemiluminescence signals in situations with constant equivalence ratio; namely, differences in temperature and in average composition of the reacting mixture included in the probed volume between different locations or instants of time.

The main goal of the present study is, consequently, analyzing the relationship between chemiluminescence intensity ratios and equivalence ratio in a swirl-stabilized, turbulent flame and its spatial variation along the combustion chamber, as well as discussing about the potential causes of the observed behavior. Chemiluminescence signals were collected at different radial and axial positions in swirl-stabilized, perfectly premixed flames. In addition, the influence of temperature and gas composition on light emission by excited radicals was evaluated by means of numerical calculations with detailed chemiluminescence mechanisms. The results obtained are discussed in order to analyze the feasibility of chemiluminescence sensor for predicting local equivalence ratio in practical flames.

2. Experimental facility and instrumentation

The experimental results presented throughout the following sections have been collected from swirl-stabilized, turbulent, premixed methane-air flames in the combustion rig shown in Fig. 1. A quartz tube (with 120 mm of internal diameter and 230 mm of length) configures the combustion chamber and allows unrestricted optical access to the flame. Two options for fuel injection existed:

(A) Methane can be injected into the air stream through orifices labeled as 'Fuel A' in Fig. 1, so that mixing is achieved upstream of choked orifices (Mach number = 1). Since pressure perturbations due to combustion instabilities do not

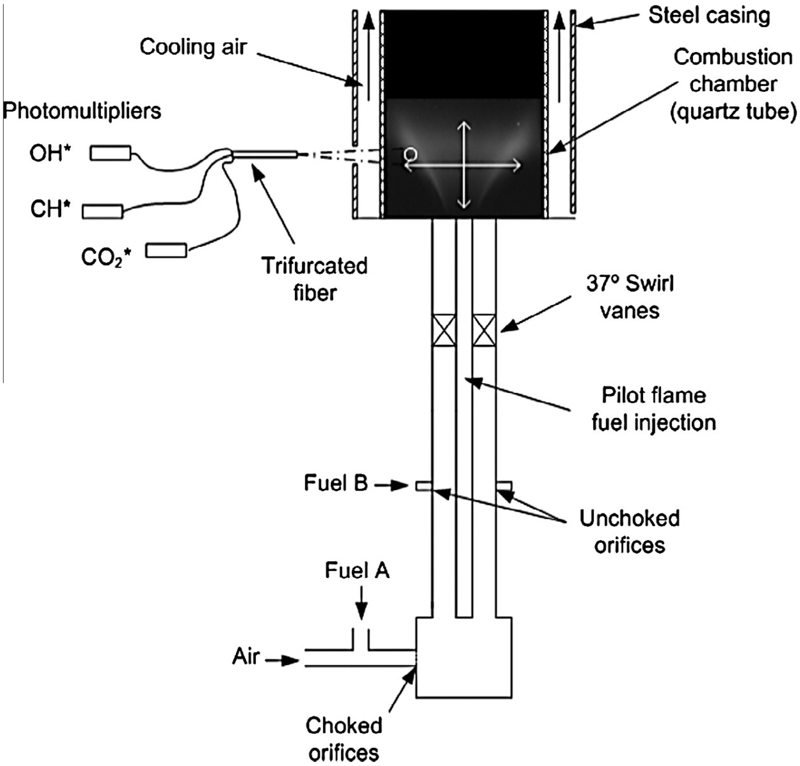

Fig. 1. Combustion rig and instrumentation.