

CHEMILUMINESCENCE MEASUREMENTS IN A MESO-SCALE COMBUSTOR FUELED WITH CH₄/AIR AT 0.3 MPa

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Abstract

In this work chemiluminescence emission from the main radical species are measured in a meso-scale combustor. Global and two-dimensional analysis is performed in order to gain information on the combustion processes occurring in the non-premixed swirled combustor fuelled with CH₄/air and working at 0.3 MPa. The investigation is carried out by changing the equivalence ratio in the range of the stability limits, keeping constant the total mass flow rate. The behavior of OH^{*}, CH^{*} and CH^{*}/CH^{*} chemiluminescence as a function of the equivalence ratio are discussed both for global and spatially-resolved measurements. The two-dimensional results evidence the significant role of mixing and turbulence with respect to the chemical kinetic mechanisms.

Introduction

Flame chemiluminescence can be considered a potential tool as a sensor application in combustion. Experiments in premixed flames suggested that the intensity of chemiluminescence from radicals could be a good marker of heat release [1-2]. Such emissions occur when radicals such as OH^{*}, CH^{*} and C₂^{*} chemically formed within the flame front return from electronically excited energy state to a lower energy state, resulting in a radiation emission at a specific wavelength. Since these species are mainly produced in the reaction zone, chemiluminescence can be indicative of the reacting conditions in the flame. For example, chemiluminescence imaging of excited radicals is often used for reaction zone marking. Similarly, the ratio of emissions from excited species, such as CH^{*}/OH^{*} or C₂^{*}/OH^{*}, show promise for equivalence ratio sensing in both gaseous and liquid fuel systems. Chemiluminescence has also been employed to characterize temporal fluctuations in global heat release rate and its spatial distribution for applications related to combustion instabilities. The monitoring and controlling of a flame's heat release rate, the local equivalence ratio, and the degree of premixeness of the reacting mixture are of great interest for industry, especially because of the dependence of pollutant formation in such systems.

In this work it is investigated the potential tool of chemiluminescence measurements of the main radicals as applied in a meso-scale combustor. Global

and two-dimensional analysis is performed in order to gain information on the combustion processes occurring in the non-premixed combustor fuelled with methane/air and working at 0.3 MPa.

Experimental set-up

In Fig. 1 the AISI 321 stainless steel non-premixed meso-scale swirl combustor is shown [3]. The cylindrical combustion chamber, perpendicular to the square face, has a diameter of 6 mm and a depth of 9 mm, corresponding to 254 mm³ total volume. For the optical access, two circular quartz windows with graphite sealing are used. Stainless steel pipes (1 mm ID) are used to feed fuel and oxidizer (air). The fuel injection is radial (at the top of the combustor in Fig. 1), while the air injection is tangential (on the right of the combustor) with respect to the combustion chamber, which provides a swirled flow. As it can be observed in Fig. 1b), while the injection holes are placed on the same plane at one extremity of the combustion chamber, the tangential exhaust hole (2 mm ID) is positioned on the opposite side. In order to operate at 0.3 MPa, the combustor is placed in a stainless steel pressurized chamber with quartz optical accesses. To achieve such condition the regulation of a Nitrogen flow and a needle valve aperture placed at the exhaust of the chamber is required. Fuel, oxidizer and N₂ flow rates are metered and regulated by thermal mass flow meters and controllers (Bronckhorst, 1% accuracy).

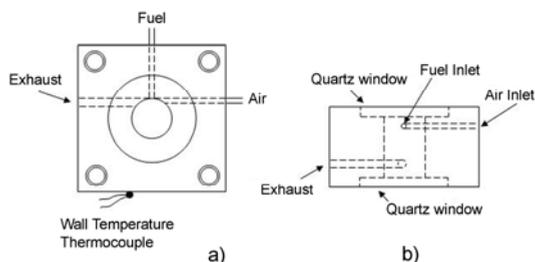


Figure 1. AISI meso-scale combustor: front view (a) and cut-out section (b)

For the alignment of the optical equipment the meso-scale combustor is positioned on a XYZ adjustable table. Chemiluminescence measurements are carried out both with a spectrograph coupled with a intensified diode array (Tracor Northern) and with an intensified CCD camera (DiCAM Pro, 12 bit) equipped with a UV-Nikon objective. In this last case, images of the radicals chemiluminescence are separately collected by using interference filters positioned just in front of the objective. The interference filters are characterized by the following central wavelength and related spectral bandwidth: 309 nm \pm 7.5 nm wavelength for OH^{*}, 430 nm \pm 5 nm for CH^{*} and 516.5 nm \pm 5 nm for C₂^{*}. Due to the spectral response of the camera, different exposure times are used to have comparable intensities for all the species. With these conditions, images with a 37 pixel/mm resolution are collected. A global behavior of the chemiluminescence is obtained with the spectrograph. In this case, the overall signal coming from the whole meso-scale combustor is properly

collected with a lens on the entrance slit of the spectroscopic system, resulting in a spectrum ranging from 280 nm to 800 nm. The chemiluminescence intensity of a given radical is evaluated measuring the area around the peak of the corresponding interference filter (which is used for 2D measurements) and with the same spectral width of the filter itself. In order to compare measurements performed with the two optical equipments, the corresponding spectral responses are evaluated by using a calibrated Xenon lamp (Oriel, 150 W). The investigation is carried out at 0.3 MPa pressure working condition with methane as fuel by changing the equivalence ratio and keeping constant the total mass flow rate at $5.66 \cdot 10^{-5}$ Kg/s.

Results and discussion

Global and 2D measurements of the chemiluminescence intensity are here presented varying the equivalence ratio in the stability region. As for the global behavior, measurements performed with the spectrograph (corrected for the instrumental factor) are compared with the ones carried out with the ICCD camera. In this last case, the global intensity is obtained from each 2D image integrating the signal value of each pixel inside the combustor, normalized to the exposure time and corrected for the instrumental function of the camera. In Fig. 2 a) and b) OH^* and CH^* chemiluminescence intensity are reported respectively versus the equivalence ratio Φ .

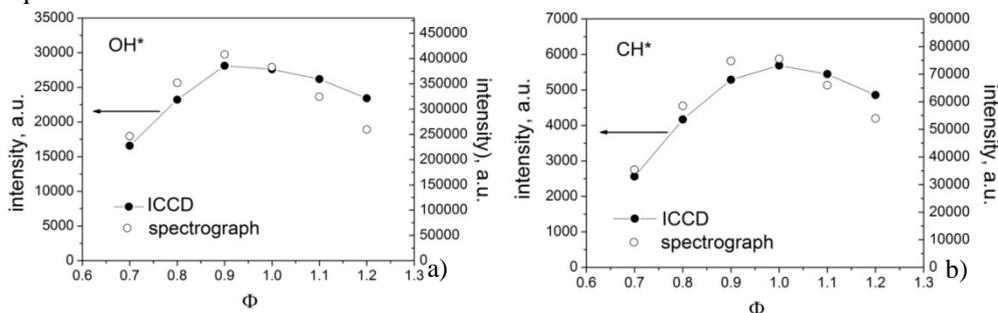


Figure 2. OH^* (a) and CH^* (b) chemiluminescence versus the equivalence ratio.

In all cases a good agreement between the two sets of measurements can be registered. Increasing the equivalence ratio an increase of the chemiluminescence intensity is obtained up to the stoichiometric condition, above which the signal decreases with Φ . Same results are also obtained for C_2^* chemiluminescence, which is here not shown for brevity. In Fig. 3 the ratio of CH^*/OH^* chemiluminescence intensities is reported versus the equivalence ratio. The resulting monotonic trend confirms that the chemiluminescence ratio can be used for sensing equivalence ratio even at the condition under study, that is non-premixed and weakly turbulent condition. Such results is in agreement with the work by Koijma et al. [4] for a premixed, laminar methane flame. As for the spatial distribution of the chemiluminescence, 2D measurements are carried out inside the combustor varying the equivalence ratio.

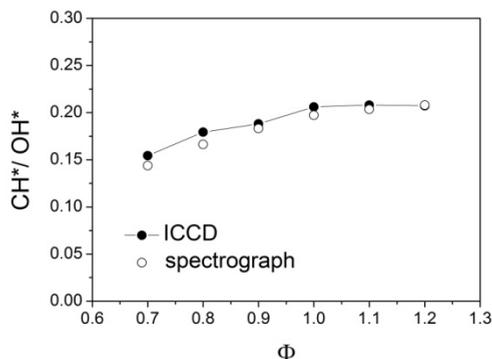


Figure 3. CH^*/OH^* ratio versus the equivalence ratio.

For example, in Fig. 4 CH^* , OH^* and CH^*/OH^* images in grey scale are reported at $\Phi = 0.8, 1$ and 1.2 . To compare the behavior of both structure and intensity of the chemiluminescence inside the combustor, the same intensity scale is used for each set of measurements. The same behavior detected in the case of global measurements is here obtained: the maximum value of the chemiluminescence of CH^* and OH^* (as well as their corresponding ratio) is observed at $\Phi = 1$ and decreases both at higher and lower equivalence ratio. As a further analysis, concerning the structure of the 2D distribution, an enlargement of the chemiluminescence region is observed increasing the equivalence ratio. In particular considering that fuel is vertically injected at the top of the image (and air tangentially on the right side), it can be inferred that chemiluminescence signal starts to be significant, increasing the equivalence ratio, closer to the fuel injection hole. To deep investigate such effect, CH^* chemiluminescence is considered being strictly related to the flame front. The 2D CH^* chemiluminescence distribution is processed measuring the distance of the flame front from the injection port. Then, taking into account the tangential gas velocity, the corresponding time interval here called “ignition delay time” is computed. In Fig. 5 a) the threshold profiles of the CH^* chemiluminescence signal are shown for all equivalence ratios; and in Fig. 5b) the corresponding delay time is reported. As it can be observed, increasing the global equivalence ratio a decrease in the delay time is obtained. This behavior could be consistent with the significant role that mixing and turbulence play with respect to the chemical kinetic mechanisms, especially in the particular geometric configuration and for the non-premixed condition under analysis. Such conclusion could be justified if one try to describe our combustor configuration as a jet in crossflow [5]. In fact, in this case the square root of the momentum ratio, J , (which is strictly related to the fuel-to-air mixing) is directly proportional to the global equivalence ratio. Therefore the increase of the equivalence ratio is responsible of an increase in mixing. In Fig. 6 $J^{0.5}$ is reported versus the inverse of the delay time. The good correlation obtained proves that the decrease in the delay time with Φ is essentially due to the mixing.

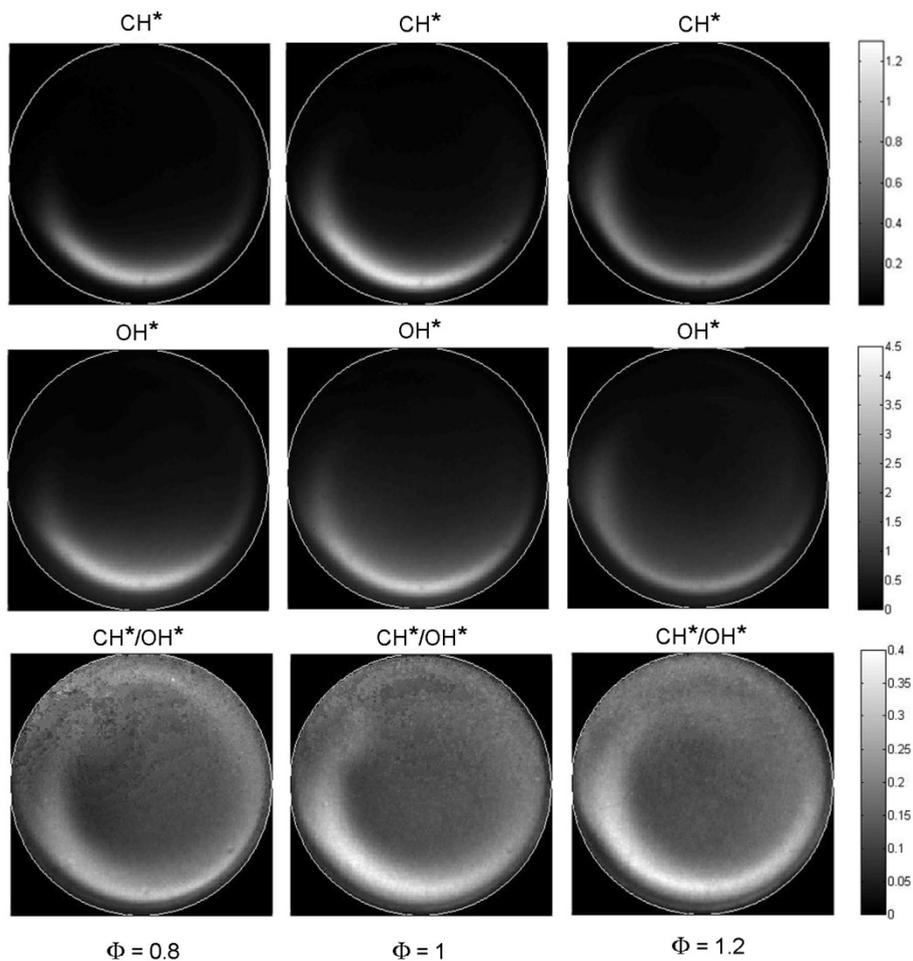


Figure 4. 2D radical chemiluminescence imaging at $\Phi = 0.8, 1$ and 1.2 .

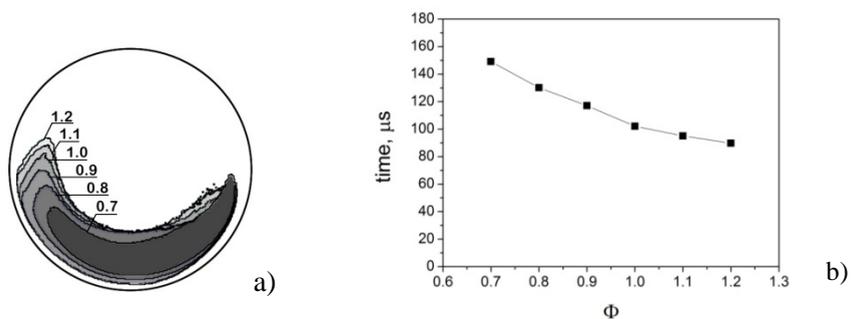


Figure 5. Threshold profiles of CH^* chemiluminescence (a); delay time vs Φ (b).

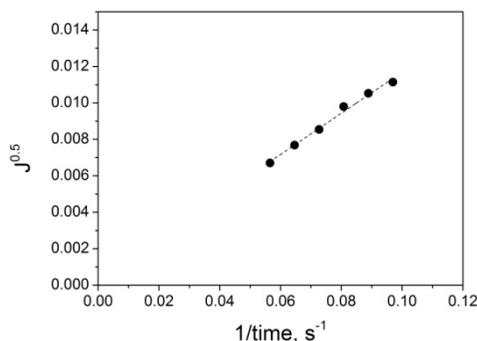


Figure 6. The square root of the moment ratio versus the inverse of time.

Conclusions

In this work chemiluminescence measurements of the main radical species are carried out in a non-premixed swirled combustor fuelled with CH₄/air and working at 0.3 MPa. The behavior of chemiluminescence versus Φ are discussed both for global and spatially-resolved measurements. Concerning CH^{*}/OH^{*} ratio, a monotonic trend obtained versus Φ confirms that such parameter can be used for sensing equivalence ratio even for non-premixed conditions, in agreement with the literature. The two-dimensional results show the significant role of mixing and turbulence with respect to the chemical kinetic mechanisms.

Acknowledgements

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