

# Time-resolved OH-PLIF in laser ignition applied to lean premixed preheated methane-air flames

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## Abstract

The minimum ignition energy required for laser supported spark as a function of inlet temperature and inlet flow rate for air-methane mixture has been studied with an OH-PLIF system. The second harmonic of a Nd:YAG laser is focused with an anti-reflection coated lens of 200mm focal length and the development of the flame kernel is measured with the OH-PLIF system at different time after the creation of the plasma. Preliminary tests are concerned with the creation of the spark at different inlet temperatures and the results obtained are in good accordance with previous publications. Afterwards, initial stages obtained with OH-PLIF show the predominance of the spark energy on the formation of the flame kernel, whereas latter times are investigated to measure the probability for ignition as a function of spark energy. The minimum of ignition energy (M.I.E.) is then deduced for the different conditions and a global balance is proposed concerning the total energy required for ignition a function of equivalence ratio.

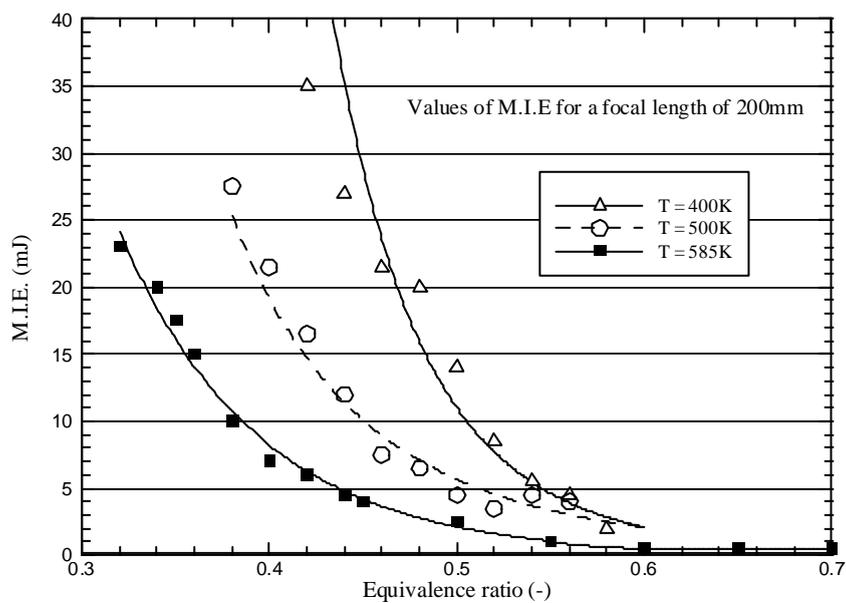


Fig. 1 Minimum Ignition Energy for flow rate of 500Nl.min<sup>-1</sup>

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## 1. INTRODUCTION

In order to reduce emission from gas turbines, an attractive solution is the lean premixed combustion. To achieve ultra low NO<sub>x</sub> and avoid strong oscillations, the mixture is usually preheated, allowing burning leaner mixtures. However, an important parameter is the ignition of such facilities that may require high energy. Traditional systems, using electrodes, will induce some heat losses and the discharge of high current may introduce some interference to the monitoring devices. An alternative solution to standard electric spark is the use of pulsed laser, focused to create plasma, which will, among other advantages, avoid the heat loss at the plug. This is the so-called laser ignition. One may decompose the laser ignition into two main subjects. The first one is the spark creation due to the local deposition of energy. This can be achieved in any gases, such as air for instance. The evolution of the plasma itself can be investigated in details using ICCD cameras with a very short gate, like reported in (Chen et al., 2000b). Breakdown is associated to the plasma formation and a shock wave. Recent studies using He-Ne laser have shown the dynamics of the spark, the plasma and the shock wave (see Phuoc and White, 2002). The second is the ignition itself that is the balance between the deposited energy and the losses. If this balance is positive, a flame kernel can develop. Many studies have already been reported concerning levels to ignite mixture in vessels (Phuoc and White, 1999) or laminar flow (Beduneau et al 2003). The effect of pressure has also been reported (Kopecek et al. 2003) as well as the number of simultaneous ignition points (see Phuoc, 2000a) and the influence of focal length used to achieve breakdown (Beduneau et al. 2003). However, very little attention has been drawn on the temperature effect of the mixture for ignition. Increasing temperature will increase the energy required to achieve a breakdown, as density is lowered (see Beduneau and Ikeda, 2004). On the other side, an increase in inlet temperature increases the laminar burning velocity, and less energy should be required to successfully achieve ignition. However, not only global quantities such as the minimum to achieve ignition is interesting but also the temporal development of the flame kernel for different energies and equivalence ratio. It is possible to use high-speed schlieren techniques (Beduneau et al. 2003) to access the kernel dynamics. In this case, a single event can be followed in time. Using time-series OH-PLIF (Dreizler et al., 2000) may yield quantitative information if a proper calibration is done between OH PLIF signal and OH concentration and here also a single event may be followed. The present paper focuses on the effect of inlet temperature and mixture flow rate in a turbulent swirl with premixed methane-air. To determine whether ignition occurred, a planar laser induced fluorescence technique is applied to OH radicals. Detecting OH radicals some time after the plasma is a consequence of ignition event, as OH emission is observed 1ms after the spark only in cases of successful events of ignition (Phuoc et al. 2002) whereas for shorter time, all sparks lead to emission of OH. Time resolved measurements also enable to understand the mean dynamics of the flame kernel. The first part of the paper presents the experimental facility. Afterwards, results obtained for the plasma alone are briefly described and compared with literature. The third part deals with the description of typical ignition and non-ignition event as seen through time series. The fourth part deals with the MIE (Minimum Ignition Energy) as function of inlet temperature, equivalence ratio and flow velocity. Finally, conclusions are drawn and some perspectives are described.

## 2. EXPERIMENTAL FACILITY

To evaluate properly the influence of temperature and flow rate, a low-swirl type burner is used (see Bedat and Cheng, 1995). Four secondary air injections may be used to stabilize the flame without recirculation zone. In the present study, only the ignition characteristics are of interest; therefore, the secondary swirl injection is set to zero to yield a turbulent jet, as shown in Figure 1. The ignition is done in a turbulent premixed combustor in which both turbulent levels as well as inlet temperature can be changed. LDV measurements as well as PIV measurements are used to determine the exact turbulent levels as well as the mean velocity profile for the different test cases investigated here. The laser-induced plasma (obtained using the second harmonic of a Nd:YAG at 532nm, New Wave Research, double cavity, maximum output of 120mJ per pulse) is always located in the center and 4 cm above the exit of the burner in the centerline. To change the turbulent characteristics, different punching plates can be used, having each a different blockage ratio. In the

present experiments, only the plate with 60% of blockage (holes of 2mm and a pitch of 3 mm, second from left on Figure 1) is used. The extension length  $L$  is set to 60mm. Energy meters are used both at the exit of the laser and after passing through the combustor to determine exact deposition of energy via a proper calibration. The validity of this procedure has been discussed in (Phuoc and White, 2000) as the losses due to diffraction are negligible and the attenuation of the laser energy can be attributed to the absorption of the spark only.

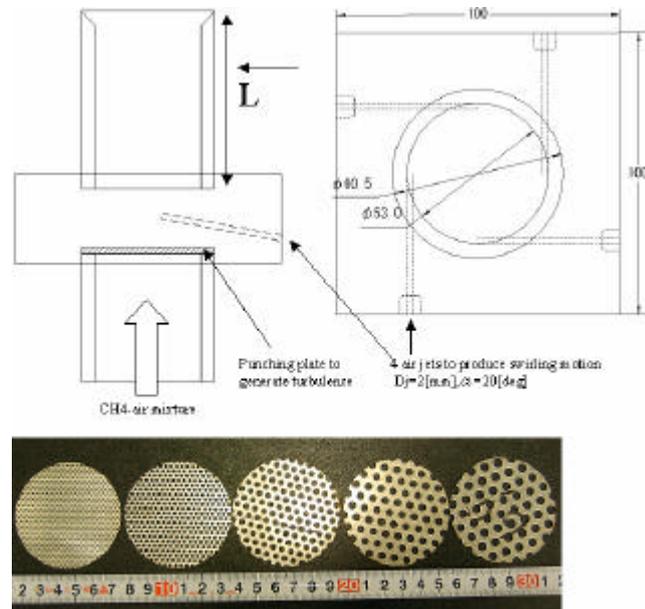


Figure 1 Sketch of the combustor

The PLIF system is composed by a Spectron Laser Systems model SL 825G-400 mJ together with a dye laser Spectron Laser Systems – 4000G (Rhodamine 590) which output wavelength was set to 283.6386 nm to excite OH transition. For this excitation wavelength, the transition A-X(1,0) and (0,0) are obtained and the typical emission is from 306 to 320 nm. To maintain sufficient energy to the OH-PLIF laser, an auto-tracker is used to maintain the KDP crystal under constant temperature and adjust the angle of the laser to have typically 20mJ issued from the frequency doubler. An ICCD (Princeton Instruments 576G/1) is used to capture the images of PLIF, with an UV-Nikkor 105mm/f4.5 lens. Its resolution is 1024 by 1024 pixels and typical measured area were 50mmx50mm, which gives a magnification 0.05 mm<sup>2</sup>/pixel. It is used in gate mode with an exposure of 100ns, synchronized with the pulse of the dye laser to minimize background emission. For each shot of Nd:YAG, only one pulse of the OH-PLIF system will be acquired, not as reported in Dreizler et al, 2000, where they could study the propagation of one single event with multiple shot. However, the experiments are reproducible and the shape is self-similar for a given class of energy of the spark. Therefore, a temporal evolution can be measured through multiple events simultaneously measuring the energy of the spark. The actual energy of each pulse is measured to yield quantitative information from the OH-PLIF images. The energy meters are Ophir PE25-SH type for high output energy measurements. The Nd:YAG laser is used in single cavity mode and the Q-switch delay is always set to 180µs. Changing the Q-switch delay will change the typical shape of the laser pulse and therefore will strongly modify the energy required achieving plasma, as the total irradiance will be modified. Therefore an attenuator is used to vary the output energy of the laser pulse.

### 3. PRELIMINARY RESULTS FOR GASEOUS BREAKDOWN

The first tests consist in measuring the levels of energy required to achieve breakdown as function of inlet temperature. Breakdown (and hence plasma formation) is achieved when the density of energy at the focal point is higher than a threshold (Ma et al., 1998). The levels will hence depend on wavelength, focal length (see Phuoc, 2000b) and of pulse shape as the main physical parameter is the irradiance (see Chen et al. 2000). For this study, only one focal length is considered: 200mm. This lens is an achromat lens to minimize aberrations at 532nm (sigma Koki NADL-30-200PY2). The effect of lens focal length has already been reported (see Beduneau et al., 2003 for instance) and therefore is not the subject of the present investigation. Experiments are carried out with a flow rate of 663 Nl.min<sup>-1</sup>, which corresponds to a velocity of 5 m.s<sup>-1</sup> at the exit of the burner for this set of measurements, as well as a total flow of 500 Nl.min<sup>-1</sup>, which corresponds to a velocity of 3.8 m.s<sup>-1</sup>.

The levels required to achieve breakdown are reported in Figure 2, where one can notice an overall linear dependence with the temperature, which was expected. The reason is that the density is inversely proportional to the temperature. To

furthermore explicit this behavior the typical time required for breakdown can be computed as function of the ratio between the spark energy and the energy  $E_0$  required for breakdown to occur at the given temperature.

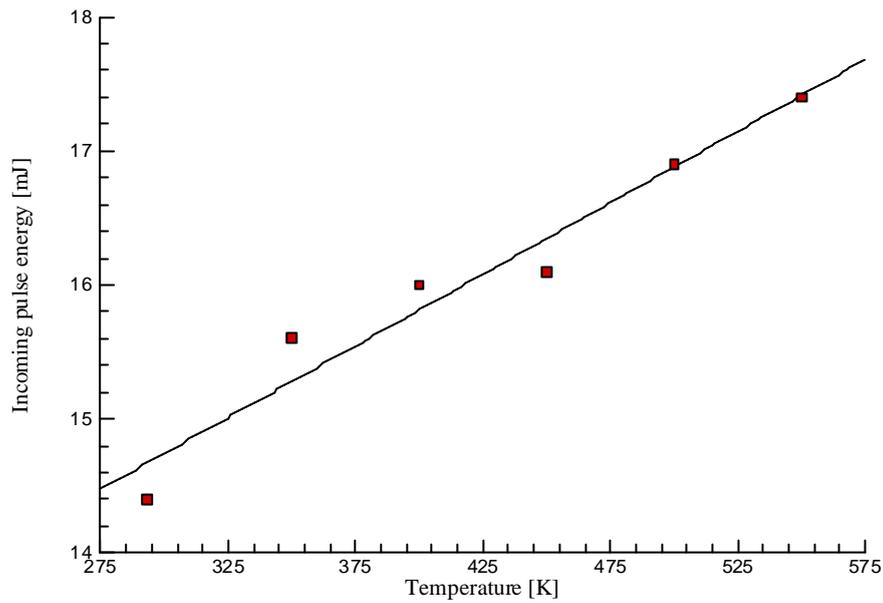


Figure 2 Breakdown levels as function of temperature

To compute such a time, the assumption of a Gaussian profile for the laser beam is made. The time for which the energy of the laser equals the total energy of the spark is taken as this breakdown time. The results are shown in Figure 3 for three different temperatures only. The energy is normalized by the energy obtained in Figure 2. One can notice a self-similar profile as far as the breakdown time is achieved when compared to this normalized incident energy. This kind of results illustrate that the effect of temperature lower than 600K has a linear influence on breakdown. This kind of results illustrate that the effect of temperature lower than 600K has a linear influence on breakdown.

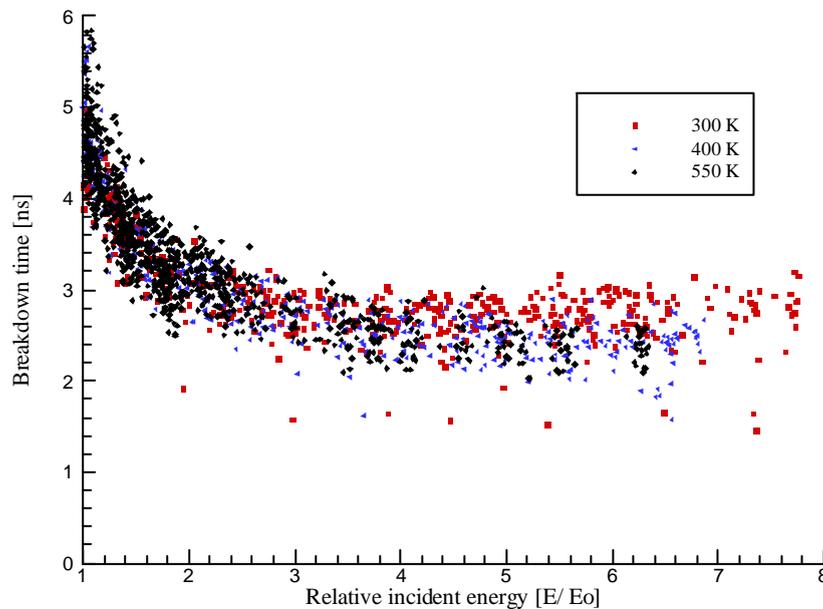


Figure 3 Effect of temperature on breakdown time

#### 4. TEMPORALLY RESOLVED OH-PLIF RESULTS

#### 4.1 Influence of spark energy on shape of the initial flame kernel

To emphasize the fact that at the early stages only the spark energy is of importance, different energies have been acquired, keeping the equivalence ratio constant. Typical results for an inlet temperature of 400K, a flow rate of 500NL.min<sup>-1</sup> and a stoichiometry of 0.40 are presented in Figure 4. The laser comes from the left to the right. The mean images obtained for energies of 2, 5, 10 and 20mJ are computed. The location of the 0 in the x-coordinate is chosen as being the position of the spark obtained with the lowest energy. All four kernels do present horizontal symmetry and the center is the initial location of the spark. However, the influence of the laser spark energy is quite obvious based on those results. An increase of the spark energy will immediately result in an increase of the initial flame kernel. The reason is that all molecules within the initial plasma will be heated up and therefore will participate to the combustion process. Another interesting information is that the location of the ignition point tends to be closer to the laser with an increase of the energy as one can notice that the center of the flame kernel is 1.5mm closer to the laser in case of 20mJ than in case of 2mJ. Furthermore a region of OH is seen before the symmetrical kernel. Its position moves towards the laser with an increase of spark energy while its intensity is increasing. This type of secondary flame has already been observed (Spiglanin et al., 1995) and with high-speed schlieren technique (Beduneau et al., 2003) as well as in (Bradley et al. 2004). The reason may be that a greater energy is absorbed by the gas at the leading edge of the plasma. As the plasma becomes almost opaque to the incident light, the trailing edge part can not absorb as much energy. The shock wave generated by the plasma discharge leaves behind it a region of hot gases (lower density than the surroundings). Therefore, hydrodynamics effects will induce a movement towards the inner side of the plasma and this will generate the discharge of hotter gases as detected by OH-PLIF measurements.

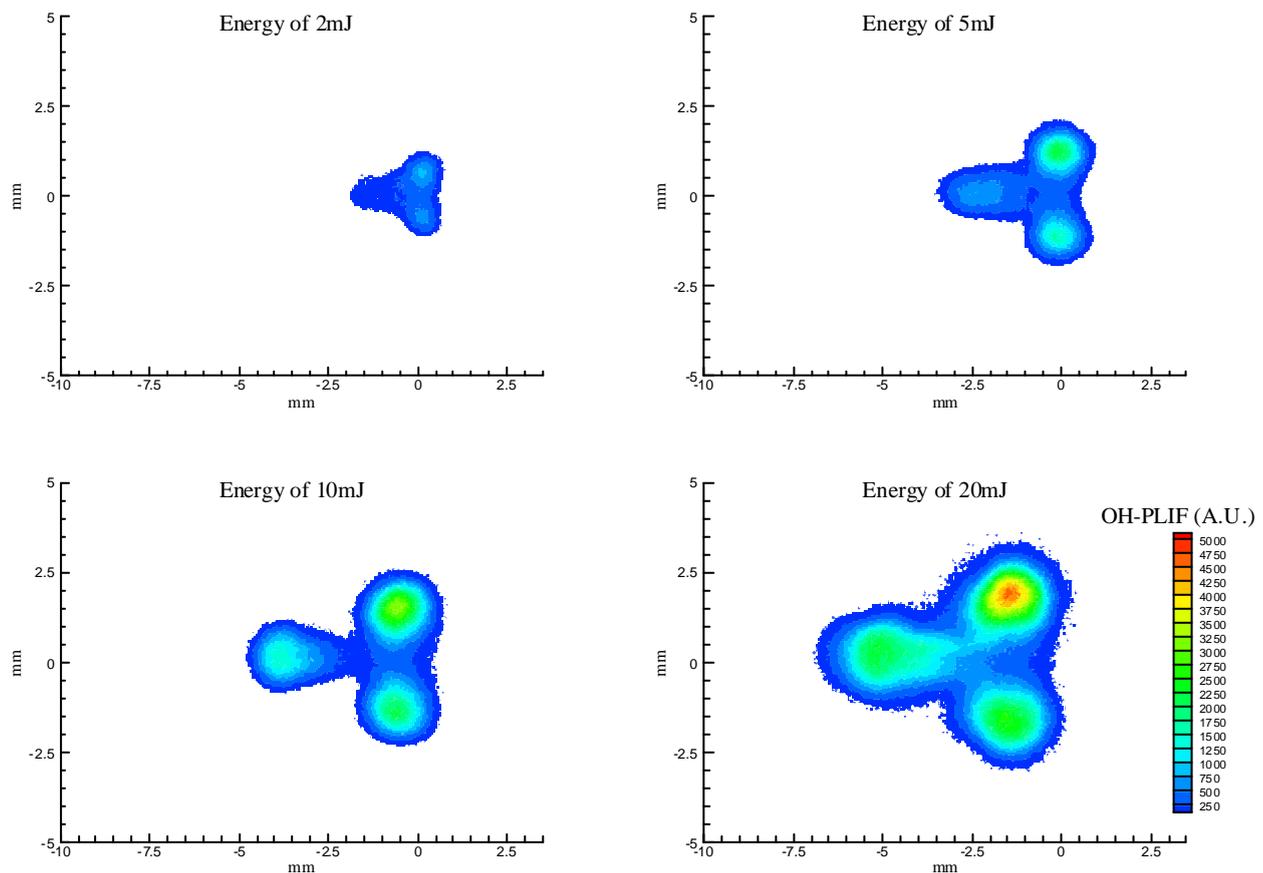


Figure 4 Influence of spark energy at initial stage (100µs) for  $T_{in}=400K$  and  $E.R.=0.40$

The evolution of the size versus the initial energy is depicted in Figure 5. The size is taken as being half the size of the flame kernel. For instance, in the case of a 20mJ spark, one can see that OH is detected for vertical position ranging from -3.1 to 3.2mm. Therefore, the size represented in Figure 5 will be 3.1mm. That information clearly shows the influence of the spark energy at the initial time in a laser ignition process. However, it is important to understand that at this early stage, even an energy that is not able to successfully ignite the mixture will create radicals. The further development and the balance between heat losses and heat release due to chemical reactions is of crucial importance for the flame kernel.

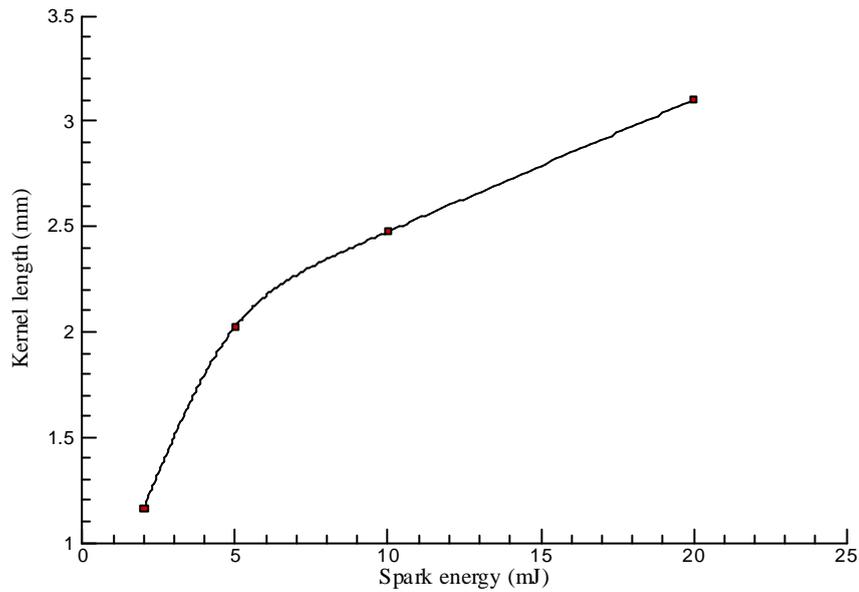


Figure 5 Initial kernel size as function of energy for  $T_{in}=400K$  and  $E.R.=0.40$

#### 4.2 Time series

For determining successful ignition events, an OH-PLIF system is used. Time-resolved OH-PLIF images are taken by adjusting the delay between the plasma creation and the PLIF laser shot. As each time, the energy of the spark is measured, classes of spark can be derived and the mean evolution of the flame kernel for a given energy can be discussed with at least 50 images in the class reported in the present article. Comparing two instantaneous images for a similar class showed almost no differences and therefore the time history is displayed even though it was acquired through different ignition events. This allows a temporally resolved flame kernel evolution, as shown in Figure 6.

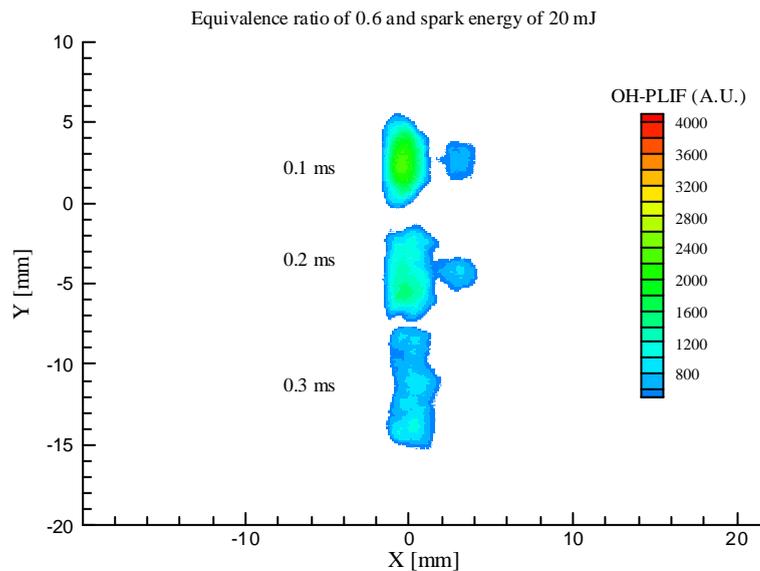


Figure 6 Temporal evolution of the flame kernel

For clarity reason, the kernel has been shifted vertically to allow the comparison. In the present case, the laser comes from right to left. One can notice that at early stages, two regions exhibit high intensity of OH. The first one, which is the

main flame kernel centered at 0mm. The other region is closer to the laser. This is a pocket of burnt gas that was ejected at early stages as this side of the flame corresponded to a low density of air, due to the laser beam. It is also interesting to notice that this secondary pocket seems to have a high initial velocity, as it is located about 3mm from the focal point after only 0.1ms. However, it does not seem to evolve as it is detected at the same position at 0.2ms after the pulse shot. Finally, for this energy of spark (20mJ) and a low equivalence ratio (0.6), after 0.3ms, only the main flame kernel subsides. It is propagating towards and with the incoming flow (vertically) in a symmetric way.

#### 4.2 Flame expansion

As time series data are taken, it is possible to measure the typical flame shape as function of time, energy and equivalence ratio. Typical results obtained showed that the spark energy has a strong influence even 1ms after its creation in the development of the flame kernel. The results shown in Figure 7 are taken for an inlet temperature of 400K and flow rate of 663 Nl.min<sup>-1</sup>. The results are based on the analysis of the images taken 1ms after the laser pulse. The spark energy is the energy has measured by the power meter whereas the flame kernel size is the size of half the flame (as it is symmetrically propagated in a vertical direction). The average image is computed for each class of energy (2,5,10,15 and 20mJ respectively) and the position of the OH signal in this mean image is measured for stoichiometry ranging from 0.50 to 0.70. One clearly notices the influence of the spark energy independently of the equivalence ratio chosen. The other important information is that one can also clearly detect the influence of the equivalence ratio as lower equivalence ratio will tend to spread less fast due to a lower flame speed velocity.

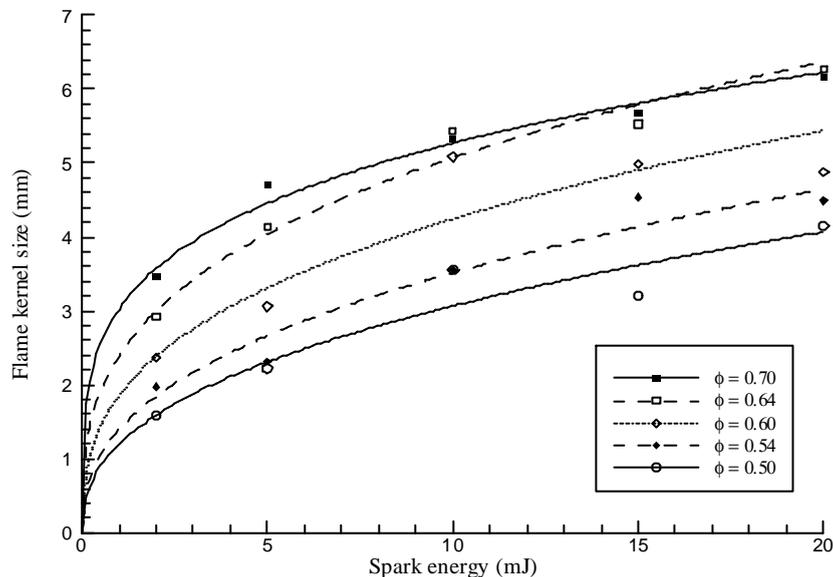


Figure 7 Flame size as function of spark energy and equivalence ratio ( $T_{in}=400K$ )

### 5. MINIMUM OF IGNITION ENERGY RESULTS

To confirm ignition, the signal taken with an adjusted delay of 1.5ms between the plasma and the OH-PLIF signal is considered. In the presence of a flame front propagating, the event is considered as successful ignition. For each condition, about 300 images are taken and afterwards sorted in spark energy. Each individual image is treated to see if ignition occurred and for each class of energy (from 0.5mJ with an interval of 0.5mJ), the total number of ignition is computed. Typical examples are given in Figure 8. The initial temperature is 585K and the flow rate is 500 Nl.min<sup>-1</sup>. Two different equivalence ratio are displayed: 0.38 and 0.40. One can notice the stochastic nature of the ignition phenomena. For the same spark energy, some cases were ignited, but some were not successfully ignited between 6 and 12mJ for a stoichiometry of 0.40 and between 9 and 15mJ for the leaner condition in this figure. Both shapes increase from 0 to 1 in a monotonic way. Some fluctuations can be seen for instance in the case of an equivalence ratio of 0.38 and energies between 10 and 12mJ. This comes from the fact that the number of samples in this region was not enough to get a smooth behavior, however, the levels of ignition may be given with an interval of 1mJ, by using a smoothed estimation of the actual ignition probability curve.

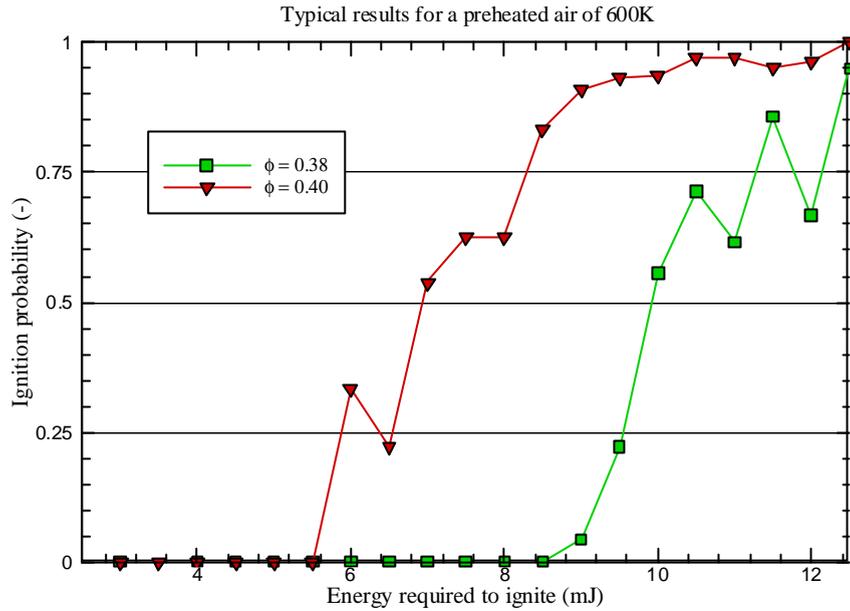


Figure 8 Typical energy-ignition probability curves

The M.I.E is defined as being the class having the lowest energy of for which more than 50% of the events lead to a positive ignition and therefore it would be of the order of 7mJ for 0.40 and 10mJ for 0.38. In Figure 9, one can notice a decrease in the M.I.E. with an increase of equivalence ratio as far as the lean side of the domain is considered. It is interesting to notice that it reaches a limit in the case if pre-heated temperature of 585K for stoichiometry between 0.55 and 0.70. In this region, the spark energy that leads to ignition is constant. This limit is basically due to the plasma formation process, as the laser induced spark type always produces a minimum of energy, much higher than the one obtained with electrodes.

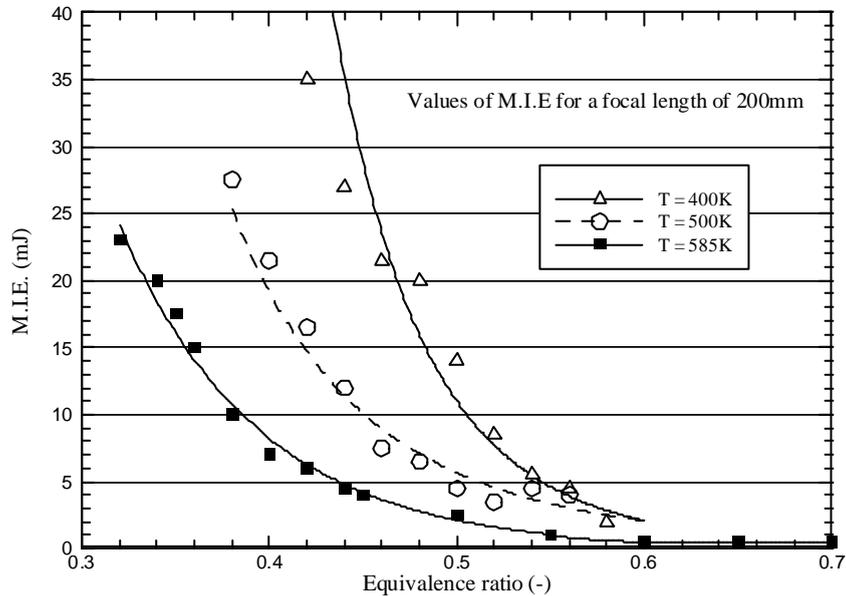


Figure 9 M.I.E. for different preheated mixture for 500NL.min<sup>-1</sup>

Increasing the flow rate does not change the typical curves shape but of course the levels required to ignite are changed. The fact that 400K and 500K have almost an identical value for stoichiometry higher than 0.60 comes from the fact that for those conditions all spark will ignite the mixture, and therefore the M.I.E. in those cases is the minimum spark energy obtained. The results obtained for M.I.E. with a higher flow rate are displayed in Figure 10 for two different inlet temperature (400K and 500K). When looking at the levels, one can notice for instance that the energy required to ignite are lower in case of a higher flow rate for lean stoichiometry compared to the case of lower flow rate. Similar results were found in cases of laminar flow (see Beduneau et al, 2003) as well. The levels are higher than the standard spark energies because, as explained by (Bradley et al, 2004) where they describe the laser spark ignition as an overkilling

process. However, the presence of fine droplets or particles may help reducing the M.I.E. and in practical situation this may often be the case.

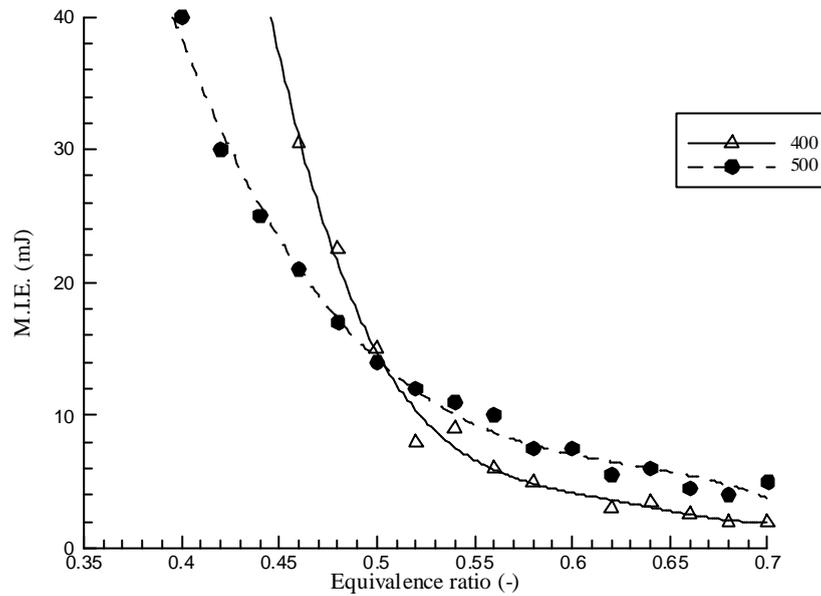


Figure 10 M.I.E. for a higher flow rate ( $663 \text{ Nl.min}^{-1}$ )

The interesting side of the present results is that they allow a discussion on the total energy required to ignite a mixture at a given stoichiometry. For this measurement, the total energy of the laser pulse is taken; not only the M.I.E., but also the energy required achieving breakdown. This is an important information as this is the actual energy that will be used to ignite the system even though for instance in cases of rich mixtures, only a small fraction of this energy will really contribute to the ignition, the most important part will help achieving gaseous breakdown. The results are presented in Figure 11 where one can notice that using preheating air does not allow an overall less energy for stoichiometry near 0.70. However the total energy required for mixture leaner than 0.60 is strongly influenced by the inlet temperature.

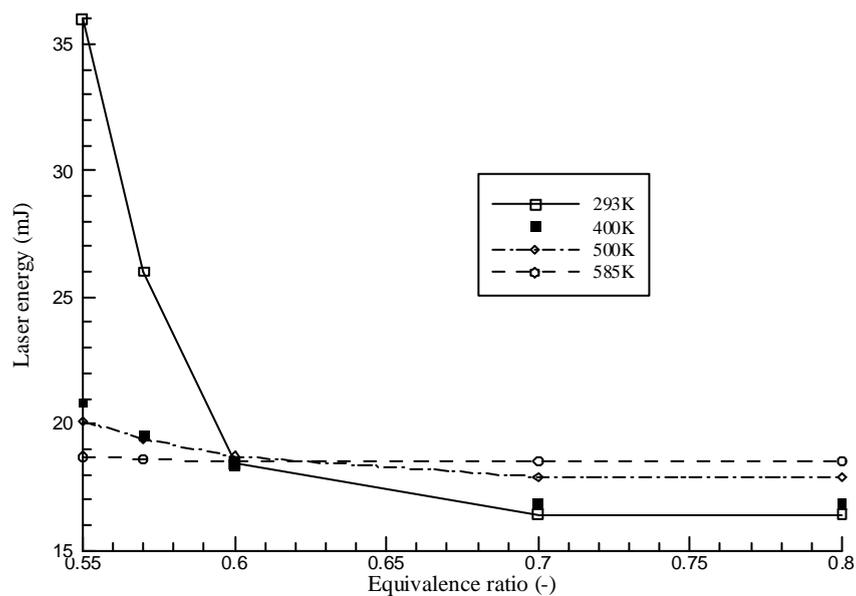


Figure 11 Total energy required to ignite the mixture

## 6. CONCLUSIONS

Laser ignition was successfully applied to a small-scale gas turbine combustor. The temporal evolution of the flame kernel is measured through mean OH-PLIF images for two different spark energies. The spark energy influences the initial diameter of the flame kernel as well as the expansion speed. However, the influence tends to diminish after few hundreds of microseconds. Looking at temporal evolution of non-ignition phenomenon lead to the conclusion that all OH cannot be symmetrically detected after 1ms and therefore criteria for ignition is defined using laser induced OH emission. This criterion is used to measure the Minimum Ignition Energy in the present combustor. It is shown that increasing temperature reduces the energy required and enables to ignite leaner mixtures but the input energy to achieve breakdown is higher. A global energy balance shows that for a given stoichiometry, preheating has no positive effect as the total energy required is at least equal to cases without preheating air. However, for stoichiometry below 0.55, the overall energy required to ignite decrease with an increase of inlet temperature. For application to real gas turbines with low-NO<sub>x</sub> emission, an important issue may be the NO<sub>x</sub> production at the early stages of the ignition.

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