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CORIA Aeronautical Combustion Facilities and Associated Optical Diagnostics

The scientific activities presented in this article are within the field of the design of new concepts of combustion chambers and the exploration of their benefits to increase the combustion and environmental efficiencies of advanced air-breathing propulsion systems. These scientific activities are performed in the "*Complexe de Recherche Interprofessionnel en Aérothermochimie*" (CORIA) research laboratory, a joint research institute organized between the CNRS, the University of Rouen and the INSA-Rouen Engineering School. CORIA contributes through its recognized expertise in numerical simulation, optical diagnostic measurements and experiments in large-scale combustors to improving the understanding of multi-scale multi-physics physical mechanisms governing the lean combustion of future combustion chambers. In this context, the “*Centre de Combustion Avancée pour l’Aéronautique du Futur*” (C-CAAF) recently created at CORIA is aimed at providing:

- An instrumentation and optical diagnostic platform gathering various laser/optical diagnostic techniques (PIV, LDV for the characterization of the aerodynamic field, PDPA, GRT for the characterization of the distribution of fuel droplets, CARS for measuring the thermal field and main species concentration, OH-PLIF and Schlieren for analyzing the flame structure, LII, NO-PLIF, CO-PLIF for measuring pollutants in the flame, etc.). These laser/optical diagnostic techniques are used to provide unique laboratory tools to perform time-resolved, simultaneous, multidimensional measurements of scalar parameters governing turbulent and multi-phase combustion. Furthermore, these diagnostic tools can be combined to obtain detailed correlations on these scalar parameters.

- Multiple set-ups, from academic burners to complex combustors operating at high pressures. Through the perfect control of their operating conditions, academic burners are designed to assist in the development and validation of innovative optical diagnostic tools. They also provide a precise determination of the relevant chemical and physical parameters, enabling conclusions to be drawn about the underlying partly-coupled combustion processes. Technical combustion chambers are developed to provide a high-fidelity experimental database, in order to improve the innovative architectures of ultra-low NOx aeronautical injectors operating with real multi-component liquid fuels (kerosene, alternative fuels, biofuels, etc.), to identify the interaction mechanisms between several fuel injection systems and to validate the predictive capability of gas turbine combustion models.

Introduction

Future aero-engines need to be affordable, highly efficient and environmentally friendly. NOx strict regulations on emissions coming into effect in 2020 (ACARE regulations) will demand further NOx and fuel burn reductions. Combined with increased pressure ratios and turbine inlet temperatures for improving the efficiency of engine components, significant steps must be taken to push these modern combustion technologies to their limits with regard to their ability to reduce pollutant emissions and preserve engine operability (combustion efficiency, ignition and light around altitude restart and pull-away capability, combustion dynamics in terms of noise an combustion instabilities). In order to meet its operational requirements, lean combustion has been selected by aeronautical manufacturers as a promising ultra-Low NOx combustion concept for aero-engine combustors. However, the success of these innovative combustion techniques strongly depends on many parameters, such as the architecture of the combustor and the design of the fuel injection system, which affect many physical mechanisms (atomization, fuel evaporation, fuel/air mixing, flame stabilization, pollutant formation, etc.).

Consequently, it is mandatory to investigate with the greatest detail most of the various physical and chemical mechanisms that govern turbulent combustion in relation with the architecture of the injection device.

In this context, the C-CAAF (*Centre de Combustion Avancée pour l'Aéronautique du Futur*) Research center, which gathers the French CORIA Research Laboratory, the public engineering-funded school INSA-Rouen and the industrial partner SAFRAN-Tech, has been created to establish a center for technological innovations in the field of aeronautical combustion systems. This platform supports the experimental and computational study of fundamental combustion phenomena, in order to expand the scientific knowledge base, validate combustor-design codes, improve the combustion performances, reduce the pollutant emissions and enhance the affordability, maintainability and reliability of current and future generation propulsion systems for commercial aviation. This complex state-of-the-art provides unique laboratory tools for the experimental characterization of combustion through the development, demonstration and application of advanced laser-based/optical diagnostic techniques on various test benches allowing academic, as well as applied experiments. These capabilities are complemented by a series of specialized modeling and simulation methodologies for assessing and predicting the detailed chemistry and physics of combustion processes occurring in aero-engine combustors. Another objective of this center is also to be recognized as a center of expertise and experimental resources and unique scientific computing in Europe gathering European R&D centers in the field of aeronautical combustion.

With this purpose, the recent educational and research industrial chair "Powering the future with Clean and Efficient Aero-engines" (PERCEVAL) has been initiated by CORIA in close cooperation with the aeronautical manufacturer SAFRAN Tech, the French National Research Agency (ANR) and ONERA to assess the optimization of combustion efficiency and reduction of pollutant emissions of innovative stage lean combustors. The methodology adopted to support this research includes 1) the optimization of the architecture of innovative injection devices by CFD, 2) the development of innovative and reliable optical diagnostics to obtain spatial and temporal quantitative measurements of various scalar parameters (velocity, temperature, species concentration, etc.) in high-pressure environments, 3) a detailed experimental investigation of the underlying generating mechanisms with non-intrusive optical measurement techniques under operating conditions relevant to aero-engines and 4) high-performance computing of the experiments with high-resolution time-resolved LES solvers (AVBP and YALES 2). In this scientific experimental activity, the research topics investigated in detail are focused on the improved understanding of high-pressure turbulent two-phase flow combustion and include:

- Fuel injection,
- Fuel evaporation,
- Vapor fuel/air mixing,
- Aerodynamics,
- Turbulence,
- Ignition,
- Flame structure & flame dynamics,
- Combustion instabilities,
- Flame/wall interaction,
- Pollutant formation (CO, NOx and soot) and exhaust emissions.

These phenomena are understandable by using a variety of optical measurements based on various light/matter interactions. For this purpose, the CORIA features a large array of advanced laser technologies, including many one-of-a-kind optical sources and detectors. The laser sources provide a broad spectral coverage, from the ultraviolet through the visible part of the spectrum to the near infrared, for flow visualization and spectroscopic investigations of complex reacting and non-reacting flowfields. Continuous-wave and pulsed (nano-, pico-, and femtosecond) laser sources are used, in conjunction with various scientific-grade cameras and ultrafast imaging devices in order to provide tremendous spatial and temporal resolution and data acquisition bandwidth for critical applications. A host of linear and nonlinear laser based/optical techniques have been specially developed and applied, in order to perform non-intrusive instantaneous measurements in multi-phase reacting flows of time-resolved, simultaneous, multidimensional flowfield and scalar distributions. The scalars of interest include temperature, fluid velocity, spray characteristics, molecular fuel composition, key intermediate species and pollutants (CO, NO and soot). Optical diagnostics are suited for high-pressure (0.1 – 5.0 MPa) and high temperature (300 – 2500 K) operating conditions. The optical techniques include emission spectroscopy (temperature, species composition), planar laser-induced fluorescence (PLIF) (flame structure, temperature minor species and fuel concentration, NO and CO pollutants), laser-induced incandescence (LII) (2D soot distribution), planar Rayleigh scattering (PRS) (density and temperature fields), reactive Mie scattering (RMS) (spray pattern), laser Doppler velocimetry (LDV) (velocity, turbulence properties), particle-image velocimetry (PIV) (2D and 3D velocity distribution), spontaneous Raman scattering spectroscopy (temperature, main species concentration, mixture fraction), coherent anti-Stokes Raman scattering spectroscopy (CARS) (temperature, main species concentration), phase Doppler particle analysis (PDPA) (particle size distribution), femtosecond ballistic imaging (velocity and structure of dense spray), ultrafast pump-probe spectroscopy and femtosecond time-resolved laser-induced fluorescence (temperature, species concentration), the global rainbow scattering technique (size and temperature of droplets), advanced techniques for Schlieren reconstruction (flow visualization), high-speed imaging and data analysis at repetition rates of up to 10 kHz (emission, PLIF, PIV) and high-speed fs/ps CARS and fs/ps LIF (10 kHz).

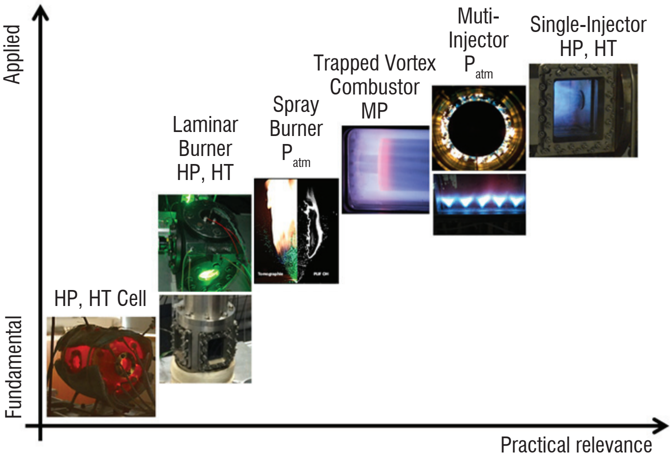


Figure 1 - Presentation of the experimental facilities with respect to the practical relevance

Test and validation cases of engine components must be performed in high-pressure high-temperature combustion facilities, with large optical accesses, in which detailed investigations of nonreactive and reactive flow fields are feasible with reliable measurement techniques. All of the experiments must also be carried out under operating conditions relevant to aero-engines, with well-controlled boundary conditions being required to accurately validate the numerical simulations. In order to do this, CORIA has adopted a stepped strategy in combustion devices and aeronautical research, which consists in systematically studying relevant combustion phenomena throughout well-balanced sets of test rigs. Figure 1 shows the experimental setups selected for this purpose, ranking the level of their practical relevance and experimental level of accessibility. In the following, these different set-ups are presented and some available results are also discussed.

High-pressure optical cell

In modern combustion chambers, evaporation and mixing effects of multi-component fuels are highly relevant. While multi-component fuel evaporation models are being developed to predict these physical phenomena, there is still a serious lack of experimental information providing guidance on the role of preferential evaporation of the fuel components during injection. Consequently, it is of great interest to conceive measurement strategies able to assess this effect on the resulting fuel/air mixture. This research is aimed at proposing innovative measurement strategies for investigating the role of multi-component fuel volatility in fuel/air preparation [1-3]. The technique is based on the identification of suitable fuel/fluorescent tracer mixtures for the study of the evaporation of multi-component fuels, including standard petroleum-derived fuels and biofuels. In a general manner, the methodology developed in the current study consists in mixing several fluorescent markers within the multi-component fuel, in order to track in real-time the evaporation of various fuel volatility classes. Fluorescent tracers were selected in order to ensure that their

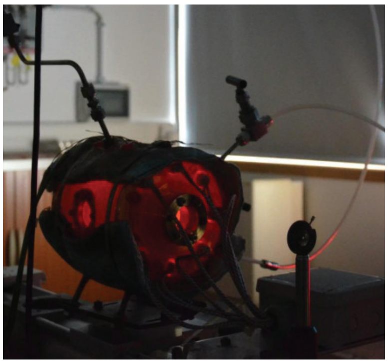
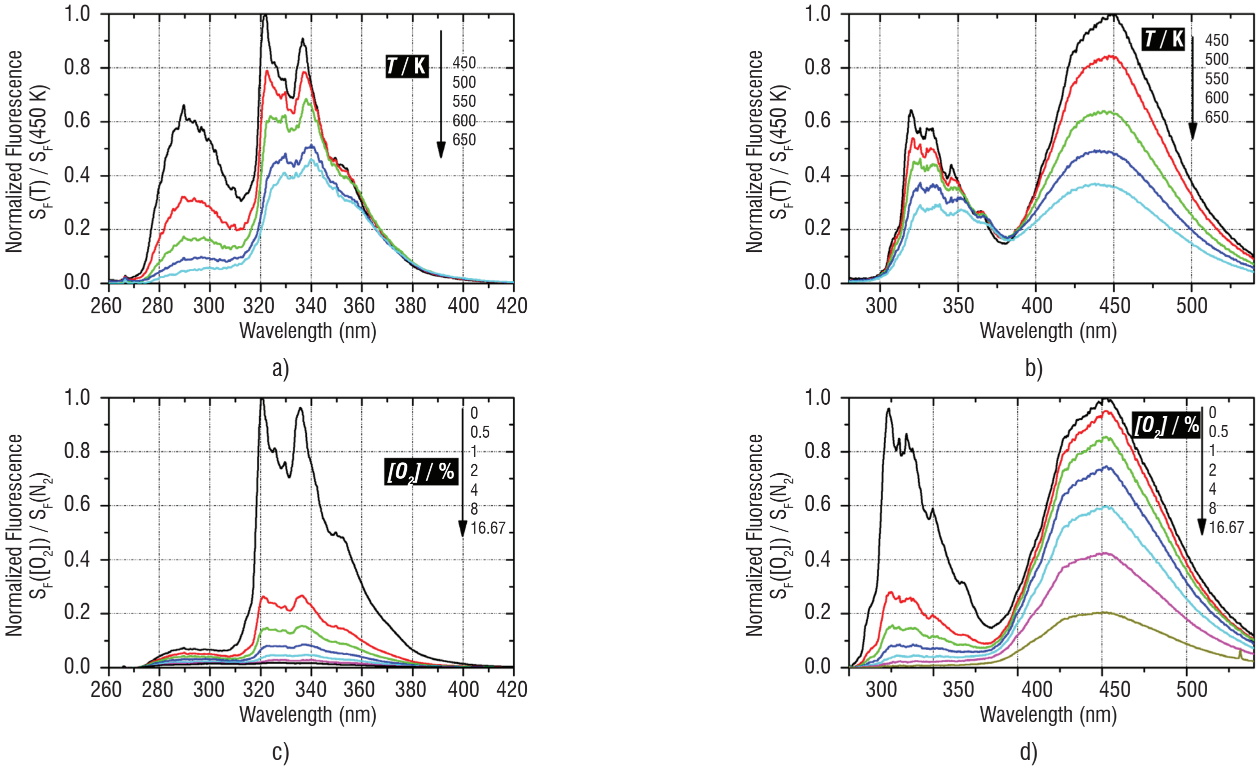


Figure 2 - High-Pressure Optical Cell
pressure range = 0.1 – 4.0 MPa, temperature range = 300 - 1000 K [4]



a)

b)

c)

d)

Figure 3 - Evolution as a function of temperature (a), (b) and oxygen concentration (c), (d) of the Fluorescence of 1,2,4-trimethylbenzene/acenapthtene and napthtalene/fluoranthene diluted in the BTL and diesel surrogate fuels respectively. The pressure is 0.1 MPa.

co-evaporative characteristics with the fuel volatility classes (i.e., boiling points) are respected and their fluorescence emission spectra are fully separated, while also providing high sensitivities with temperature and species composition. This selection is obtained from spectroscopic parameters (fluorescence, absorption, etc.) of various organic molecules recorded in a high-pressure high-temperature optical cell, in which the operating conditions of the experiments are well-controlled (Fig. 2).

In order to illustrate some of these experiments, fluorescence measurements on suitable tracer mixtures enabling the analysis of the evaporation of multi-component fuels including standard petroleum-derived diesel and Biomass-to-Fuel (BtL) fuels are presented [5]. Among the fluorescent organic molecules, the aromatic mixtures 1,2,4-trimethylbenzene/acenapthtene and napthtalene/fluoranthene were selected to separately track the co-evaporation of the lightest and heaviest products within BtL and diesel fuels respectively. In order to evaluate the effects of temperature and oxygen quenching on the photophysical properties of these tracers, the fluorescence spectra were recorded in the high-pressure optical cell under various conditions. Fig. 3 depicts results for both aromatic mixtures in cases in which a 266 nm excitation laser wavelength is used. As observed in Fig. 2, the resulting fluorescence spectra of both tracers appear in two distinct spectral domains, easily separated by the use of convenient optical filters. Furthermore, the intensity of the fluorescence emission displays different trends with temperature and oxygen concentration. Similar dependences with pressure then offer opportunities for imaging scalar parameters, such as the equivalence ratio and temperature during BtL and diesel spray evaporation via a dual-channel filtered detection of the resulting fluorescence tracers [5].

This optical cell is also used to evaluate the performances of various laser diagnostic techniques (CARS, PLIF, Spontaneous Raman scattering, etc.) and to assess their accuracy and their quality under various thermodynamic conditions [6]. As an illustration of these studies, the detection of nitric oxide by LIF was developed because NO is considered as one of the key combustion-generated pollutants. For this purpose, LIF experiments were conducted in the high-pressure optical cell, in order to record and quantify the behavior of NO fluorescence with scalar parameters like temperature, pressure and species composition. As an example, a portion of the NO (0,0) excitation fluorescence spectra is shown in Fig. 4 for various temperature and pressure conditions. Here, there are several features that remain fairly well isolated at high pressures, although their peaks are substantially reduced between 0.1 and 0.5 MPa. As identified in the figure, not all of these features are single lines; for instance, the feature at 225.63 nm is $Q_{21}(20.5) + P_{21} + R_{21}(10.5)$. Although not a single transition, this group of rotational transitions is still suitable for both validation experiments, as well as PLIF imaging, in which a simulation model is to be applied to render the images quantitative.

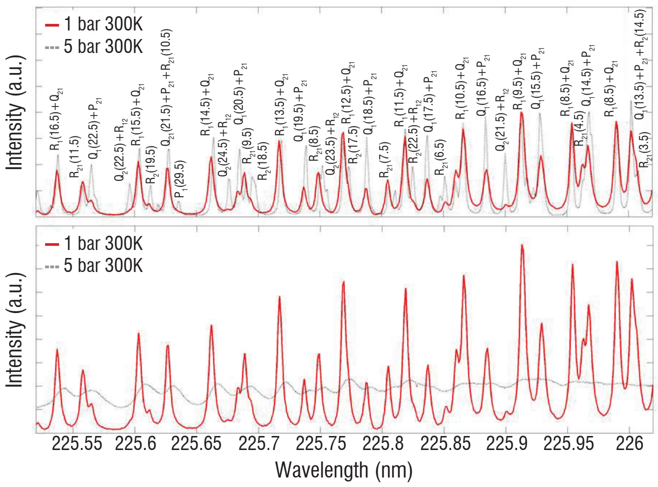


Figure 4 - Excitation fluorescence spectra of NO transitions near 226 nm at (top) T= 300 and 800 K, P=0.1 MPa, (bottom) 0.1 and 0.5 MPa, T=300 K.

The knowledge of the fluorescence emission spectra of NO in the 0.1 - 2.0 MPa pressure range (Fig. 5) has furthermore facilitated the development of a comprehensive experimental database so that the fluorescence signal simulation results with an in-house fluorescence software application can be compared under a wide range of thermodynamic conditions [6]. Furthermore, the knowledge of the evolution of the dependences of the fluorescence signal on both temperature and species composition (especially O_2 concentration) enables the implementation of new NO measurement strategies suitable for quantifying the NO fluorescence signals in terms of species concentration in combustion engine experiments.

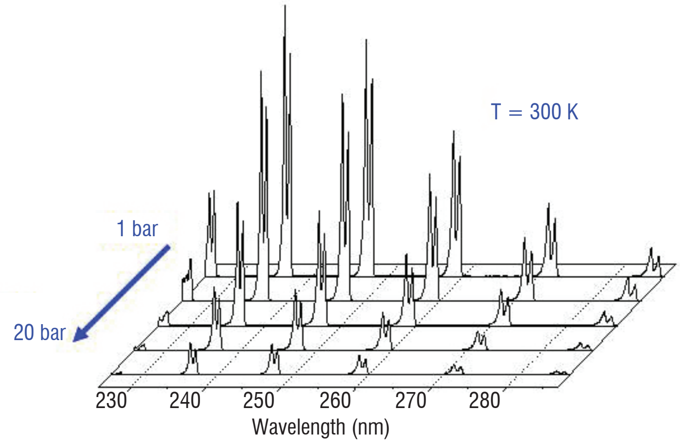
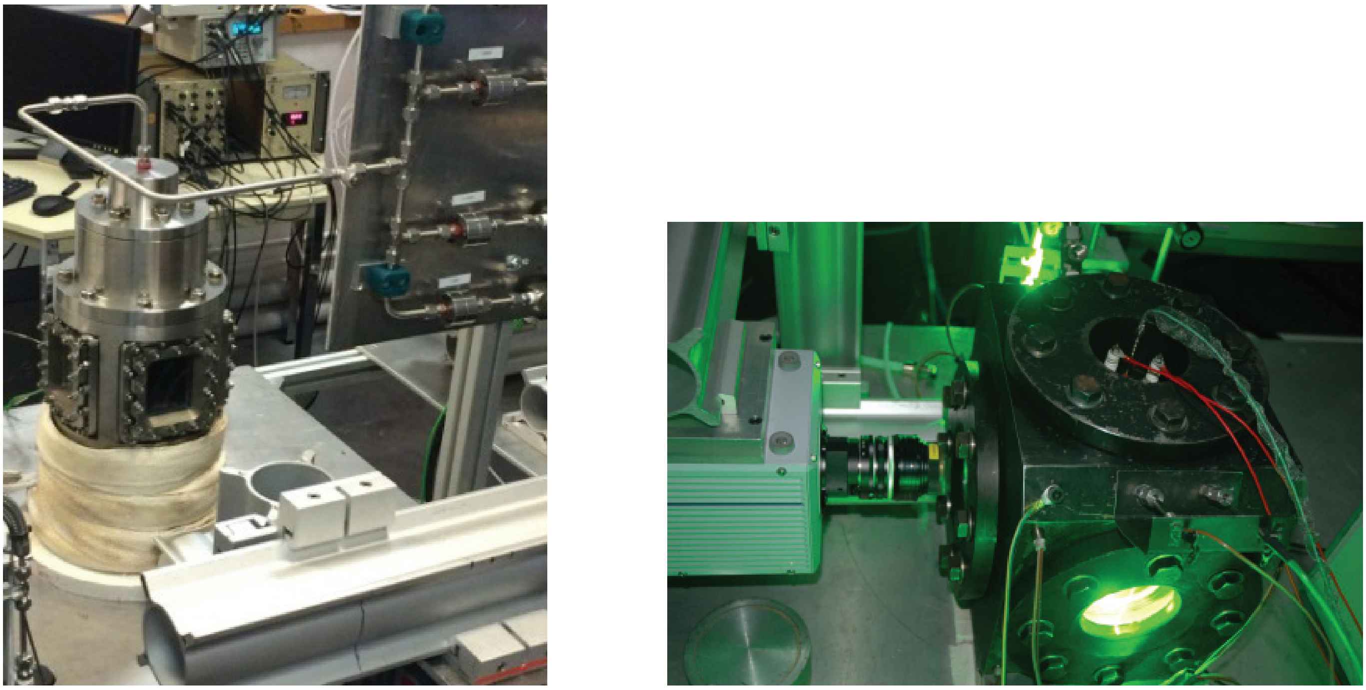


Figure 5 - Emission fluorescence spectra of NO as a function of pressure; T = 300K.

High-pressure laminar burners

The purpose of this scientific activity is to give experimental insight about the detailed analysis of the pollutant formation mechanisms and flame stability criteria during the combustion of multi-component fuels. In order to do this, a current approach used to reduce pollutant emissions is to burn the fuel/air mixture under lean conditions. This solution is not without consequences for the flame dynamics, which can produce combustion instabilities leading to flashback. One approach to quantify the flame stability is then to know the laminar burning velocity. This parameter is also useful for kinetic scheme validation and for qualifying turbulent flame structure and turbulent flame velocity. Another physical parameter to be considered is the chemical composition of multi-component fuels. Given that their chemical kinetic models are not yet optimized for real operating conditions, their effects on combustion instability production and pollutant formation are still imprecise. Two academic high-pressure setups have been developed to be used to develop criteria regarding flame stability and to validate the performances of the fuel kinetic model under those conditions (Fig. 6).



a)

b)

Figure 6 - (a) Laminar high-pressure burner operating at pressures of up to 3.0 Mpa and an inlet temperature of 600K. (b) Spherical bomb operating at pressures of up to 2.0 Mpa and T=580K..

The first high-pressure burner is designed to measure the behavior of the laminar burning velocity with pressure (0.1-3.0 MPa), equivalence ratio (0.5 – 1.4) and inlet temperature (300 – 600 K). An axisymmetric premixed burner was designed to generate a steady conical laminar premixed flame, stabilized on the outlet of a contoured nozzle in a high pressure vessel [7]. The high-pressure vessel, constructed out of stainless steel, has an inner surface of 100 x 100 mm^2 and a length of 160 mm (Fig. 6a). It is equipped with four large UV quartz optical windows customized to probe the flame with optical imaging diagnostics. Preheating of the pressure vessel is performed using electrical wire heaters positioned around its external surface. The burner can operate with a large variety of gaseous fuels (CH_4, C_3H_8, etc.) or liquid fuels (kerosene, biofuel, diesel, gasoline, etc.). Liquid fuel was pressurized in a 1.0 liter tank connected to a liquid flow-meter associated with a Controlled Evaporator and Mixer (Bronkhorst), which heats and mixes fuel vapor with N_2 inert carrier gas at controlled mass flow rates and temperature. The CEM outlet is connected to a stainless steel mixing cell preheated at a temperature ranging between 373 and 600 K, and controlled with a type K thermocouple in order to prevent any condensation of the fuel vapor. Additional nitrogen and oxygen initially mixed and preheated by a heater before the mixing cell inlet are used to reproduce the synthetic species composition of air and to modify the equivalence ratio of the heated fuel vapor/air mixture. The non-invasive diagnostics used to perform these experiments are the Schlieren, OH* chemiluminescence and OH-PLIF diagnostics to measure the laminar flame velocity, NO- and CO-PLIF to probe the gaseous pollutants, Coherent anti-Stokes Raman scattering to measure the temperature in the exhaust gases and 2-λ Indium laser-induced fluorescence to measure the 2D temperature distribution in the fresh gases.

As an illustration of the performances of the high-pressure burner, the laminar burning velocities for two aviation multi-component fuels are presented in this section [8]. The multi-component fuels investigated are the Jet A-1 fuel, which represents the common aviation commercial fuel, and the LUCHE surrogate jet fuel consisting in a reduced mixture of n-decane ($C_{10}H_{22}$), aromatic (C_9H_{12}) and naphthenic (C_9H_{18}) molecules. Measurements of laminar burning velocities are performed using two optical imaging techniques, the OH* chemiluminescence and the OH planar laser induced fluorescence (OH-PLIF) diagnostic. For instance, images of the laminar flames produced in the high-pressure burner and recorded with OH-PLIF are shown in Fig. 7. From each image, the laminar burning velocity is then deduced from the flame surface area methodology.

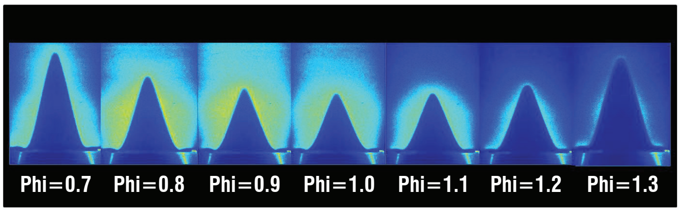
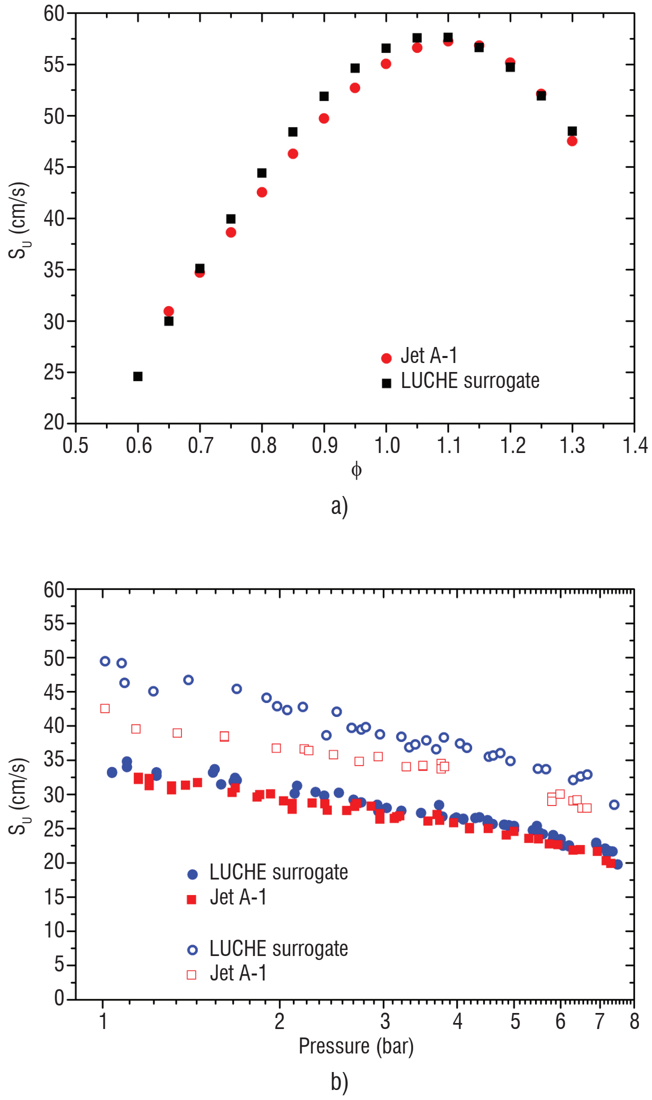


Figure 7 - Evolution of the structure of the laminar flame of a premixed kerosene/air combustion for various equivalence ratios. P=0.5 MPa, T_{air}= 400 K.

As shown in Fig. 8a, the comparison between the burning velocities of Jet A-1/air and LUCHE fuel/air mixtures, recorded at atmospheric pressure and a preheating temperature of 400 K, reveals that the laminar burning velocity of the surrogate fuel is slightly greater than the laminar flame speed for the Jet-A1 fuel in situations where the equivalence ratio ranges between 0.8 and 1.1. For the other equivalence ratios, both values are found to be equivalent. The same tendency is also observed for higher pressure conditions (Fig. 8b). For instance, the laminar flame speeds recorded in the 0.1- 0.8 MPa pressure range differ slightly when $\phi = 0.7$, whereas noticeable discrepancies can be observed for $\phi = 0.8$. These results enable us to draw conclusions regarding the performance of the chemical kinetic mechanism of the LUCHE surrogate jet fuel to simulate the combustion of Jet-A1 commercial fuel.



a)

b)

Figure 8 - (a) Evolution of the laminar flame speed as a function of the equivalence ratio for Jet A1 and LUCHE surrogate fuels, P=0.1 MPa (b) Behavior of the laminar flame speed of Jet A1 and LUCHE surrogate fuels as a function of pressure, T=400 K.

The second experimental facility is a spherical closed vessel that enables stretched laminar flame speeds and the associated Markstein lengths of a selection of hydrocarbon fuels (Fig. 6b) to be determined. Experiments can be performed under thermodynamic conditions close to those encountered in internal combustion engines (2.0 MPa and maximum temperature of 573 K). The radius of the inner chamber is 85 mm and the inner volume of the stainless steel combustion chamber is 2.6 l. Two types of fuels, gaseous or liquid, can be used. Fuels that are gaseous under ambient conditions are loaded directly from bottles through mass controllers. Liquid fuels are first vaporized in a heated chamber by using a controlled evaporator mixer and then loaded through heated lines into the vessel. In order to obtain a homogeneous mixture, all gases are premixed in a tank before injection into the combustion chamber and the equivalence ratio of the mixture is measured and regulated by Coriolis or thermal mass flow controllers. An electrical heating system regulates the temperature of the mixing tank and of the combustion chamber. The compressed fuel/air mixture is supplied continuously from the bottom of the combustion chamber. Ignition takes place 1 min later, in order to avoid any flow perturbation during the flame propagation. The combustible mixture is spark-ignited at the center of this chamber by two stainless steel electrodes linked to a capacitive discharge ignition system using minimum spark energies to avoid ignition disturbances. During the ignition process, the evolution of the chamber pressure is measured by a dynamic pressure transducer and both the time evolution of the flame radius and the spatial fresh gas velocity are obtained by high speed tomography [9, 10].

Based on a new tool for extracting the laminar burning velocity from the flame propagation speed and the local fresh gas velocity at the entrance of the flame front [10], this facility has been used, among other things, to evaluate the effects of the pressure, equivalence ratio and ethanol mole fraction on laminar burning velocity of isooctane/air flames. This approach gives additional information in terms of flame sensitivity to flame stretch represented by the Markstein length relative to the fresh gases and a direct measurement of the unstretched laminar burning velocity without any assumptions on regarding adiabaticity and regarding the fuel mixture properties. The overall accuracy of the measurements obtained from the repeatability of the experiments was less than ±1.5 cm/s at P = 0.1 MPa and increased with pressure to reach ±3 cm/s at P = 1 MPa. Fundamental burning velocities and associated Markstein lengths have been experimentally determined and compared with numerical results. A globally good agreement was obtained with the literature data for pure fuels [11]. A general correlation has been proposed to express the effect of the pressure, equivalence ratio and ethanol mole fraction in isooctane at a temperature of 373 K. The accuracy of this correlation and the ranges of validity are provided in Figure 9. Giving the potential of this facility, the matrix of experimental conditions could be completed to include the temperature effect, in order to achieve thermodynamical conditions similar to those encountered in SI engines.

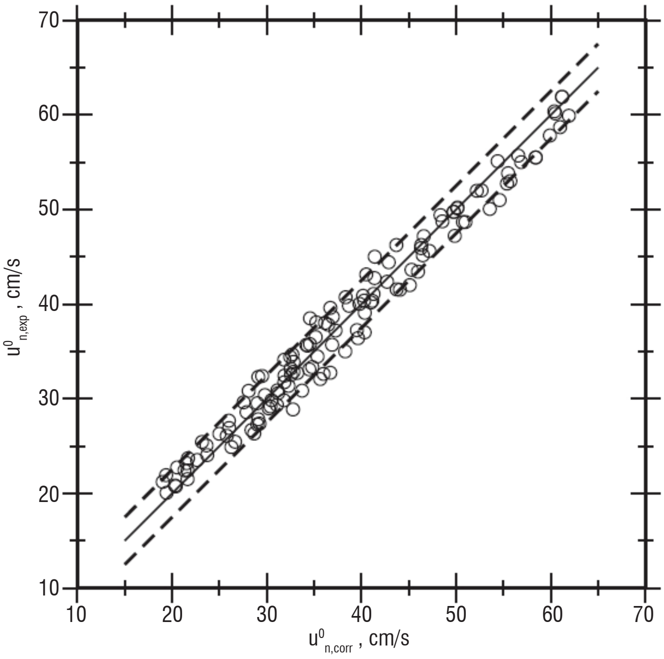


Figure 9 - Burning velocity obtained by correlation compared with the experimental data. The dashed lines indicate two-sigma uncertainties. The solid line indicates the equality between measured laminar burning velocity and the values predicted by the correlation. Reprinted from [11].

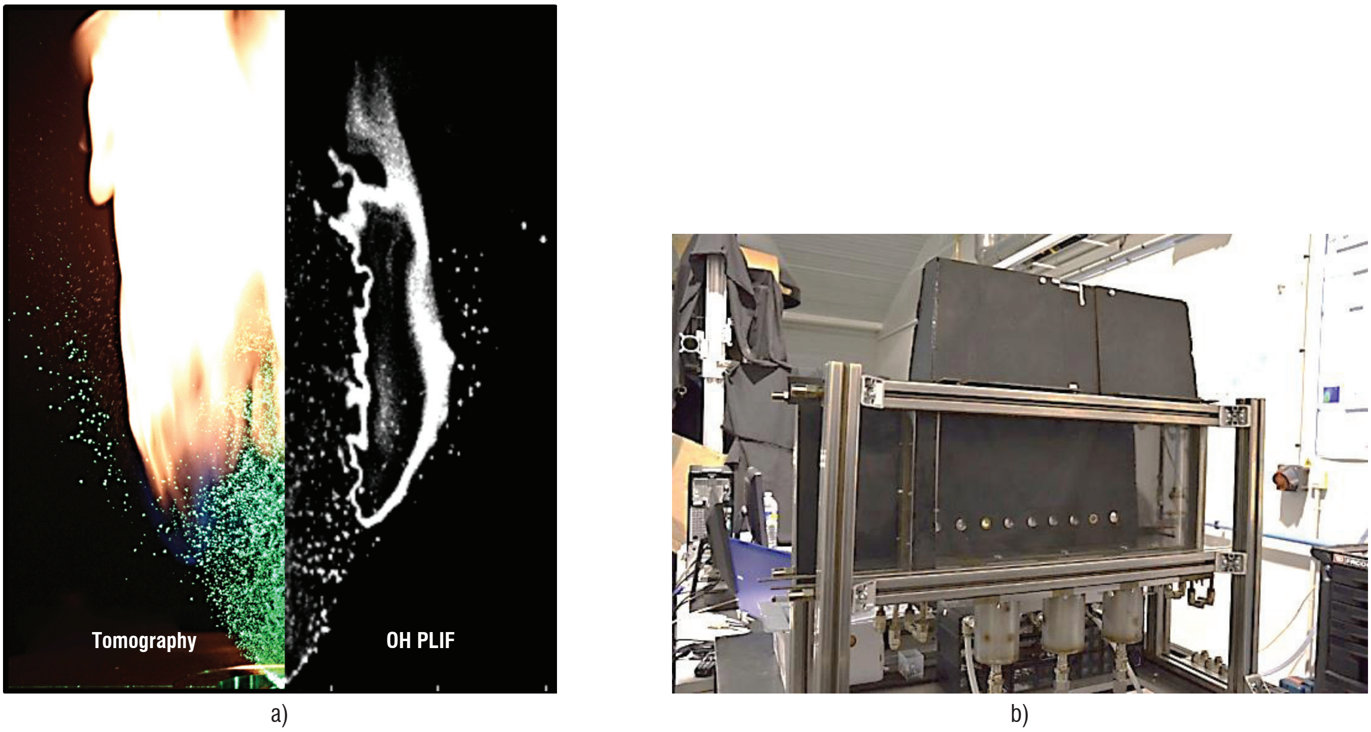


Figure 10 - (a) Spray jet flame burner. (b) Multi-injector KIAI burner

Ignition and lightening around

In many combustion applications, such as during the relight of an aviation gas turbine during flight, the phenomenon of ignition from a localized spark is important. Understanding the mechanisms involved can provide tools to alter the design of gas turbine burners and combustion chambers for improved flight safety and fuel efficiency. In this context, two burners were dedicated to the experimental study of ignition phenomena in confined swirled flows, operating in gaseous or two-phase flows (Fig. 10). The operating conditions are relevant to aeronautical conditions and the various ignition steps (flame kernel ignition, ignition and flame stabilization at the exit of the first injector and light around) are studied accurately by means of spatially and temporally resolved optical diagnostics.

The first burner consists of one liquid fuel injector, with or without confinement (Fig. 10a), and ignition can be performed at various locations within the combustion chamber, in order to [12]:

- evaluate the optimal spark location to achieve an efficient burner ignition,
- understand the ignition mechanisms related to the effects of local conditions: turbulence, mixing, fuel evaporation, flame kernels trajectories and ignition scenario.
- achieve extended and accurate experimental databases for a relevant validation of CFD codes dedicated to the design of aeronautical combustion chambers.

The second burner is made of five injection systems (similar to the previous one) with a variable distance between two-successive injectors (Fig. 10b). This facility leads the impact of this distance (which is a key parameter for the design of the combustion chamber) on the mechanism of light around to be identified. These experimental studies are also carried out with the purpose of providing open databases to enable a joint analysis of these phenomena with LES numerical simulations (AVBP or YALES 2 numerical codes) [13]. In order to illustrate these purposes, experimental and numerical approaches (LES) have been conducted simultaneously to analyze the light around phenomena in the multiple-injector burner facility and to evaluate the influence of spacing between two consecutive fuel injectors [13, 14]. Increasing spacing between consecutive injectors directly impacts the flame propagation mode and thus the ignition delay. Two major propagation modes were identified both in LES and experiments. Small spacing (less than 150 mm) enables a purely spanwise, rapid and safe propagation (Fig. 11). A critical distance is identified (160 mm), above which propagation mechanisms begin to change. Above this limit, propagation occurs not only in the spanwise direction, but also in the axial direction. When this distance is further increased, flame propagation becomes mainly axial and full ignition is delayed or fails (seen only in the experiments).

A detailed analysis showed that the various propagation modes where basically driven by two key mechanisms:

- The flame is affected by the flow aerodynamics, which change with the injector spacing. Low spacing flow aerodynamics promote a rapid suction through the swirling motion leading to a spanwise flame propagation mode, while high spacing flow structure changes are favorable to an axial propagation mode. The spanwise propagation mode is associated with a short traveling time of the flame from one injector to the other and a low variability, while the axial propagation mode is characterized by longer propagation times and a much higher variability.
- A thrust effect due to the thermal expansion of the burnt gases has been revealed. It produces a continuous flame progress that modifies the surrounding cold gas flow. It may increase the spanwise velocity and is the major flame propagation mechanism in regions of weak mean flow, such as the LRZ (Lateral Recirculation Zone). These propagation modes result in different overall ignition times, which increase with the injector spacing.

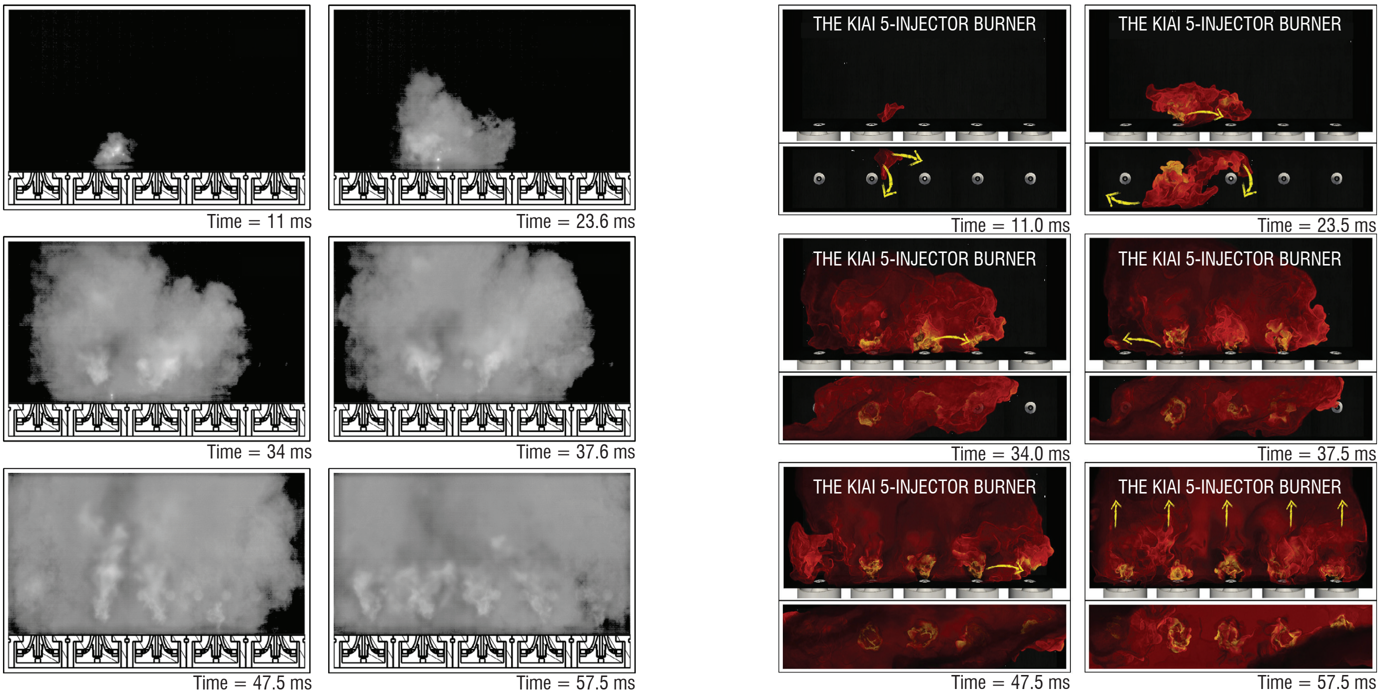


Figure 11 - (Left). High-speed flame emission visualization of the flame showing a spanwise propagation for a small spacing case, 90mm. (Right). Instantaneous snapshots of the same ignition sequence visualized by the volume rendering of heat release, front and top views. Reprinted from [13].

Comparisons between experiments and LES have shown the capability of LES to reproduce ignition sequences, as well as the added value of LES in this ignition process investigation, using the additional data available.

Trapped vortex combustor (TVC)

Flame stability is a key fundamental issue in the design of new aero-engine combustors. In conventional aero-engine combustors, flame stabilization is commonly achieved through the use of a swirler, under which a central recirculation zone is formed to transport hot combustion gases back toward the injection nozzle, thereby providing the heat required to maintain combustion. However, this technology can produce combustion instabilities, especially in lean combustion regimes. In order to overcome these limitations, an innovative burner based on the concept of a trapped vortex combustor (TVC) has been developed (Fig. 12).

The operating conditions of the test rig are controlled up to 500 K, 100 g/s for the air mass flow rate and 0.5 MPa [15 - 17]. This burner uses a cavity in which vortices are trapped to stabilize the flame. The effectiveness of this geometry lies in the presence of a shear layer at the flow separation and significant flow recirculation zones within the cavity. Both contribute to improving the mixing of the burned gases contained in the cavity and the incoming lean mixtures. The cavity-based combustor was experimentally investigated by laser metrology (PIV and CH*-chemiluminescence phases of the pressure signal), in order to analyze the effects of various parameters, such as the geometry of the cavity (height, width) and the fuel injection characteristics (wealth, location of the fuel channel). Recent developments in time-resolved measurement techniques (PIV, OH-PLIF) at 5 kHz repetition rates also provide additional insight into the importance of the shear layer behavior on the flame stability and flame-holding [17]. For example, the interaction of the reactive zone located in the shear layer within the flow dynamics of the three inlets of the TVC was clearly observed and studied in unstable cases (Fig. 13).

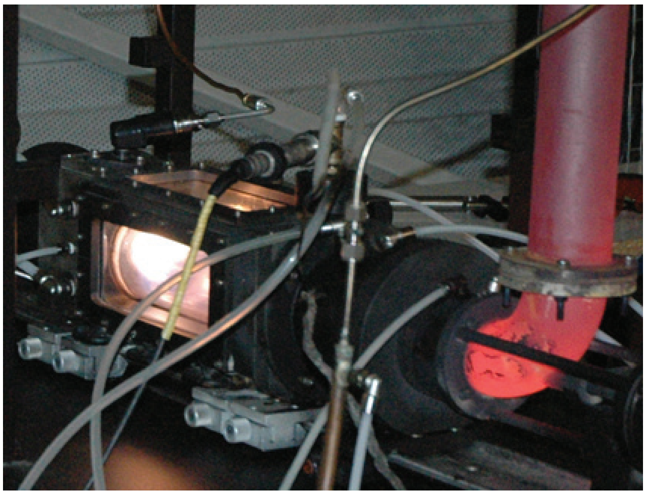


Figure 12 - Test Rig equipped with TVC combustor; Operating conditions: P_{max}=0.5 MPa, T_{inlet}=500 K, Air flowrate: 100 g/s

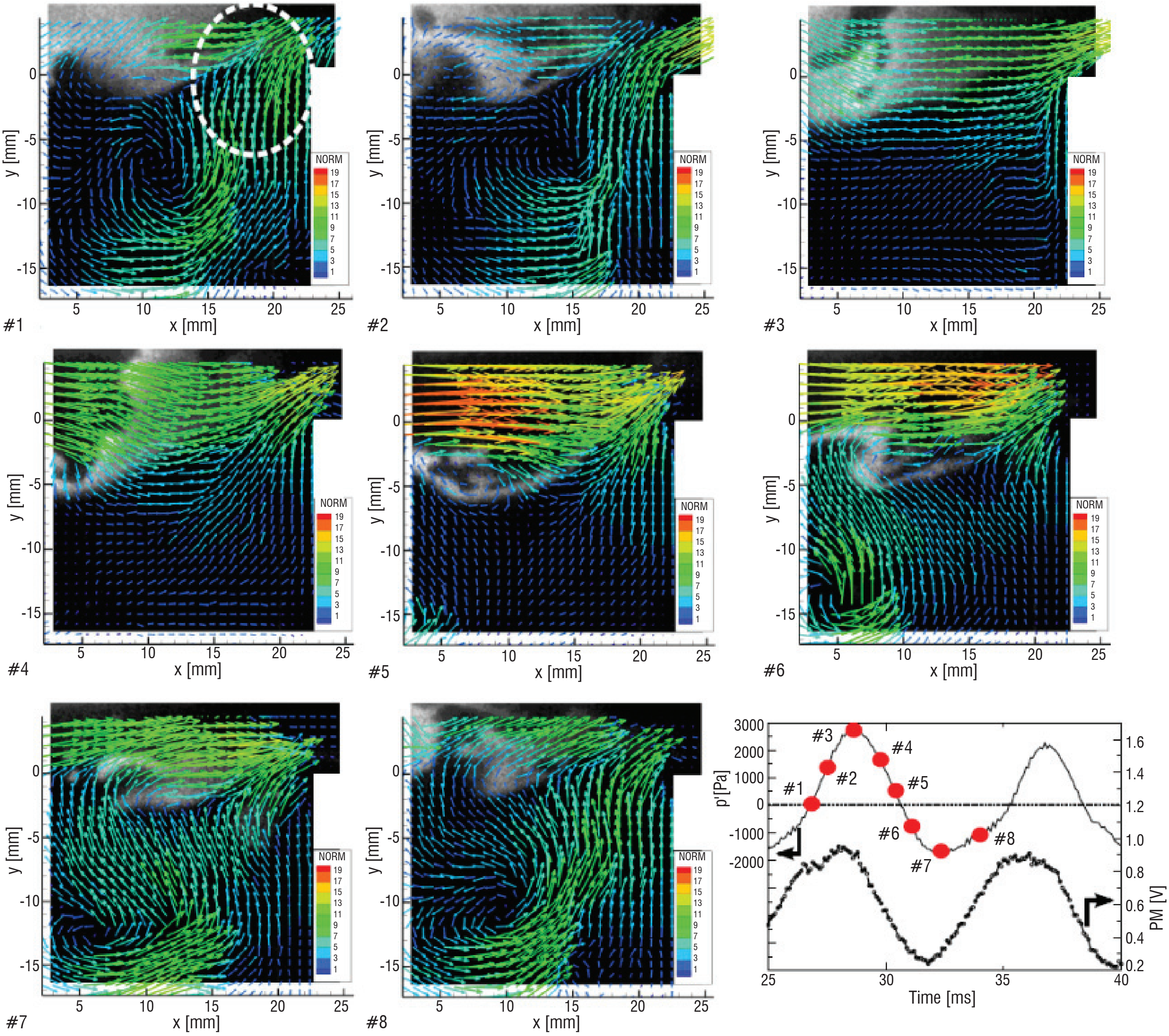
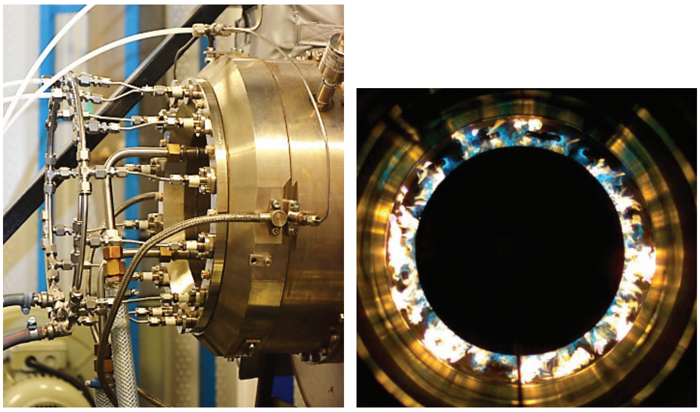


Figure 13 - Simultaneous and time-resolved PIV and OH-PLIF measurements during an unstable pressure cycle (5 kHz) and the corresponding chamber pressure and flame luminosity during the cycle. Reprinted from [17].

Annular combustion chamber (ALICE)

The purpose of the ALICE combustion facility is the development of an atmospheric test rig, in order to evaluate the performances of a real aeronautical combustion chamber (Fig. 14). The setup enables the operating conditions encountered in an Auxiliary Power Unit (APU) and observed during the ignition phase of a helicopter engine at ground level to be faithfully reproduced. Numerous sensors, such as piezo-resistive pressure and thermocouple transducers, enable the measurement of the pressure and temperature conditions inside and at the exit of the combustion chamber. The combustion chamber monitoring allows the following operating conditions: air mass flow rate between 0 and 300 g/s, air inlet temperature between 300 and 480 K and fuel flow rate between 0 and 5 g/s. A gas analyzer is also available for measuring the temperature profiles and/or the chemical composition of the exhaust gases (NO, CO, CO_2, HC, O_2).



a) b)

Figure 14 - (a) ALICE facility; (b) view of the combustion chamber during lean extinction.

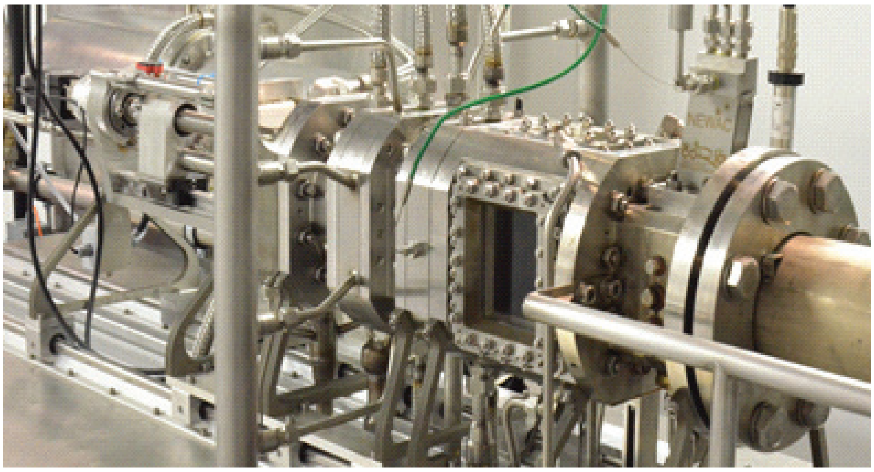


Figure 15 - High-pressure, high-temperature single injector test rig (HERON). Operating conditions: P_{max}=2.0 MPa, T_{inlet}=900K, Air flowrate=300g/s

The objectives of this test rig are mainly to:

- study the various steps of the ignition process (energy deposition, lightening around and flame stabilization) using a high speed flame imaging technique,
- define the combustion chamber stability diagram,
- determine the relevant physical and chemical parameters leading to flame blow off,
- study the effect of the combustion chamber architecture on the combustion efficiency.

HIGH pressure facility for aero-engine combustion (HERON)

Lean-burn involves inherent challenges with respect to weak extinction stability due to fuel air premixing prior to combustion and drives the development of practical solutions with respect to operability, altitude relight and combustion efficiency at fuel staging points. Lean-burn combustors require fuel staging to obtain full combustor operability and to enable typical aero-engine turn-down ratios while burning lean at high power conditions. In order to derive detailed design rules for producing low pollutant emissions, the application of non-intrusive measurement techniques is also a very key challenge within the development process. Conventional tests giving information at the combustor exhaust provide insight into whether a design is successful or not, but they do not tell why. The effort of building optically accessible combustors and probing the flame with optical techniques is thus a promising approach to contribute to the development and optimization of these injection systems [18 - 19]. In order to study such combustion concepts, the new optically accessible test rig HERON (High prEssuRe facility for aerO-eNgine combustion) was designed to operate under the severe pressure and temperature conditions encountered in ground and aeronautical gas turbines. The combustion chamber modules offer a well-adapted infrastructure to the study of industrial fuel injection systems. The combustion chamber performances are optimized to study advanced low-NOx injection systems for helicopters up to their nominal operating ranges and aero-engines injection systems up to 2/3 of their nominal ranges. A fuel preparation skid enables the injection module to be controlled and fed with liquid multi-component fuels (kerosene, biofuel, etc.) or a gaseous fuel mixture (CH_4, CO_2, CO and H_2) with well-controlled chemical composition. The pressure chamber is regulated by an adaptive nozzle up to 2.0 MPa. The mass flow and air temperature are controlled up to 300 g/s and 900 K. HERON is an optically accessible test rig enabling the investigation of a single sector of a combustion chamber. Large optical accesses (100 mm x 80 mm) have been designed, in order to apply all of the optical diagnostics developed in the CORIA Laboratory (Fig. 15).

Among the various studies performed with the HERON test rig, the characterization of innovative low-NOx injection systems (Lean Premixed Prevaporized, Lean Premixed and multi-point injection systems) was investigated. In most cases, the flames are aero-dynamically stabilized by swirl, leading to compact flames over a wide tuning range. Swirl-induced breakdown induces burned gas recirculation to the flame root and the mixing of hot gas and radicals with fresh gas leads to continuous ignition and flame stabilization. The dynamic processes of the flowfield/flame interaction governing such behavior are complex and not well understood today. However, this process can be subject to instabilities in the form of thermoacoustic pulsations, unsteady stabilization or even flame extinction. Until recently, the measurement strategies used to study such processes were commonly focused on laser-based point-wise as well as planar measurements of scalar parameters (velocity, temperature and species concentration) enabling the determination of mean and statistical variations of thermo-dynamic and thermo-chemical properties. However, several questions still remain, which cannot be answered by such temporally non-correlated single-shot information. This concerns, for instance, the origin of the local flame extinction or the evolution of coherent flow field structures and their interplay on the flame front. It is then advantageous to complement these "conventional" measurements by additional information recorded at high repetition rates allowing the tracking of specific flowfield/flame interactions. In order to promote this methodology, particle image velocimetry (PIV) and planar laser-induced fluorescence of the hydroxyl radical (OH-PLIF) were applied simultaneously at 5 kHz in the HERON test rig to study the dynamics of a lean partially-premixed turbulent swirl-stabilized kerosene/air flame from an LP injection system developed by TURBOMECA [20]. For instance, Fig. 16 shows a sequence of four consecutive images from simultaneous PIV and OH-PLIF measurements. The field of view is 60 mm x 50 mm and lies above the nozzle, as indicated in Fig. 16. The images in gray represent the OH-PLIF distributions. The vectors represent the in-plane component of velocity and the colors indicate the out-of-plane motion of the flow field. The simultaneous PIV and OH-PLIF measurements revealed that the reaction zone is

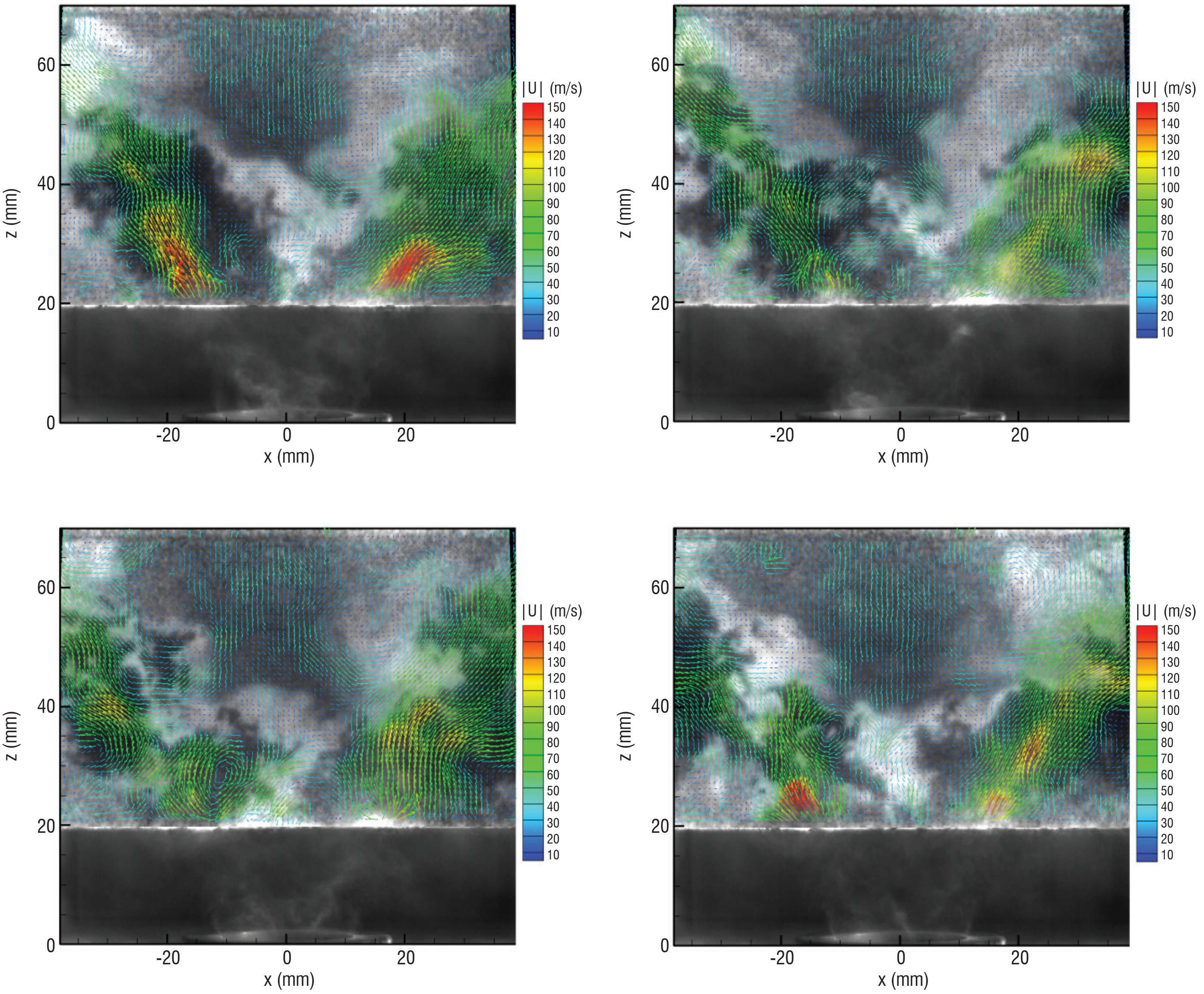


Figure 16 - Image sequence from simultaneous OH-PLIF/PIV measurements in a Lean Premixed burner at a 5 kHz frame rate. The field of view is 60mm x 50 mm. The position and shape of the nozzle are shown below the distributions. Operating conditions: P=0.1 MPa, $Qm_{air}=30g/s$, $T_{air}=473K$.

mainly located between the hot product recirculating flow within the central part of the flow and the incoming flow of fresh gas, resembling a stagnation flow flame. Furthermore, large-scale vortical structures that appear to dominate parts of the flow field and to strongly contort the reaction zone are observed.

In the near future, another laser diagnostic technique (CARS, PDA, NO-and CO-PLIF, kerosene-PLIF, etc.) will be used to provide an exhaustive evaluation and understanding of the complex underlying turbulence-chemistry interaction in the combustion chamber. Furthermore, given that the wall of the combustion chamber being is optically accessible, the wall/flame interaction will be also investigated for various boundary conditions (perforated walls, etc.), in order to quantify its impact on combustion and pollutant formation. On this basis, new innovative technological solutions will be proposed to the industrial partner, in order to improve the architecture of future fuel injection systems. Experiments will be also performed with special attention to the definition of the boundary conditions, which is of paramount importance when the data will be used to validate the combustion models and the LES simulation codes ■

Acknowledgements

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References

[1] M. Orain, P. Baranger, B. Rossow, F. Grisch - *Fluorescence Spectroscopy of 1,2,4-Trimethylbenzene at High Temperatures and Pressures: Application to Temperature Measurements*. Applied Physics B, 100, Issue 4, 945-952, 2010

[2] M. Orain, P. Baranger, B. Rossow, F. Grisch - *Fluorescence Spectroscopy of Naphthalene at High Temperatures and Pressures: Implications for Fuel-Concentration Measurements*. Applied Physics B, 102, Issue 1, 163-172, 2010

[3] M. Orain, P. Baranger, C. Ledier, J. Apeloig, F. Grisch - *Fluorescence Spectroscopy of Kerosene Vapour at High Temperatures and Pressures: Potential for Gas Turbines Measurements*. Applied Phyics B, 116, Issue 3, 729-745, 2015

[4] B. Rossow, F. Grisch - *Étude de l'évaporation différentielle carburants multi-composant par fluorescence induite par laser de traceurs aromatiques*. 14ème Congrès Francophone de Techniques Laser (CFTL) - Marseille (France) 2014

[5] C. Ledier, M. Orain, F. Grisch - *Measurement of Biofuel Vapor Concentration in Sprays Using New Planar Laser-Induced Fluorescence*. 4th European Conference for Aero-Space Science (EUCASS) - Saint-Petersburg (Russia) 2011

[6] P. Gautier, B. Barviau, G. Godard, J. Apeloig, S. Hochgreb, F. Grisch - *Détection des émissions des polluants NO et CO dans les flammes par fluorescence induite par laser (LIF)*. 14ème Congrès Francophone de Techniques Laser (CFTL) - Marseille (France) 2014

[7] Yi. Wu, V. Modica, F. Grisch - *Elevated Pressure and Temperature Effect to Laminar Flame Speed of Acetone/Air Mixture*. Proceeding of the 25th International Colloquium on the Dynamics of Explosions and Reactive Systems (ICDERS) – Leeds (UK) 2015

[8] Yi. Wu, V. Modica, F. Grisch - *Laminar Flame Speed Measurements of Multi-Component Jet A1 and LUCHE Kerosene Surrogate Fuels in Elevated Pressure and Temperature Conditions*. 7th European Combustion Meeting – Budapest (Hungary) 2015

[9] J. Jayachadran, A. Lefebvre, R. Zhao, F. Halter, E. Varea, B. Renou and F. N. Egolfopoulos - *A Study of Propagation of Spherically Expanding and Counterflow Laminar Flames Using Direct Measurements and Numerical Simulations*. Proceedings of the Combustion Institute, 35, pp. 695-702, 2015

[10] E. Varea, V. Modica, A. Vandel, B. Renou - *Measurement of Laminar Burning Velocity and Markstein Length Relative to Fresh Gases Using a New Post-processing Procedure: Application to Laminar Spherical Flames for Methane, Ethanol and Isooctane/Air Mixtures*. Combustion and Flame, 159(2): pp. 577-590, 2012

[11] E. Varea, V. Modica, B. Renou, M.A. Boukhalfa - *Pressure Effects on Laminar Burning Velocities and Markstein Lengths for Isooctane–Ethanol–Air Mixtures*. Proceedings of the Combustion Institute, 34(1): pp. 735-744, 2013

[12] M. Cordier, A. Vandel, G. Cabot, B. Renou, M.A. Boukhalfa - *Laser-Induced Spark Ignition of Premixed Confined Swirled Flames*. Combustion Science and Technology, 185, pp 379-407, 2013.

[13] D. Barré, L. Esclapez, M. Cordier, E. Riber, B. Cuenot, G. Staffelbach, B. Renou, A. Vandel, L.Y.M. Gicquel, G. Cabot - *Flame Propagation in Aeronautical Swirled Multi-Burners : Experimental and Numerical Investigation*. Combustion and Flame, 161, pp. 2387-2405, 2014

[14] M. Cordier, A. Vandel, B. Renou, L.Y.M. Gicquel - *Experimental and Numerical Analysis of an Ignition Sequence in a Multiple-Injectors Burner*. ASME Turbo Expo. 2013 GT 2013 – 94681 - 2013

[15] P. Xavier, A. Vandel, G. Godard, B. Renou, F. Grisch, G. Cabot, M.A. Boukhalfa, M. Cazalens - *Analysis of the Flame Structure in a Trapped Vortex Combustor Using Low and High Speed OH-PLIF*. ASME Turbo Expo2014, GT2014-25207, 2014

[16] P. Xavier, M. Pires, A. Vandel, B. Renou, G. Cabot, M.A. Boukhalfa, M. Cazalens - *Determination of Criteria for Flame Stability in an Annular Trapped Vortex Combustor.* ASME Turbo Expo2015, GT2015-43214, 2015

[17] P. Xavier, A. Vandel, G. Godard, B. Renou, F. Grisch, G. Cabot, M.A. Boukhalfa, M.L Cazalens - *Investigation of Combustion Dynamics in a Cavity-Based Combustor with High-Speed Laser Diagnostics*. Exp. Fluids, 57:50, 2016

[18] J. Burguburu, G. Cabot, B. Renou, M.A. Boukhalfa, M. Cazalens - *Comparisons of the Impact of Reformer Gas And Hydrogen Enrichment on Flame Stability and Pollutant Emissions for a Kerosene/Air Swirled Flame with an Aeronautical Fuel Injector*. International Journal of Hydrogen Energy, 36:6925-2936, 2011

[19] J. Burguburu, G. Cabot, B. Renou, M.A. Boukhalfa, M. Cazalens - *Effects of H_2 Enrichment on Flame Stability and Pollutant Emissions for a Kerosene/Air Swirled Flame with an Aeronautical Fuel Injector*. Proceeding of the Combustion Institute, 33, pp. 2027-2935, 2011

[20] E. Salaün, P. Malbois, A. Vandel, G. Godard, F. Grisch, B. Renou, G. Cabot, A.M. Boukhalfa - *Experimental Investigation of a Spray Swirled Flame in a Gas Turbine Model Combustor*. 18th International Symposia on Applications of Laser Techniques to Fluid Mechanics, Lisbon (Portugal) 2016

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