

Study of high pressure counter-flow methane flames

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Abstract

A new high pressure combustion facility has been recently set up at the ICARE laboratory. It consists of twin counter-flow burners located in a high pressure chamber equipped with four optical accesses for laser techniques diagnostics (Laser Induced Fluorescence LIF, Emission and Absorption Spectroscopy). This facility allows the stabilisation of laminar, flat (1D) twin-premixed flames up to 1 MPa and the investigation of their structures for a large range of equivalence ratios, temperatures and pressures. The aim is to obtain a new database on high pressure combustion in order to develop and validate detailed chemical mechanism at pressures above 0.1 MPa. This paper presents the description of the facility, the flame stability study on CH₄/air flames and preliminary OH radical relative profiles obtained by LIF.

Introduction

The optimisation of practical combustion devices requires a detailed knowledge of the combustion kinetic. Moreover, most practical combustion systems operate at pressures well above 0.1 MPa (gas turbines, aeronautic turbines, engines). The development and validation of detailed combustion kinetic mechanisms must therefore take into account the influence of pressure. Most of the combustion kinetic mechanisms have been validated in well-defined laboratory conditions (shock tubes, flow and homogeneous reactors, premixed flames). Flame structures have usually been performed at sub-atmospheric [1, 2] or atmospheric pressures [3] as it allows a good spatial resolution and advantages for optical measurements application (possible quenching corrections from the measurable fluorescence lifetimes at low pressure for example). Detailed kinetic mechanisms validated in atmospheric or low pressure conditions can not generally be directly extrapolated towards high pressure, due to the lack of experimental data or uncertainties of the rate constants of elementary reactions. Then, it is necessary to complete the experimental database and to extend the validation domain of combustion mechanisms at high pressure.

A new high pressure combustion facility has been recently set up at the ICARE laboratory. It consists of twin counter-flow burners located in a high pressure chamber equipped with four optical accesses for laser techniques diagnostics (Laser Induced Fluorescence, Emission and Absorption Spectroscopy). This facility allows the stabilisation of laminar, flat (1D) twin-premixed flames up to 1 MPa and the investigation of their structures for a large range of equivalence ratios, temperatures and pressures. The main difference with the water-cooled flat flame is that the flames are stabilised by aerodynamic strain rate rather than by heat losses to the burner and nearly adiabatic premixed flames can be obtained. The second advantage of this configuration is that it allows the resolution of species concentrations profiles even for moderately high pressures (0.1 - 1 MPa), which is impossible with a standard flat flame burner (in this case, the flamefront

sits extremely close to the burner at high pressure). This kind of burner has been extensively used for the determination of global parameters of high pressure combustion, like laminar flame velocities of several fuels in Law and Davis groups [4-6] or extinction limits [7]. The EM2C group has performed chemiluminescence measurements [8,9] and Planar Laser Induced Fluorescence measurements of heat release [10] in this kind of burner for active combustion control. They also developed numerical tools to simulate counter-flow flames [11]. Laurendeau's group has extensively used this kind of burner for NO_x kinetics studies at high pressures [12-14].

In this paper, the new high pressure facility is described, then we present the flame stability study performed on CH₄/air flames. Methane is chosen here as it is the main constituent of natural gas, generally used in gas turbines and because its combustion chemistry is relatively well known. Preliminary OH Laser Induced Fluorescence measurements were performed in the CH₄/air flames at atmospheric and high pressure. OH has been chosen as its concentration profile in the flame can mimic the temperature profile and then it allows the localization of the flamefronts.

Description of the high pressure facility

An overall view of the experimental set-up is given in Fig. 1, it is composed of the high pressure vessel, the counter-flow burners and the gas control system. The high pressure chamber (Fig. 2) has been tested to support 6 MPa. It is composed of a cylindrical main body, composed of a double wall, sealed by two flanges at each end. The vessel is composed of stainless-steel (316L) and can support a maximum temperature of 200°C at its inner wall. To respect those conditions, the body and the upper flange of the vessel are fitted with an inner cooling system. Furthermore, the cooling of the exhaust gas is completed with a cooling brass coil. The high pressure vessel is equipped with four quartz windows of 4cm in diameter and 3cm in thickness. Water condensation on the windows is avoided owing to

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a continuous nitrogen circulation that licks the inner surface. The window located opposed to the laser beam entrance is tilted at 5° to avoid reflections on the sampling volume. The bottom flange includes ports used for gas supply, the burners cooling system and the electrical wiring (translation system, ignition system and thermocouples). Condensed water inside the vessel is led out to a water trap through a drainpipe located at the surface of the bottom flange. The pressure within the vessel is controlled with a pressure transducer coupled with a control valve. Many safety systems are installed in this facility to prevent any flame flashback or extinction (Hamamatsu UVtron flame sensor device) and uncontrolled temperature and pressure increases (thermocouples, pressure relief valve and rupture disk) inside the chamber. Those systems are coupled with electro-pneumatic isolation valves on the fuel lines.

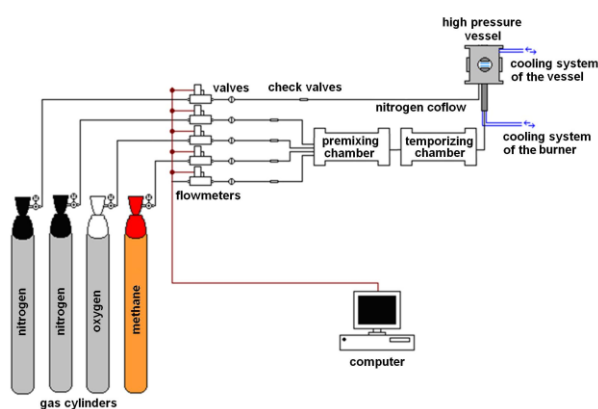


Figure 1: Overall view of the experimental set-up

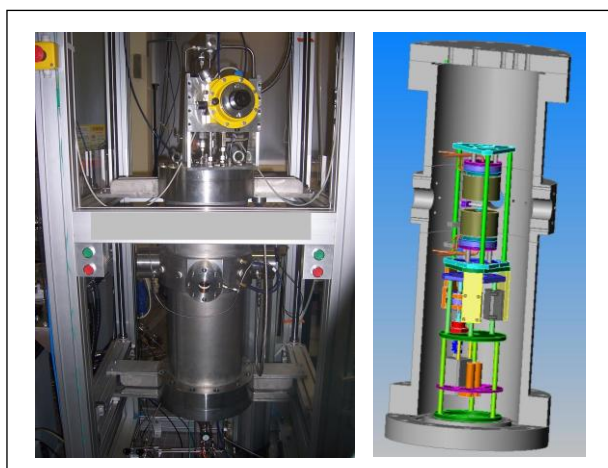


Figure 2: Picture and schematic of the high pressure facility

Flow rates of gases are monitored by mass flowmeters through a Labview[®] program developed in our laboratory. Isolation valves are placed after the flowmeters. Gases are then mixed in a premixing chamber filled with glass beads and, then, pass through

a temporizing chamber used to reduce flow variations before the burners.

Both burners are mounted on a vertical translation system composed of a planetary roller screw driven by a step motor located inside the chamber below the burners. The positioning accuracy is $\pm 1\mu\text{m}$. The distance between the burners (L) can be manually adjusted by moving the top burner compared with the bottom one. The precision is around $\pm 0.1\text{mm}$.

A diagram of the twin counter-flow burners is presented in Fig. 3. The two nozzles of 7mm of diameter were made to be aerodynamically converging using an empirical equation to build them. It results in a nearly uniform velocity profile on their exit which enhances the flame stability range. A nitrogen coflow around the burner permits to isolate the flame from the surrounding gases. The burners are cooled using a closed loop water circulation at a fixed temperature between 30 and 45°C depending on the flame conditions and to avoid water condensation at the burner surfaces. The gas premixture enters the burners from the bottom and passes through a laminarisation grid prior to enter the central nozzle of the burner. Flames are ignited at atmospheric pressure with a hot kanthal wire, retractable after ignition.

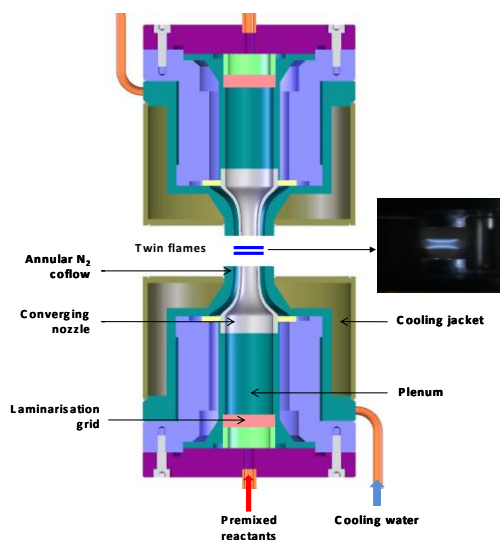


Figure 3: Diagram of the twin counter-flow burners

Methane-air flames stability study

As mentioned above, the premixed gas mixtures entering the burners are ignited at atmospheric pressure and the pressure within the vessel is progressively increased while the control valve regulates the pressure with an accuracy of 1kPa. For this stability study, the distance between the burners was fixed to $L=14\text{mm}$ ($=2xd$, where d is the diameter of the premixture nozzle) and the total flow rates were adjusted in order to obtain the best visible flame stability (flatness, stability, symmetry). The premixture flow and the coflow velocities at the exit of each burner, the adiabatic flame temperature and the laminar flame velocity are summarized in Tables 1 and 2, respectively for a lean

(equivalence ratio $\phi = 0.7$) and a rich (equivalence ratio $\phi = 1.3$) CH_4/air flame for different pressures. The adiabatic temperatures and the laminar flame velocities were calculated using the PREMIX code [15] from the CHEMKIN II package [16] and the GRImech3.0 mechanism [17]. Visual flame instabilities appear for a pressure of 0.8 MPa for the lean flame and 1 MPa for the rich one. This is due to very low flames velocities at those pressures. One can notice that the adiabatic flame temperature varies very slightly with increasing pressure.

Pressure (MPa)	Premixture flow velocity (cm/s)	Coflow velocity (cm/s)	Adiabatic temperature (K)	Flame velocity (cm/s)
0,1	72,79	72,92	1818	18,9
0,2	58,17	32,41	1823	13,6
0,3	51,71	38,90	1823	10,9
0,4	48,53	32,45	1824	9,3
0,5	38,82	27,69	1825	8,1
0,6	32,35	23,73	1825	7,3
0,7	33,27	20,76	1825	6,7
0,8	35,15	21,73	1826	6,2

Table 1: Premixture flow velocity, coflow velocity, adiabatic temperature and flame velocity for the lean ($\phi = 0.7$) CH_4/air flames at different pressures

Pressure (MPa)	Premixture flow velocity (cm/s)	Coflow velocity (cm/s)	Adiabatic temperature (K)	Flame velocity (cm/s)
0,1	145,59	145,97	2047	25,4
0,2	78,86	52,56	2062	17
0,3	72,79	46,32	2063	12,9
0,4	66,73	47,84	2065	10,9
0,5	58,23	42,42	2066	9,9
0,6	52,57	39,12	2067	9,2
0,7	45,06	36,63	2066	8,7
0,8	40,95	38,56	2068	8,4
0,9	20,27	34,27	2069	8,2
1	18,92	31,61	2069	7,9

Table 2: Premixture flow velocity, coflow velocity adiabatic temperature and flame velocity for the rich ($\phi = 1.3$) CH_4/air flames at different pressures

OH Laser Induced Fluorescence

Experimental set-up

Fig. 4 shows the experimental set-up employed for the Laser Induced Fluorescence measurements of the OH radical. A dye laser (Quanta-Ray PDL-2) is pumped by a Nd:YAG pulsed laser (Quanta-Ray DCR-3), delivering 7 ns pulses at a repetition rate of 10Hz. The laser beam of the dye laser is then doubled in frequency through a Wavelength Expander (WEX) device. Given

the dye used (Rhodamine 590) and the non linear crystal used in the WEX, the laser can be tuned to the $A^2\Sigma^+ - X^2\Pi (1,0)$ band of OH. At the exit of the laser, the beam has a diameter of 6 mm, is horizontally polarized and its energy per pulse is higher than 2 mJ. This latter value does not permit to work in the linear regime of fluorescence for the OH radical. Hence, we introduced a variable attenuator composed of a half-wave plate and a Glan – Taylor prism. The attenuation is made by rotating the wave-plate and the beam at the exit of the prism is vertically polarized. The beam is then focused, with a $f = 300\text{mm}$ lens in the high pressure chamber, on the axis between the two counter-flow burners. Parts of the laser beam are directed onto photodiodes, before and after the chamber, in order to monitor the laser beam energy variations as well as the attenuation of the beam after crossing the flames and the chamber.

Fluorescence signal is collected through a $f = 500\text{mm}$ lens and focused on the entrance slit of a monochromator with a $f = 300\text{mm}$ lens, giving a magnification ratio of 1.6 times the dimensions of the entrance slit. A 90° rotating periscope is installed between those two lenses in order to rotate the image entrance slit according to the laser beam axis. The monochromator is a Jobin-Yvon, HRS-2 model, with a focal length of 500mm and equipped with 1200 lines/mm grating, blazed at 500 nm. Fluorescence signals are observed at the 2nd order of diffraction of the grating. A bandpass filter centred around 320 nm is installed just before the entrance slit in order to avoid other perturbing signals that should appear at the first order. A photomultiplier tube (Photonis, XP2020Q model) is placed behind the exit slit of the monochromator and the detected signals are finally sampled with a 1GHz bandwidth oscilloscope (Tektronix, TDS5014B model).

The superimposition of the focal volume and the collection volume is optimized through collection of Rayleigh scattering in air (or nitrogen), with slit widths of 10 μm . The obtained accuracy is about 10 μm .

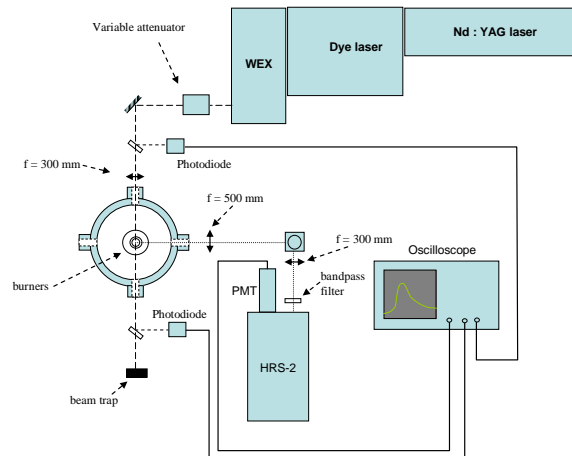


Figure 4: Diagram of the experimental set-up for the Laser Induced Fluorescence measurements

LIF saturation measurements

OH profiles were measured in the lean ($\phi = 0.7$) flames at 0.1 MPa and 0.5 MPa in the linear regime of LIF excitation using the $Q_1(7)$ line of the (1,0) band in the $A^2\Sigma^+-X^2\Pi$ system of OH near 283 nm. The rotational level $J=7$ was chosen as its Boltzmann fraction varies very slightly through the flame temperature domain ($\sim 8\%$ between 1000 and 2000 K). The fluorescence was collected over a spectral window of 5 \AA centred on the $Q_1(7)$ line of the (0,0) band near 309 nm. In order to ensure that measurements are performed in the linear regime of excitation, we performed saturation tests at each pressure. For that, the laser beam energy was attenuated by rotating the half-wave plate and measured by a joulemeter (Gentec QE12SP-H-MB-D0 model + QE-X amplifier). The fluorescence signal collected just after the flamefront of the bottom flame is averaged over 100 laser shots. Fig. 5 shows the saturation test performed in the lean ($\phi = 0.7$) flame at 0.1 MPa and 0.5 MPa. It shows that the linear regime is reached for laser energy lower than $40 \mu\text{J}$ for both pressures.

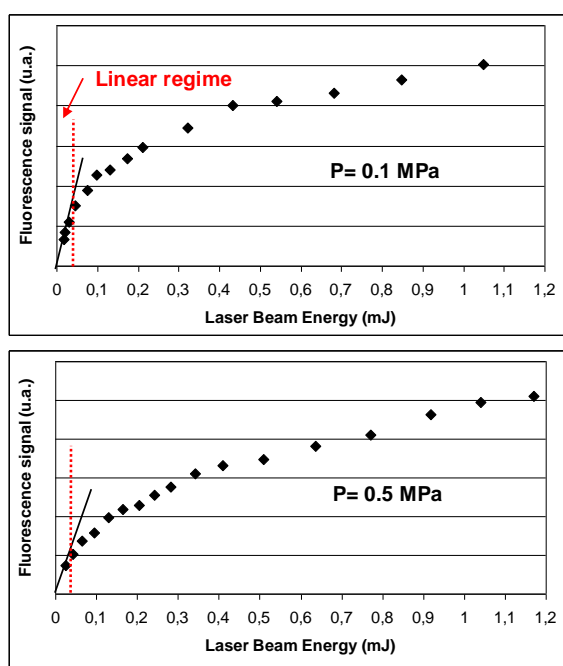


Figure 5: Saturation tests in the lean ($\phi = 0.7$) flame at 0.1 MPa (top) and 0.5 MPa (bottom)

OH relative concentration profiles

Figure 6 shows the OH profiles, normalized at the peak position signal, for the lean ($\phi = 0.7$) CH_4/air flame at 0.1 MPa and 0.5 MPa. Note that those profiles are neither corrected for quenching rate variations along the flames axis, nor for auto-absorption, nor for trapping of the laser beam passing through the flame diameter. Those corrections are under investigation. At atmospheric pressure, the two flamefronts are roughly symmetric compared to the median horizontal plane between the two burners. However it is not the case for higher pressure. At 0.5 MPa, the OH profile is

dissymmetric in position and in amplitude. The lower OH LIF signal on the top flame might be due to higher auto-absorption and trapping compared to the bottom one, caused by convection effects that are more important at high pressure. This assumption will be verified through future Planar Laser Induced Fluorescence measurements of OH.

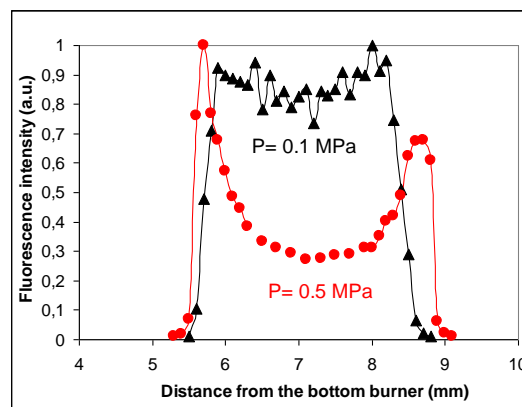


Figure 6: Normalized OH relative concentration profiles in the lean ($\phi = 0.7$) flame at 0.1 MPa and 0.5 MPa

Conclusions

This work presents a new high pressure combustion facility, recently set up at the ICARE laboratory. It consists of twin counter-flow burners located in a high pressure chamber allowing the stabilisation of laminar, flat (1D) twin-premixed flames and the investigation of their structures using laser diagnostics. The objective is to obtain a new database on high pressure combustion in order to develop and validate detailed chemical mechanism at high pressure. The flames stability study shows that we managed to stabilize CH_4/air counter-flow flames up to 1 MPa. The preliminary OH LIF measurements show the feasibility to measure OH profiles at high pressure. Corrections related to these LIF measurements (quenching, auto-absorption, trapping) are under investigation. Future works will concern the NOx formation in high pressure flames. LIF measurements of key species involved in NOx formation mechanism in flames (NO, CH) will be performed.

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