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# Optical Diagnostics Used at Onera to Characterize Turbulent Reactive Flows and to Validate Aero- and Rocket Engine Combustor Modeling

The reactive flows encountered in combustion systems are very complex and varied. Optical diagnostics have been a great help in improving our understanding of the physics of combustion because they can give information on the core of the flow without perturbing it. Optical measurements are essential for validating the CFD codes for reactive flows. These techniques have undergone continuous improvement so that we can now obtain 2D visualizations and simultaneous measurements of different quantities with high resolution on combustor systems operating in tough conditions of pressure and temperature. Examples of such measurements are given in this article; they concern industrial combustors as well as burners dedicated to basic research. The article also compares numerical simulations to these measurements. Optical diagnostics still need further improvements, for instance, so that they can operate in dense sprays or characterize soot particles accurately. Higher data acquisition frequency is also needed in order to better understand and remove combustion instabilities.

## Introduction

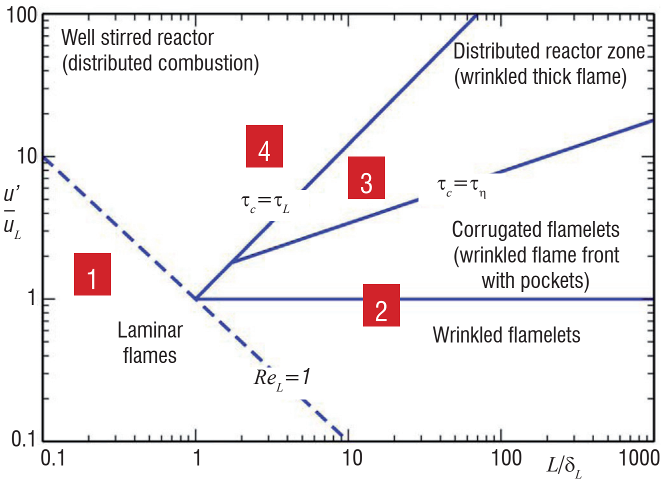
In many cases, the production of heat or mechanical energy depends on combustion devices. In order to prevent energy waste and to limit pollutant emission, it is therefore essential to improve the control of turbulent reactive flows in which heat release is produced by exothermic reactions between a fuel and an oxidizer. The physics involved in such a reactive flow are not simple because they are highly multi-scale and result from the interaction of many basic phenomena. For instance, as shown in figure 1, the interaction between turbulence and chemistry gives rise to different combustion regimes according to the ratio between their characteristic length or time scales. The Borghi-Peters diagram, [1], [2] aims to characterize these combustion regimes as a function of an integral turbulent scale ($L$ in abscissa) and the turbulence intensity ($u'$ in ordinate). For the sake of simplicity, the diagram shown here applies to premixed flames but the conclusions drawn from this diagram concerning the variety of the combustion regimes can be extended to flames that are not perfectly premixed.

Figure 1 demonstrates that very different situations are encountered in combustion systems. Moreover, physical phenomena are not limited to turbulence and chemistry. For sub-critical pressures, the fuel or the oxidizer is often introduced in the shape of a liquid phase and, for super-critical pressure, in the shape of a dense phase. If a liquid phase is present, the corresponding species must evaporate; sometimes oxidizer and fuel are premixed before introduction in the combustion chamber but, most of time, they have to mix or at least to meet each other before burning. The next step is the ignition, which is obtained by a temperature rise resulting from a heat exchange between burnt and fresh gases. Lastly, the combustion reactions must propagate to the rest of the reactants before the burnt gases leave the combustion chamber.

The physical phenomena involved in this set of events are the following:

- atomization of the injected liquid fuel or oxidizer,
- turbulent dispersion of the liquid droplets,
- vaporization of the liquid droplets,
- turbulent mixing on a small and large scale,
- complex chemistry,
- turbulent heat transfer in the core of the reactor and near the walls,
- radiative transfer between the different parts of the fluid and between the fluid and the walls.

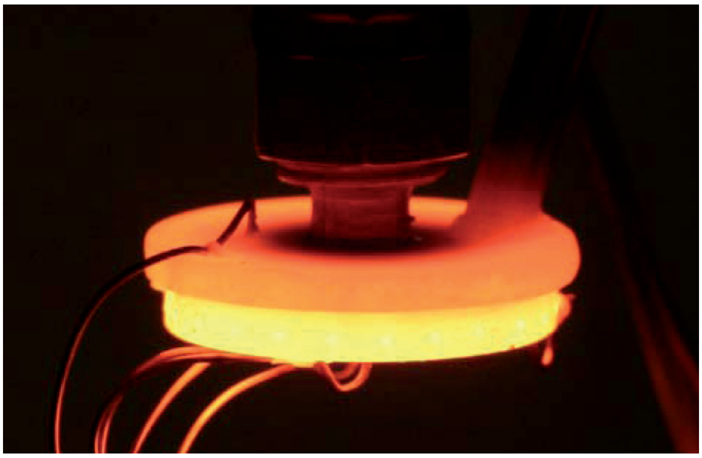
All of these phenomena are in interaction with each other. Most of the time the pressure can be considered spatially constant in the combustion chamber from the point of view of the thermodynamic phenomena such as vaporization and chemical reactions but an exception is the supersonic combustion envisioned for very high speed propulsion, which involves shock waves and expanding fans.




$L$ = integral length scale of turbulence
$\delta_L$ = laminar flame thickness
$u'$ = turbulent velocity fluctuation
$u_L$ = laminar flame velocity
$\tau_c$ = characteristic chemical time
$\tau_L$ = integral turbulent time
$\tau_\eta$ = Kolomogorov turbulent time

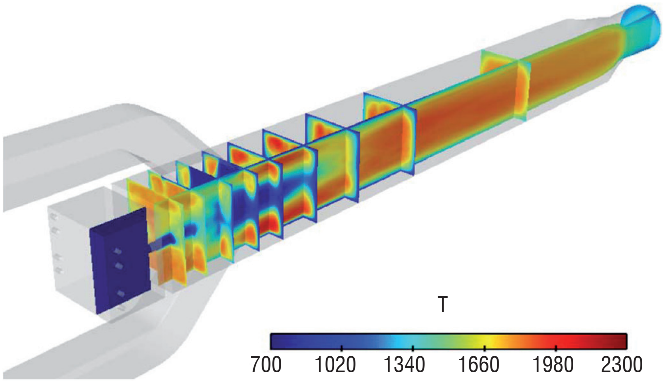
The different combustion regimes can be illustrated by the following examples:

1 Miniature combustion chamber (< 1 cm³): laminar distributed combustion



2 Bunsen flame: corrugated flame (corrugated in instantaneous pictures)

3 Ramjet combustion chamber: wrinkled thick flame in the combustion chamber downstream from the air inlets (below temperature field obtained by numerical simulation in the combustion chamber of a ramjet engine)




4 Gas turbine combustor using gaseous or prevaporized fuel: distributed turbulent combustion in the recirculations taking place in the primary zone (below the temperature field obtained by numerical simulation in a dual annular combustion chamber of a gas turbine; distributed combustion is expected behind the upper row of prevaporized fuel injectors)

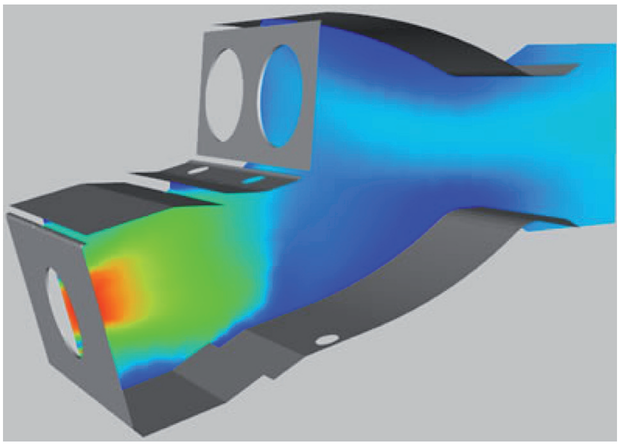


Figure 1 - Combustion regimes proposed by Borghi and Peters in terms of turbulence-combustion scales and turbulence intensity.

Despite rapid technical evolution, some improvements have still to be realized. They involve combustion efficiency, especially at transient regimes for devices with changing operating conditions, the control of combustion instabilities, the limiting of hot points on walls, the reduction of pollutant emissions to comply with more and more stringent standards for aircraft emissions, the decrease in combustor volume, maintaining a satisfactory possibility of re-ignition in the case of aeronautic gas turbines, the efficiency of thermal transfer in the case of devices producing heat, the homogeneity of the outlet temperature profile for gas turbine combustors, etc. All of these objectives can be achieved by different means. Short-term improvements are empirically obtained using global measurement techniques such as gas sampling and ex-situ analysis, applied to experiments on industrial or semi-industrial scales. To go beyond the limitations of an empirical approach, some more fundamental experiments including accurate, non-intrusive measurement techniques resolved in time and space are required. These experiments, associated with numerical simulations, are needed to understand the physics of combustion and to find intelligent and efficient solutions to combustion problems. The experiments must reproduce all the characteristic time ratios of the physical phenomena occurring in real combustors, but the geometry can be simplified in order to make possible large optical access for observation and measurements. For example, an annular chamber can be replaced by a parallelipipedic sector including a reduced number of injectors. There is an expectation for the measurement of many physical quantities, such as droplet size and velocity, gas velocity, gas temperature, concentration of major and minor species. However, the measurement of a given quantity in one given point at a given instant is not very valuable for understanding the organization of a turbulent reactive flow if this measurement is not connected to other information. A major improvement in our understanding of turbulent combustion will require instantaneous 2D visualizations, simultaneous measurements of different physical quantities and, if possible, high frequency measurements. Simultaneous measurements give access to important turbulent quantities such as the Reynolds stress tensor appearing in the Navier-Stokes equations for turbulent reactive flows. They also facilitate the understanding of the interaction between various physical phenomena, such as fuel vaporization and chemical reactions. High frequency measurements are useful to obtain the dissipation rates of velocity and concentration fluctuations. These dissipation rates have a great influence on the organization of the flow and on the consumption rate of the fuel. They can also be used to reveal instability cycles. Such time-resolved information is more and more sought after to validate unsteady simulations, such as Large Eddy Simulation (LES) or Delayed Detached Eddy Simulation (DDES). 3D or quasi 3D measurements, made possible by high frequency laser pulses, can give interesting information on the size of the structures found in the reactive flows.

Progressive improvement of optical measurement techniques leads to the possibility of obtaining more and more advanced experimental results of this type. At Onera, research teams of the “Physics, Instrumentation and Sensing” Department, on one hand, and the “Fundamental and Applied Energetics” Department, on the other hand, work together to apply these techniques to different types of combustion devices. This paper gives some examples of measurement campaigns done by advanced optical diagnostics in Onera combustion facilities, with an outline of the conclusions drawn from these measurements and the associated numerical simulations. The experiments involve combustion with air on a laboratory scale, semi-industrial or industrial scale and combustion with liquid oxygen (LOx combustion). They apply directly to aeronautics and space propulsion, except for the first one on the laboratory scale which is only for fundamental research purposes.

## Optical diagnostics applied to air breathing combustion: fundamental work

Manufacturers of aeronautic jet engines are nowadays able to make combustion chambers that take up little space and that are easier to integrate in the engine than older combustors. At full power, the combustion in these chambers is stable and the combustion efficiency is over 98 %, so no gain can be expected on this side. However, in order to reduce the fuel consumption and $CO_2$ emission, the thermodynamic efficiency of these gas turbines can be improved by increasing the pressure and the inlet gas temperature in the combustor. With the usual combustion chambers, this unavoidably leads to higher NOx emission. Indeed, NOx formation is strongly influenced by the gas temperature, the gas residence time in the zone of high temperature and the chamber pressure (see box 1). NOx formation in flames is therefore an important issue for the development of new environmentally-friendly aircraft engines. In contrast with ground combustion devices, the problem of NOx formation in aircraft gas turbines cannot be solved by post-treatment but only with new combustion chamber concepts. These NOx concerns imply the need for broad activity ranging from fundamental research to applied action.

### Unsteady $H_2$-air diffusion flame

Initially, some fundamental work was carried out at Onera in the framework of cooperation between the “Physics, Instrumentation and Sensing” Department of Onera and the Air Force Research Laboratory (Wright Patterson AFRL) concerning NO formation in an unsteady axisymmetric $H_2$-air diffusion flame [3],[4]. This flame was carefully characterized in terms of temperature by Coherent Antistokes Raman Spectroscopy (CARS) and in terms of $H_2$, O, OH, H and NO concentration by Laser Induced Fluorescence (LIF) and Degenerate Four Wave Mixing (DFWM) [20]. Thanks to the synchronization of the measurements with the movement of the periodic aerodynamic structures, it was possible to obtain the time evolution of the temperature and of the various species concentrations. Figure 2 gives the results of these measurements as well as the results of a Direct Numerical Simulation (DNS) of the flame performed by AFRL[5],[6]. This figure clearly shows that high NO concentrations do not coincide exactly with high temperature. High NO concentrations can be found in the vortices resulting from the unsteady behavior of the flame, because the residence time of the hot gases in these structures is high, while the NO concentration in the thin part of the flame is much lower due to a shorter residence time for the hot gases. One can deduce from these NO measurements that thermal NO is the major contributor to NO formation in this type of flame and that flamelet models, assuming that all the chemical reactions take place in a thin wrinkled interface, are not adequate to predict NO formation in that case. The DNS of the flame is in good agreement with the measurements overall and this combustion experiment validates the DNS technique applied to $H_2$-air chemistry. DNS of this flame was successfully carried out at Onera as well [7].

## Box 1 - NOx formation in gas turbine combustors

NOx is the designation for the nitrogen oxides, NO, $NO_2$, $N_2O$, that can be found in the atmosphere and that are created directly or indirectly by combustion devices. In practice, mainly NO is produced in gas turbine combustors, even if $NO_2$ can be found during a transient phase of combustion. Two types of mechanisms are involved in NO formation: the prompt NO and the thermal NO mechanisms [18], [19]. The effect of these mechanisms is illustrated in the following figure, taken from [18], which gives the evolution of the NO concentration in a combusting gas pocket as a function of the time spent by this gas pocket in a premixed flame (Phi is the stoichiometry of the flame):

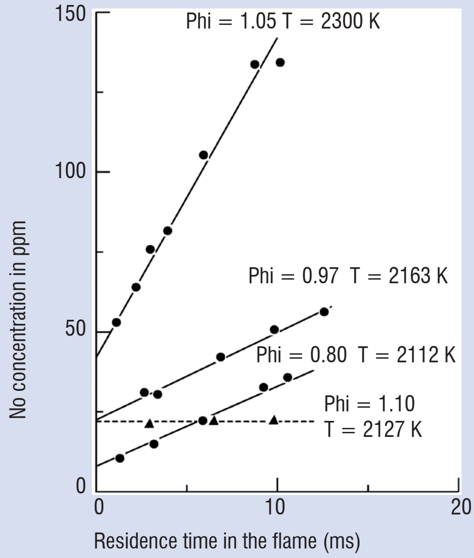



Figure B1 - 01 - Concentration of NO as function of the residence time in a premixed flame for different mixture ratio conditions; the time needed to cross the zone where the main fuel oxidation reactions take place is less than 1 ms.

The prompt NO appears quasi instantaneously when the gas pocket starts crossing the flame, i.e. it leads to non-zero concentrations of NO when the residence time is approximately zero. It can be seen that a higher Fuel-Air Ratio (FAR) results in a larger prompt NO concentration. The chemical path which leads to prompt NO is complex and includes very fast reactions involving amines and cyano compounds.

After the prompt NO has been created, i.e. as soon as the residence time becomes significant, some additional NO appears continuously during the progress of the gas mixing behind the flame. This slowly created NO is called “thermal NO”. The rate of thermal NO formation is proportional to the slope of the plotted lines of the above figure, which depends on the conditions of premixed combustion. The slope is maximal for slightly over-stoichiometric FAR (Phi=1.05) because higher temperatures, which are obtained near or just above stoichiometry, lead to larger NO concentration as long as a small amount of O radicals is available. For higher FAR, i.e. Phi=1.1, all the O radicals are consumed by other oxidation reactions and no more thermal NO is created. The thermal NO mechanism, also called the Zeldovich mechanism, is simple and is composed of the following reactions, the kinetics of which are well known:

$$O + N_2 \leftrightarrow NO + N$$
$$O + O_2 \leftrightarrow NO + O$$
$$N + OH \leftrightarrow NO + H$$

In gas turbine combustors, the residence time of the burnt gases ranges from 10 to 30 ms so that thermal NO formation is preponderant.

Optical diagnostics such as LDV or PIV are required to experimentally obtain a good estimation of the mean residence time of the burning gas and optical techniques such as CARS or Rayleigh give information on the temperature and its fluctuations which is very useful for understanding the NO formation process.

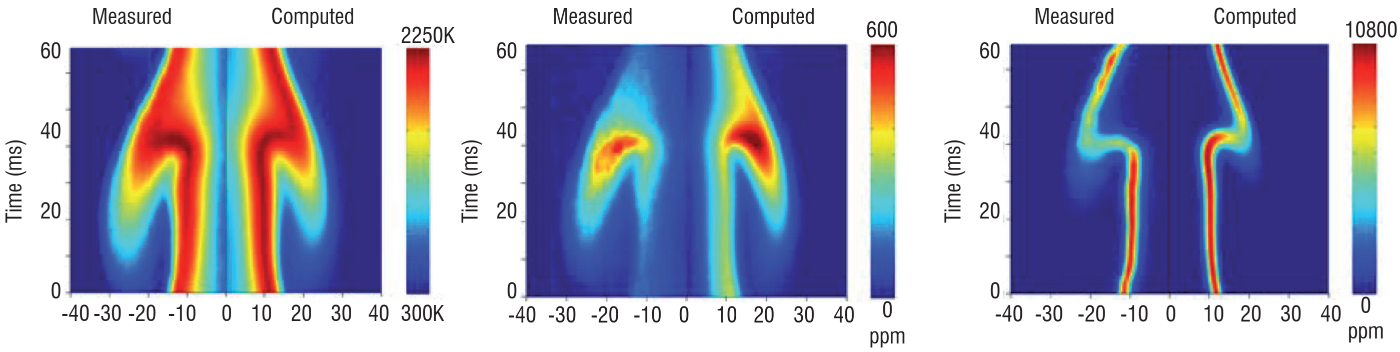



Figure 2 - Comparison of experimental and numerical time evolution at a given flame height for temperature, NO concentration and OH concentration in an unsteady $H_2$-air diffusion flame

## Turbulent premixed flame

In parallel, new combustor concepts must be developed to solve the problem of NOx emission (see box 2). Premixed combustion is a good candidate for low NOx emission but is prone to instabilities and flame flash-back. This type of combustion has been studied in the LAERTE facility of Onera [8, 9].Although the geometry of the combustor is relatively simple, the quantitative determination of the reactive flow organization requires accurate measurements provided by optical diagnostics because the size of the recirculation zone, which acts as a flame stabilizer, and the angle the flame, which influences the length of the combustor, are not imposed by the combustor geometry but are dependent on the operating conditions. The fields of temperature and velocity including averaged values and turbulent fluctuations have been obtained by Laser Doppler Velocimetry (LDV), and CARS. As shown in Figure 3, they have been used to validate an unsteady simulation of the LAERTE combustor by the DDES technique [10]. The main features of the reactive flow are well reproduced by the numerical simulations despite local discrepancies.

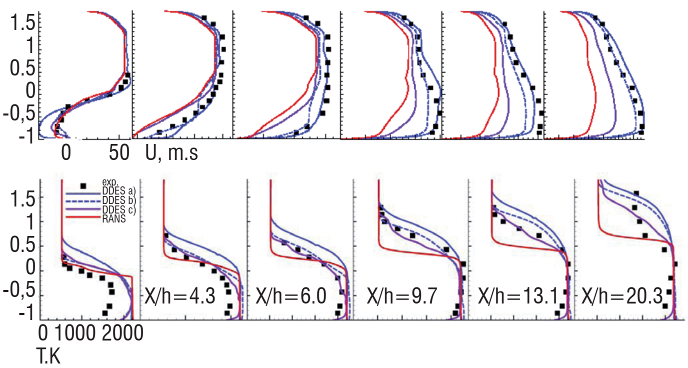



Figure 3 - Comparison of the velocity (lengthwise component) and temperature profiles obtained, on one hand, experimentally by LDV and CARS and, on the other hand, numerically by RANS and by three different types of DDES simulations.

Instantaneous 2D pictures of the flow are required to characterize the tendency of the reactive flow to instabilities and flashback. Planar LIF (PLIF) on the OH radical has been achieved to give such pictures for different operating conditions. Large OH concentrations are correlated with high combustion rates. Figure 4 exhibits snapshots of OH concentration obtained at different instants for a stoichiometry equal to 0.82 and a pressure equal to 1.35 bar resulting from a partial closing of the outlet section. The sequence of pictures reveals instabilities and intense flashback phenomena because OH radicals can be found upstream from the step corner in pictures (4) to (9). We note that some pockets of OH are disconnected from the main combustion zone. These pockets are more visible on visualizations, not shown here, performed in the cross section of the combustor. For a stoichiometry of 0.8, very close to the previous one, but with a smaller outlet obturation giving a pressure of 1.12 bar and some different acoustic impedance, the instabilities and the tendency to flashback disappear, so that instantaneous PLIF visualizations lead to pictures similar to picture (1) of Figure 4 whatever the time of the snapshot. Visualizations based on the chemiluminescence of the excited OH* radical, shown in Figure 5, could be done simultaneously with measurement of the pressure on the upper wall of the combustor at the location of the step. The PIV technique, requiring seeding of the flow with small particles [21], was also used to obtain instantaneous 2D pictures of the reactive flow velocity field. An example of the velocity field is given in Figure 5. The sequence of OH* visualizations indicates that flame flashback, which can be seen in the 2nd, 3rd and 4th snapshots from the top, starts just after a pressure drop. This tendency to flashback can be reproduced by DDES, as shown by Figure 6 displaying two instantaneous simulated temperature fields with flashback visible on the first one.

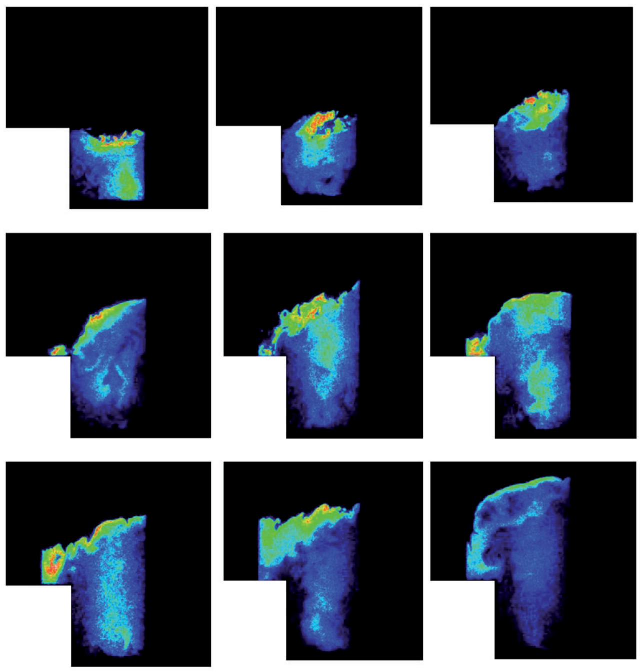


Figure 4 - Reconstructed cycle of instability from samples of OH radical visualizations by PLIF.

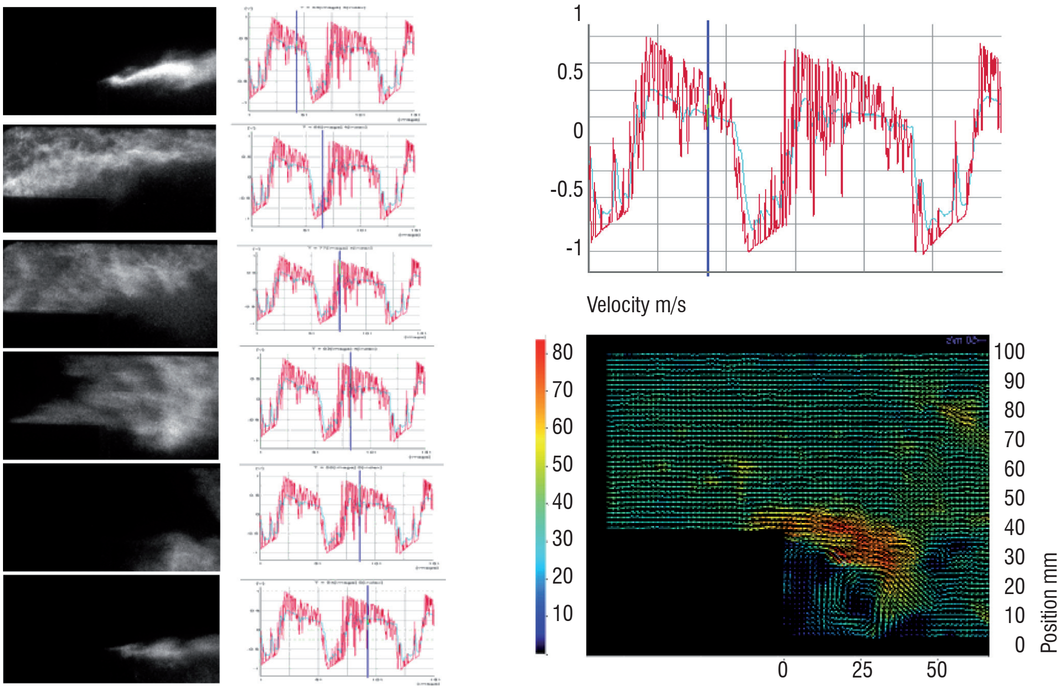



Figure 5 - Sequence of visualizations by OH* chemiluminescence around the step corner and corresponding time (blue bar) during pressure evolution (left); evolution of the pressure measured on the upper wall displayed on a larger scale (upper right); Flow visualization around the step corner by PIV (lower right).

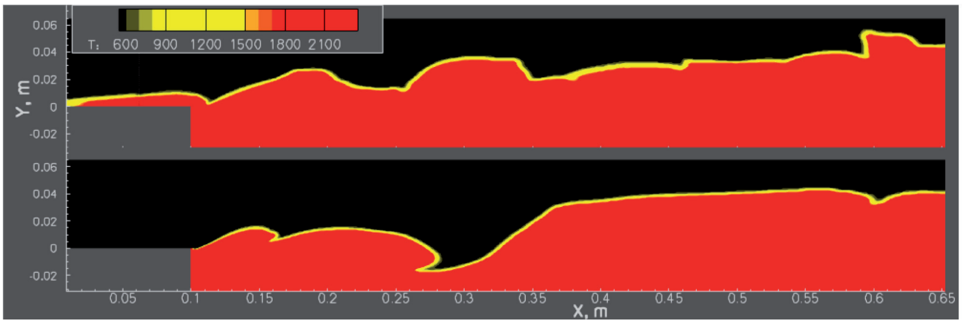



Figure 6 - Temperature fields obtained by DDES numerical simulation at two different instants.

## Optical diagnostics applied to air breathing combustion in industrial burners

### Soot measurements

Another candidate for lowering NOx emissions is the RQL concept (see box 2). In this type of combustor, the existence of an extended zone with a high Fuel Air Ratio (FAR) unavoidably leads to high soot production. For efficiency and environmental reasons, the soot must be oxidized before the burning gases leave the chamber. The soot formation is the result of a very complex process which includes different steps occurring partly successively, partly in parallel (see box 3). Non-intrusive measurements of the concentration of soot particles are not easy. Emission or absorption techniques applied to axisymmetric flames require spatial deconvolution which must be very carefully carried out and are misleading in the case of turbulent flames, since emission is integrated along the direction of the view and absorption along the laser beam [11]. The technique of Laser Induced Incandescence (LII) [22] however allow us to obtain instantaneous measurements of soot concentration. Within the framework of cooperation between Onera and DLR, this technique was applied to a turbulent ethylene-air jet flame, as shown in Figure 7, and to a semi-industrial burner equipped with a multi-point fuel injector, as shown in Figure 8. In the first case the measurements were used to validate a numerical model described in [12]. In the second case, the objective was to check that the pilot flame is not producing a large quantity of soot particles and, if any are produced, that they are oxidized within the combustor [13]. Figure 8 clearly indicates that the concentration of soot is very low and that the soot particles are correctly oxidized before the outlet section of the combustor.

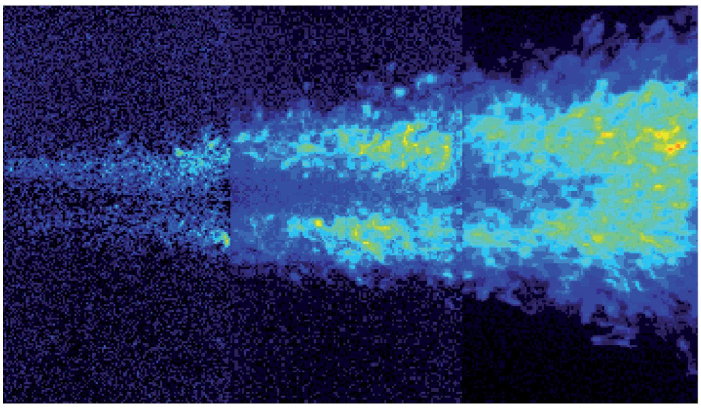


Figure 7 - Field of soot concentration in a turbulent ethylene-air jet flame obtained by LII (arbitrary scaling).

## Box 2 - Low NOx combustor technology

Conventional combustors, see Figure B2 - 01, include a primary zone with gas recirculation where the fuel-air ratio is large and the temperature is high. This primary zone acts as a flame stabilizer and allows the reactive flow ignition in high altitude conditions when the pressure and the gas inlet temperature are low. After the primary zone, the reactive flow receives some additional air in the secondary and dilution zones to complete the combustion and to lower by dilution the burnt gas temperature to a level acceptable for the turbine.

The combustor NOx reduction technology is based on the fact that (see box 1):

- NOx production requires high temperatures (> 1800 K)
- thermal NO is the largest part of the NO produced in gas turbine combustors and thermal NO is produced when the gas residence time is high,
- thermal NO production requires the presence of O (oxygen) radicals, i.e. fuel-air stoichiometry not larger than 1.1.

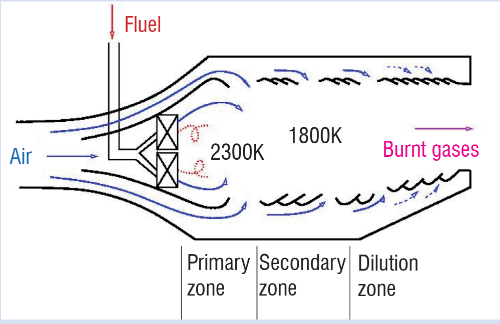



Figure B2 - 01 - Schematic view of the lengthwise section of a conventional gas turbine combustor.

A decrease in the residence time can be obtained in two-head combustors in which a part of the chamber of relatively small volume is dedicated to combustion in full power operating conditions. This type of combustor is currently used in aircraft engines of the CFM 56 and GE 90 types but is not totally satisfactory.

Limitation of the temperature resulting in low NO production can be obtained in Lean Premixed Prevaporized combustors (LPP combustors) in which the uniform fuel-air ratio prevents the reactive flow from temperature peaks. Combustion instabilities and flame flash-back are possible in this type of combustor however. Optical diagnostics are of great help to characterize the unsteady behavior of these combustors.

NOx production can also be limited by the use of Rich-Quick quench-Lean combustors (RQL combustors). In the first part of the combustor, the fuel-air ratio is very high so that no oxygen radical is available for NO production. Downstream from this zone of high fuel-air ratio, sudden dilution by air occurs in such a way that the rest of the oxidation takes place at a relatively low temperature. Optical diagnostics are used to check the complete oxidation of the reactants in the exit section of the combustor.

An example of a two-head combustor including both LPP and RQL heads is given in Figure B2 - 02.

A new concept that is now being explored consists of creating in the same volume behind the same fuel injector a small zone with high stoichiometry acting as a pilot flame and located in the axis of the combustor, and, around this pilot flame, a larger zone with a low stoichiometry, relatively homogeneous in fuel-air ratio. Good mixing between air and fuel in the low stoichiometry zone is obtained by a multi-point fuel injection device, as shown in Figure B2 - 03. Optical diagnostics are very useful for finding the best compromise between homogeneity of the reactive mixing and stability of the combustion.

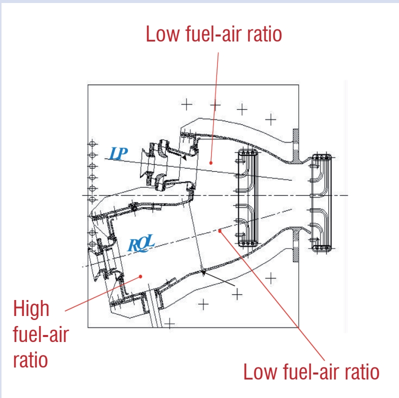



Figure B2 - 02 - Lengthwise section of a two-head LPP-RQL combustor

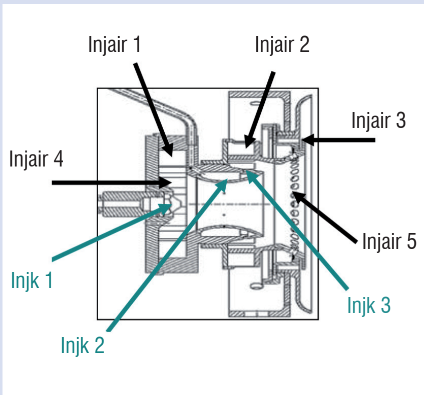



Figure B2 - 03 - Lengthwise section of a multi-point fuel injector (injk1: pilot fuel injection, injki, i=2,3: multi-point fuel injection, injairi, i=1-5: air injection)

## Box 3 - Soot formation

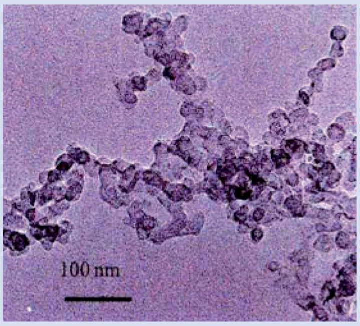
The formation of soot particles includes the following steps:

• The starting point is the reaction between small aromatic molecules (molecules including carbon rings with electron loops) which gives rise to bigger aromatics. The agglomeration of big aromatic species leads to small solid particles (size of a few nm) of approximately spherical shape containing a large amount of carbon. This is the nucleation step.

• From this point, the increase of the mass of soot mainly results from surface growth with the HACA process while agglomeration by collision between soot particles, i.e. coalescence, tends to increase the size of the particles and to decrease their number. If AnH is a soot particle with n carbon atoms and a H atom on its surface, the HACA reaction sequence is:

$$A_nH + H \leftrightarrow A_n^\bullet + H_2$$
$$A_n^\bullet + H \leftrightarrow A_nH$$
$$A_n^\bullet + C_2H_2 \rightarrow A_{n+2} + H$$

If the residence time in the reactor is large enough, the spherical particles agglomerate to form much bigger particles (a few hundred nm) of very irregular shape, as shown by this picture.




• Lastly, oxidation by $O_2$ and the OH radical tends to decrease the mass and the size of the soot particles if oxidizing species are available and if the temperature is still high enough.

The soot particles greatly influence the heat transfer by enhancing the radiative transfer in flames. For that reason, they have to be characterized experimentally. Non-intrusive optical techniques are the most convenient tools for that. However, reliable characterization of soot particles in a reactive flow is a challenge because the interpretation of the detected signals in terms of concentration or particle size depends on the optical properties of the soot particles which are not well known. Indeed the interpretation of the optical measurements requires the knowledge of the complex refractive index of the soot particles which is known with a large uncertainty. Numerical simulation of soot formation is possible: It is based on the resolution of equations giving the evolution of the soot volume fraction and soot particle number [12]. These equations include source terms taking into account the above mentioned phenomena of nucleation, surface growth, coalescence and oxidation. These simulations are difficult because they require the calculation of the concentration of the soot precursors which are minor species resulting from a complex chemistry.

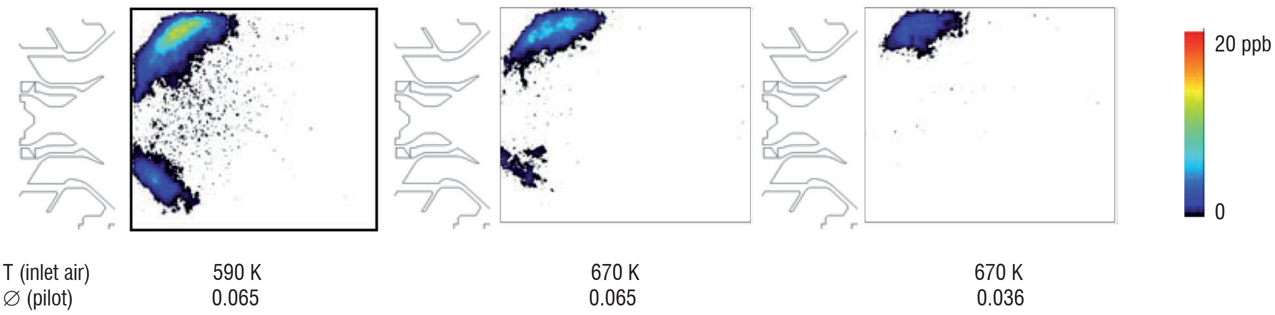



Figure 8 - Field of soot volume fraction obtained by LII downstream from a multi-point injector; pressure: 16.5 bar; global  (stoichiometry): 0.36.

### Other measurements in combustor equipped with multi-point injector

Nowadays, a large share of the work on low NOx concepts involves multi-point injection. Thanks to pilot fuel injection, the reactive flow is kept alighted even at low power operating conditions which are not favorable to combustion. In these low power conditions, the combustor is prone to CO emission and to combustion instabilities. In order to correct such possible dysfunctions, knowledge of the flow features downstream from the injector is required. The distribution of the fuel droplet size and velocity is important, especially if the experimental analysis of the combustor is completed by a numerical simulation which requires known intake conditions for the liquid fuel and fresh air. The information on fuel droplets can be obtained from Phase Doppler Particle Analyzer (PDPA) measurements, an example of which is given in Figure 9 [23]. The measurement by PDPA is similar to LDV for the particle velocity and uses the information on the phase difference between signals obtained on different detectors for the size of the particle.
This technique gives simultaneously the size and the velocity of the fuel droplets in a small probe volume but, until now, the measurements for droplets could not be done in real pressure and temperature conditions. These experimental results therefore could not be used directly in numerical simulations made in real operating conditions. However, with the PLIF technique, it was possible to achieve, in real conditions, simultaneous visualizations of the kerosene vapor and the OH radical. Kerosene vapor is detected through the fluorescence of monoaromatic and diaromatic species selected by an appropriate laser wavelength (266 nm). These visualizations show that combustion takes place in a widely open region slightly shifted downstream with regard to the vaporization zone, as shown in Figure 10. Information deduced from PLIF visualizations was used to adjust the inlet conditions concerning fuel droplets in numerical simulations. The left part of Figure 11 exhibits the experimental OH concentration field obtained just downstream from the injector and the right part exhibits the temperature field obtained by a 3D numerical simulation. The opening of the combustion region downstream from the injector is similar in the experiment and in the calculation. The correct numerical result can be obtained only after adjusting the initial diameter of the injected fuel droplets. It should be noted that visualizations can be achieved at pressures as high as 22 bar [14].

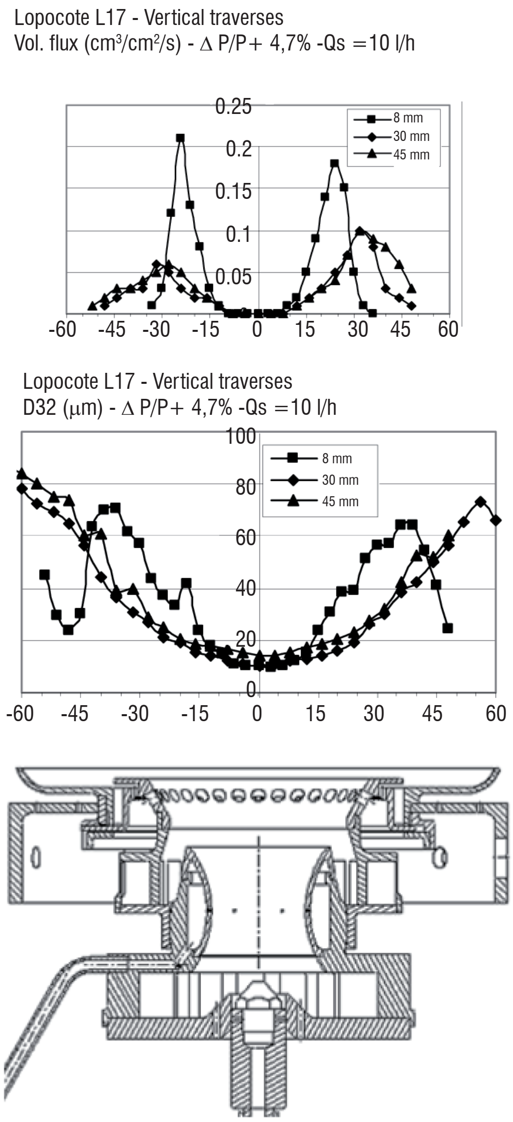



Figure 9 - Profiles of mean Sauter diameter (D32) of droplets and liquid flow rate behind a multi-point injector (profiles obtained by PDPA).

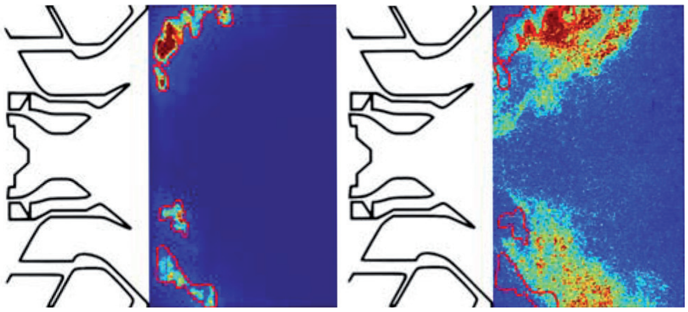


Figure 10 - Simultaneous PLIF visualization of the kerosene vapor (left) and of the OH radical (right); the OH visualization is completed by the contour indicating the presence of kerosene vapor; inlet temperature: 590 K, operating pressure: 9.5 bar.

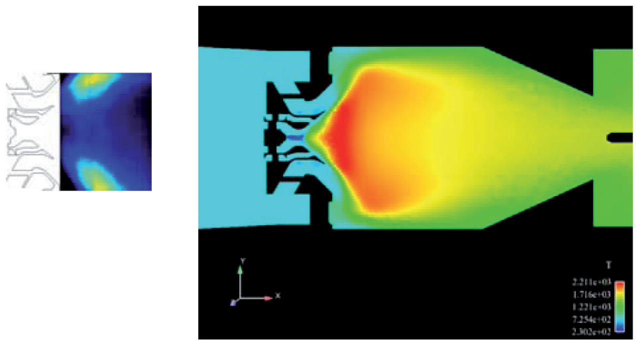


Figure 11 - PLIF visualization of the averaged OH concentration (left) and temperature field obtained by numerical simulation (right).

### Combustion with liquid oxygen

Liquid oxygen (LOx) associated with a liquid or gaseous fuel such as hydrogen, methane or kerosene is often used in rocket engines to obtain a good specific impulse. In fact, if the LOx is really liquid during the short transient phase of the engine ignition, the pressure increases rapidly to frequently reach a level much higher than the critical pressure of oxygen. For example, the operating pressure of the Vulcain 2 engine is 115 bar while the critical pressure of oxygen is 50.4 bar. 2D optical visualizations are of primary importance for characterizing the mixing between the dense oxidizer generally injected in the center of a co-axial injector and the fuel injected in the periphery of the oxidizer jet. As can be seen in Figure 12, shadowgraph visualizations [24] of such flows [15], although they are not spatially resolved in the observation direction, show the difference of behavior between sub-critical and trans-critical conditions (trans-critical in the sense that the pressure is higher than the critical pressure but the LOx injection temperature is lower than the critical temperature, equal to 154.6 K for oxygen).

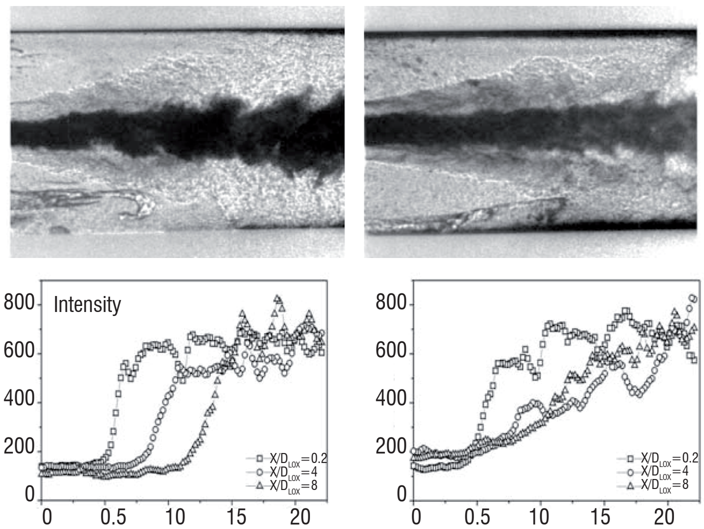



Figure 12 - Flow visualization by shadowgraphy and corresponding radial profiles of light intensity, (left) P=30 bar, (right) P=60 bar.

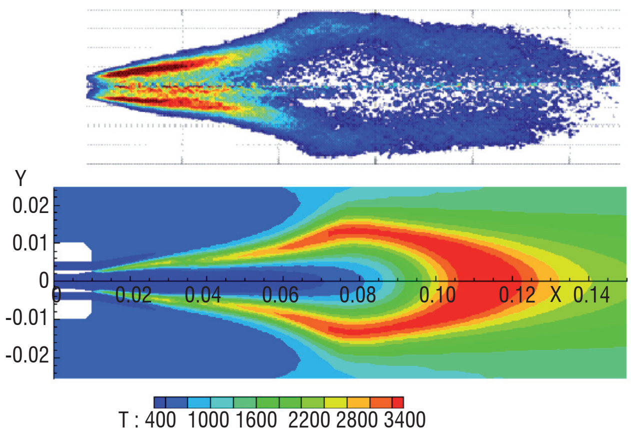



Figure 13 - Flow visualization by emission of OH* obtained after Abel transform in transcritical conditions (top); temperature field obtained by RANS numerical simulation (bottom) in the same conditions.

In the sub-critical case the region located around the injector axis and occupied by oxygen is totally dark without any gradient of light intensity while, in the trans-critical case, a zone of smooth gradient separates the dark region occupied by oxygen and the bright region occupied by hydrogen. That means that, at 60 bar, density gradients are present in the core of the oxygen jet. Moreover, the structures appearing at the periphery of the oxygen jet indicate the development of a usual liquid-gas shear layer at 30 bar but of a one-phase like mixing layer at 60 bar. These observations suggest that, in sub-critical conditions, the combustion rate is limited by the vaporization rate which depends directly on the size of the liquid droplets created by atomization of the liquid oxygen, whereas, in sub-critical conditions, it is limited by the oxygen-fuel mixing, which seems relatively intense on a large scale but can be much slower on a small scale. As for air breathing combustion, useful visualizations can also be obtained by LIF or from spontaneous emissions of excited radicals [16]. Figure 13 gives an example of visualization by spontaneous emission of the OH* radical and the temperature field obtained by numerical simulation in the same operating conditions [17] (case A60 of MASCOTTE [15] experiment). It appears that the structure of the flame is correctly reproduced by the calculation.

## Conclusion

Continuous improvement is necessary to adapt optical diagnostics to the demands of the scientific community for combustion, i.e. more and more stringent requirements concerning the quality of the information provided by the diagnostics as well as adaptability to the tougher operating conditions of combustors, such as higher pressures and stiffer temperature and concentration gradients. It is not even enough that the measurements are resolved in space and time; in addition, understanding the complex physics of turbulent reactive flows requires 2D visualizations and simultaneous measurements of several physical quantities. The use of 2D lasers associated with different synchronized detection devices gives us the possibility of highlighting correlations existing between various physical phenomena in reactive flows. For example, simultaneous kerosene-OH LIF measurements have shown that, in a multi-point combustor, a large opening of the flame zone was the consequence of the particular location of the vaporizing kerosene region. The fact that these measurements are now possible under high pressure conditions greatly enhances the benefit of the experiments. However, some additional improvements of optical diagnostics are expected. They involve measurement of sprays, soot particles and other minor pollutant species in the real operating conditions of industrial combustors. In dense sprays, the absorption of the laser beam or sheet, higher than in a pure gas, is problematic. With regard to soot particles, the reliability of the results must be improved through better knowledge of the optical properties of the particles. Also, the possibility of higher frequency measurements could help to analyze instabilities which may appear in combustion devices, especially when new concepts for low NOx emission are tested ■

**Acknowledgements**

We thank our colleagues of the DMPH and the DEFA for their help and for providing documentation.

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**Acronyms**
CARS (Coherent Antistokes Raman Spectroscopy)
LIF (Laser Induced Fluorescence)
DFWM (Degenerate Four Wave Mixing)
DNS (Direct Numerical Simulation)
LAERTE (LAboratoire des Ecoulements et de leurs Techniques d'Etude - Reactive flows and their research techniques laboratory)
LDV (Laser Doppler Velocimetry)
DDES (Delayed Detached Eddy Simulation )
PLIF (Planar LIF)
FAR (Fuel Air Ratio)
LII (Laser Induced Incandescence)
DLR (Deustches Zentrum fur Luft und Raumfahrt (German Aerospace Center))
PDPA (Phase Doppler Particle Analyzer)
RQL (Rich-Quick quench-Lean)
PIV (Particle Image Velocimetry)
LES (Large Eddy Simulation)

## AUTHOR

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