Experimental Analysis of Laser-Induced Spark Ignition of Lean Turbulent Premixed Flames

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1 Introduction

Since the use of lean combustion in order to decrease NOx emissions, the study of lean turbulent combustion is a fundamental subject in combustion science [1]. Even if lean turbulent flames are encountered in many applications, such as car or aeronautical engines, many problems are still observed. The increase of the levels of turbulence and the reduction of the introduced fuel quantities are at the origin of instabilities [1] which can lead to difficulties to stabilize the flame on the burner. Local extinctions in the flame front can occur, leading to pollutant production (HC, CO), and problems of ignition are also encountered.

Ignition of fuel/air mixtures has been the subject of numerous studies [2, 3]. In laminar flows, ignition mechanisms are well known [4]. However, when the flow becomes highly turbulent, ignition is more complex and some questions are still open. Analysis of ignition mechanisms can be conducted by measuring the Minimum Ignition Energy (MIE), which is the energy that has to be deposited in the mixture in order to ignite a self-sustained flame kernel. When the levels of turbulence increase, the flame kernel is subjected to more intense disruptions from the eddies, at the origin of higher heat losses by diffusion to the surrounding unburned gas, leading to an increase of the MIE [5]. Moreover, the recent studies of Shy et al. [6] report an ignition transition phenomenon in turbulent mixtures, based on the measurements of the MIE of lean turbulent premixed flames as a function of the turbulence intensity *u'*. First, the MIE increases gradually with the turbulence intensity, then, from a certain threshold ($Ka \sim 10$) depending on the equivalence ratio, the MIE increases abruptly. The authors explain that this ignition transition indicates the existence of two distinct modes of ignition, corresponding to the transition between the flamelet regime and the broken reaction zones regime. These MIE measurements are obtained thanks to ignition by electric sparks, in a confined flow, which presents an isotropic and homogeneous turbulence, generated by two counter-rotated fans.

The present study contributes to the analysis of spark ignition, in lean and highly turbulent premixed flows. The different parameters influencing initiation and propagation mechanisms of a flame kernel are studied, for laser-induced spark ignition in methane/air mixtures, by measuring the MIE as a function of turbulent flow properties (mainly *u'*), equivalence ratio (Φ) and volume of energy deposition (focal length *f* of the focusing lens). Turbulence is generated thanks to a multi-scale injector [7], allowing to generate a homogeneous, isotropic and highly turbulent flow. The burner provides a stationary and 2-D flow. From these experimental results, the ignition transition phenomenon in turbulent mixtures is discussed over broad range of experimental conditions, in terms of ignition system, flows properties and turbulence intensity.

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2 Experimental set-up

Air and methane flows are injected and mixed in a wind tunnel, before being directed to a divergent-convergent chamber constituted of glass ball bed, honeycomb and screens to attenuate residual turbulent perturbations. The convergent, which has a 8 cm square exit section, provides a 2-D stationary flow, with a flat velocity profile equal to 4 $m.s^{-1}$.
Turbulence is generated by a multi-scale injector, developed by Mazellier et al. [7] and constituted by three perforated plates whose mesh size, hole diameter and blockage ratio increase along the flow. This turbulence generator is placed at the exit of the convergent and provides a highly turbulent flow, conserving stationarity, homogeneity and isotropy properties of classic grid turbulence. To measure the MIE as a function of turbulent flow properties, ignition trials are realized at several heights above the grids, between h = 60 and 164 mm, where u' varies from 2.05 to 0.60 $m.s^{-1}$.
Ignition are performed thanks to laser-induced sparks, generated by a Nd:YAG laser (Quanta-Ray Pro, Spectra-Physics) which operates as a Q-switched laser and which has a nominal energy equal to 500 mJ/pulse. The beam delivered by the laser has a pulse width of 8 ns, a wavelength of 532 nm, a frequency of 10 Hz, a diameter of 10 mm and a divergence of 0.5 mrad. In order to generate a spark in the methane/air flow, a plano-convex lens focuses the laser beam above the exit of the turbulence generator. To study the influence of the volume of energy deposition on the ignition process, three different focal lengths (f = 75 mm ; 100 mm ; 150 mm) are used. An attenuator and a shutter allow to modify respectively the pulse energy thanks to a rotating beam splitter, and the pulse frequency thanks to a rotating mirror, without modifying the setting of the laser (Fig. 1).
To measure the incident and the deposited energies in the methane/air mixture, a beam splitter (Melles Griot, 16 BPB153-523-532nm) and two energy meters (Ophir, PE25-DIF) are used (Fig. 1). A small amount (~ 14 %) of the laser beam is reflected by the beam splitter toward the first energy meter. Thanks to a calibration, the measurement of this small portion of energy allows to know the value of the incident energy sent to the focal point. The second energy meter measures the rest of energy which has not been absorbed in the spark at the focal point. Thus, the deposited energy in the mixture can be deduced from the measurement of the two energy meters.

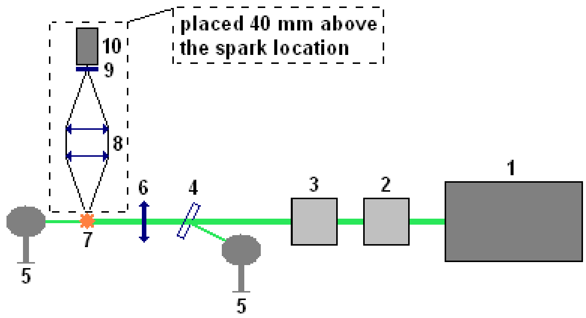

Figure 1. Measurement and ignition systems. (1) Nd:YAG Laser - (2) Attenuator - (3) Shutter - (4) Beam splitter - (5) Energy meter - (6) Focusing lens - (7) Spark location - (8) Two lenses afocal system - (9) CH filter - (10) Photomultiplier tube

To obtain the MIE, the deposited energy in the mixture has to be recorded, but the success or the failure of the flame kernel initiation also has to be known, at each attempt of ignition. Thus, an afocal system constituted by two lenses (f = 200 mm), a CH filter (Melles Griot, 03FGC013 / BG12) and a photomultiplier tube (Hamamatsu, 6780-20) with a pinhole of 2 mm diameter, collect the temporal evolution of light (CH radical emission) emitted 40 mm above the spark, a few milliseconds after the laser pulse (Fig. 1). Thanks to this device, the success or the failure of an ignition trial can be determined. Consequently, by averaging one hundred ignition trials in a fixed configuration, the ignition probability can be obtained for an average deposited energy. By repeating this operation for different deposited energies, the curve displaying the average deposited energy in the methane/air mixture as a function of the ignition probability can be plotted (Fig. 2). Finally, the MIE, defined as the ignition energy having 50% successful ignitability, can be obtained by interpolation of this curve.

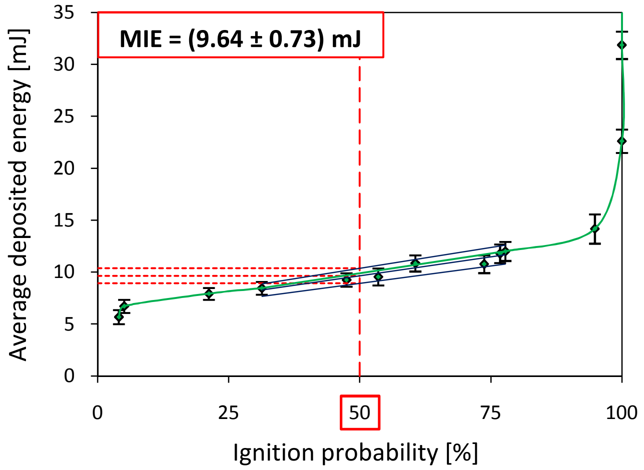

Figure 2. Measurement of the average deposited energy as a function of the ignition probability, for the determination of the MIE (h = 80 mm, f = 100 mm, Φ = 0.60)

3 Results and discussion

Fig. 3 displays the turbulent MIE normalized by the laminar MIE of a methane/air mixture as a function of the turbulence intensity *u'*. Sparks are created by a lens of a 100 mm focal length and the mixture has an equivalence ratio equal to 0.6. According to Fig. 3, the MIE increases as a function of *u'*. This trend is in good agreement with previous studies dealing with ignition in turbulent flows [5, 6]. When *u'* increases, the MIE raises, since the turbulent scales are more energetic and, thus increase the heat losses by diffusion at the flame front toward the surrounding unburned gas.

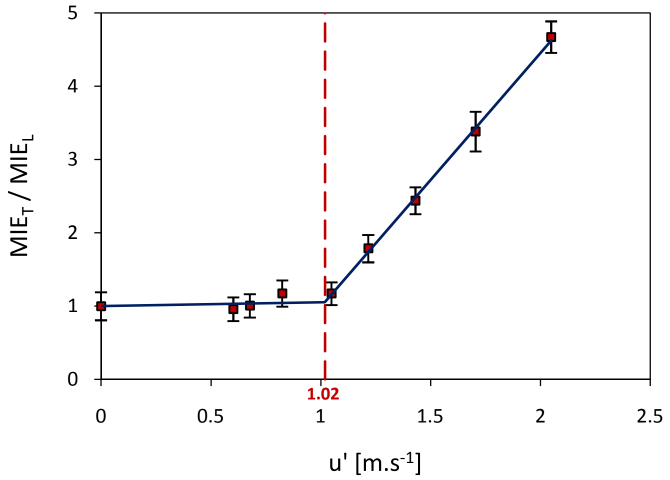

Figure 3. Turbulent MIE normalized by laminar MIE of a methane/air mixture as a function of *u'* (f = 100 mm, Φ = 0.60)

Fig. 3 also displays a clear transition on values of MIE_T/MIE_L when *u'* increases. This transition has already been reported by Shy et al. [6] for different flow conditions and turbulence properties, for a broader range of *u'* values and for a different ignition system. On Fig. 3, MIE measurements describe linear slopes, with a slope breakdown (for *u'* ~ 1 m/s) which could be due to the transition between two distinct modes of flame structures. Indeed, according to Glassman [8], the MIE is proportional to δ^3, where δ is the flame thickness. Before the transition, for low levels of turbulence, the structure of the flame kernel would be close to a laminar structure; the flame front is wrinkled by turbulent motions, but the inner flame structure remains similar to the laminar flame structure. Thus, in this flamelet regime, turbulent MIE is comparable to laminar MIE and increases slightly with *u'*. Whereas, after the transition, for higher levels of turbulence, eddies would become sufficiently energetic and small to disturb efficiently and modify the inner flame front structure, in the first stages of the development of the kernel. According to the turbulent combustion diagram, when the Karlovitz number, defined by $Ka = (L_i/\delta_L)^{-1/2}.(u'/S_L)^{3/2}$ (where δ_L and S_L are respectively the thermal flame thickness and the laminar flame velocity and L_i is the integral length-scale), becomes higher than 1, Kolmogorov scales are able to thicken the flame preheat zone, leading to intense stretch and possibly local extinctions. However, a significant change in the combustion regimes is actually observed when the Karlovitz number is of the order of 100, which corresponds to the thickening of the flame reaction zone by the Komogorov scales [9]. The Karlovitz number calculated at the transition on the Fig. 3 is of the order of 10, but this result is in good agreement with that of Shy et al. [6]. Moreover, the Damköhler number, defined by $Da = (L_i S_L)/(\delta_L u')$, is of the order of 1 (*Da* = 0.66) at the transition on the Fig. 3, meaning that the flame chemical time is larger than the turbulent time of all the eddies. In this case, reactants and products are mixed by turbulence motions, and the overall reaction rate is limited by chemistry. This process of intense mixing by eddies would contribute to the modification of the flame front structure, leading to an increase of the energy required for a successful ignition.

Thus, since the MIE is proportional to δ^3 [8], an ignition transition occurs from a certain threshold of turbulence, because the flame kernel would not develop anymore in a flamelet regime, but in a regime where it would be strongly modified by the turbulence. The flame front would undergo a thickening by the small eddies (*Ka* ~ 10) and an intense mixing by all the eddies of the flow (*Da* < 1). Consequently, these phenomenons would explain the abrupt increase of the MIE as a function of *u'*, for high levels of turbulence.

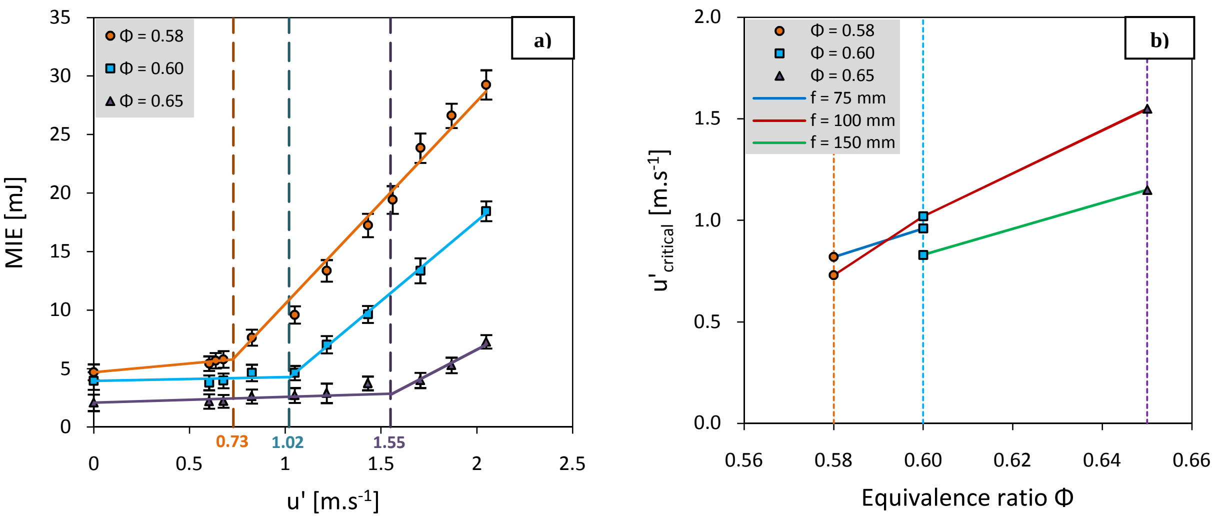

Figure 4. (a) MIE measurement of a methane/air mixture as a function of *u'* (*f* = 100 mm, *Φ* = 0.58 ; 0.60 ; 0.65) – (b) Values of *u'* for which an ignition transition is observed, as a function of the equivalence ratio, for three focal lengths of focusing lens (*f* = 75 mm ; 100 mm ; 150 mm)

Fig. 4.a displays MIE measurement as a function of *u'*, for three equivalence ratios (*Φ* = 0.58 ; 0.60 ; 0.65), with sparks created by a lens of 100 mm focal length. It has to be noted that, the leaner the mixture, the more the MIE increases. This trend is in good agreement with previous works measuring the MIE as a function of the equivalence ratio [4, 5]. Indeed, for leaner mixtures, less exothermic reactions occur and thus, the flame kernel releases less energy to allow its growth in a self-sustained

manner. Consequently, ignition of lean mixtures requires that higher energy is deposited in the flow, in order to assist the flame kernel during the first stages of its development.
Moreover, the MIE measurement displays an ignition transition, for the three equivalence ratios. The influence of the equivalence ratio on the ignition transition has also been studied, using others focal lengths of focusing lens (*f* = 75 mm ; 150 mm). The results are displayed on Fig. 4.b, where the values of $u'_{critical}$, that is to say values of *u'* for which an ignition transition is observed, are plotted as a function of the equivalence ratio. For a fixed focal length of lens, ignition transition occurs for higher levels of turbulence, when the equivalence ratio increases. When a lean mixture reaches the stoichiometry, the increase of the flame temperature involves an increase of the viscosity of the flame front, which can lead to a more intense phenomenon of relaminarisation at the origin of a faster dissipation of eddies. Consequently, for a lean mixture close to the stoichiometry, since the phenomenon of relaminarisation is more intense, higher levels of turbulence must be reached to observe an ignition transition, in order that the flow contains sufficiently small and energetic eddies, able to thicken and modify the flame front structure, before that the phenomenon of dissipation happens.

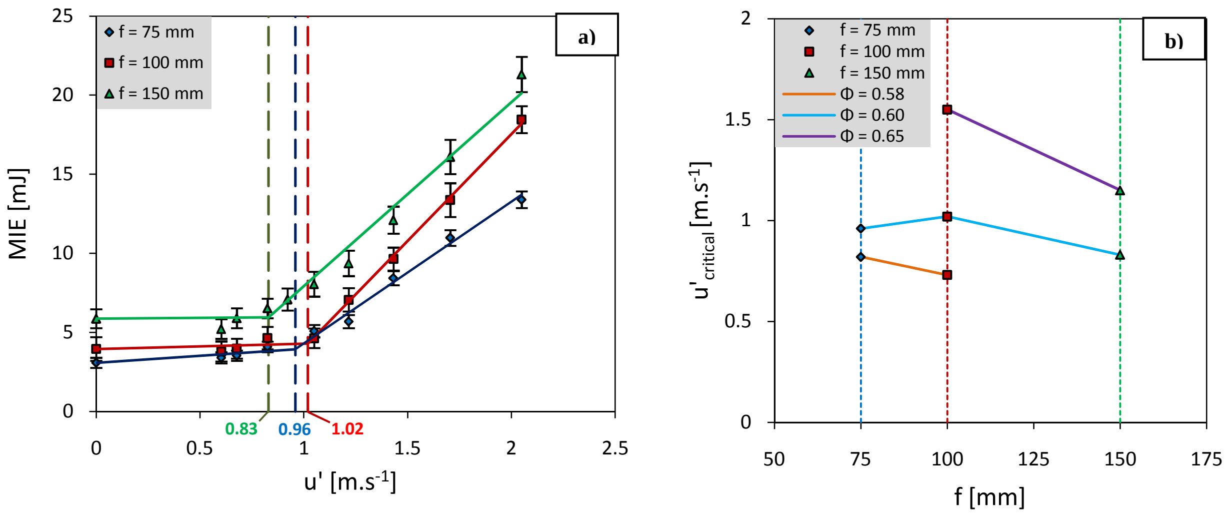

Figure 5. (a) MIE measurement of a methane/air mixture as a function of *u'* (Φ = 0.60, *f* = 75 mm ; 100 mm ; 150 mm) – (b) Values of $u'_{critical}$ as a function of the focal length of the focusing lens, for three equivalence ratios (Φ = 0.58 ; 0.60 ; 0.65)

Fig. 5.a displays the MIE measurement of a methane/air mixture (Φ = 0.60) as a function of *u'*, for different focal lengths (*f* = 75 mm ; 100 mm ; 150 mm). According to Fig. 5.a, the MIE decreases when the focal length decreases. This phenomenon has already been observed in previous studies [4] and is explained thanks to the calculation of the volume of energy deposition, defined by the volume of the laser beam at the focal point where the spark is generated. The volume of energy deposition depends on the laser characteristics and is proportional to the focal length of the focusing lens at the power of three. Thus, when the focal length decreases, since the volume of energy deposition is smaller, a higher energy per unit of volume is deposited, which allows to reach more rapidly the breakdown threshold [4] and to observe a larger expansion of the spark. Indeed, the measurement of the maximum volume of the spark, which is reached about ten nanoseconds after the breakdown, displays an increase when the deposited energy goes up and when the focal length decreases (for a fixed deposited energy). Beduneau et al. [10] revealed that if the spark is initially larger, it equals more rapidly the critical volume [8] that must be reached by the kernel for a successful ignition. Thus, for a fixed deposited energy (MIE), the decrease of the focal length allows to ignite more turbulent mixtures (Fig. 5.a), since bigger sparks and thus, larger kernels of hot gases are generated. And, for a fixed level of turbulence, a higher MIE is required to obtain a successful ignition, when the focal length increases. Moreover, the MIE measurement displays an ignition transition, for the three focal lengths. The

influence of the focal length on the ignition transition has also been studied, for two others equivalence ratios (*Φ* = 0.58 ; 0.65). The results are displayed on Fig. 5.b, where the values of $u'_{critical}$ are plotted as a function of the focal length. Despite the $u'_{critical}$ value obtained when *Φ* = 0.6 and *f* = 75 mm, an ignition transition seems to occur for higher levels of turbulence, when the focal length decreases, for a fixed equivalence ratio. Thus, the decrease of the focal length would allow the initiation of flame kernels which would be more resistant toward the disruptions induced by the turbulent flow.

In order to find a common criterion for the ignition transitions previously observed, the critical turbulence conditions, that is to say turbulence conditions for which an ignition transition occurs, are plotted on the turbulent combustion diagram (Fig. 7). For the different equivalence ratios and focal lengths, an ignition transition is observed for a Damköhler number lower than one and for a Karlovitz number of the order of 10. The calculation of the turbulent Reynolds number ($Re_t = (u'.L_i)/\nu$ where ν is the kinematic viscosity of fresh gases mixture) reveals that, whatever the equivalence ratio and the focal length, ignition transitions occur from a sufficiently high level of turbulence, corresponding to a constant turbulent Reynolds number of the order of 360.

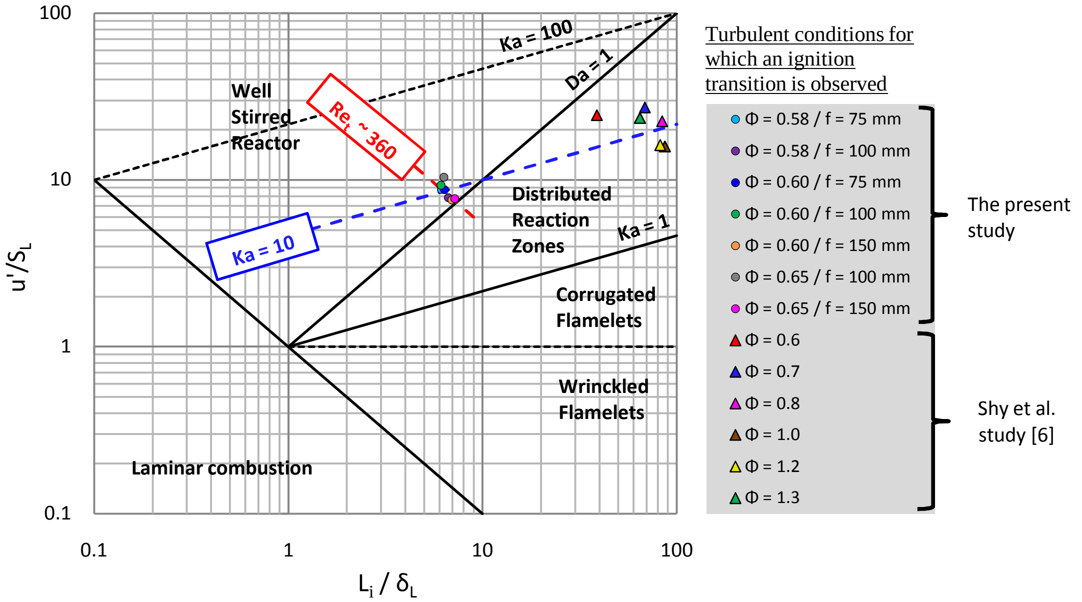

Figure 7. Turbulent combustion diagram, displaying critical turbulence conditions observed in the present study and in that of Shy et al. [6]

Ignition transitions observed by Shy et al. [6] also happen for a Karlovitz number of the order of 10 and for a constant Peclet number (*Pe* ~ 4.5), which is proportional to Re_t and defined by Shy as: $Pe = Re_t^{1/4}.(\nu/\alpha)$, where α (thermal diffusivity of the mixture), ν and Re_t are calculated at the average temperature between the temperature of the fresh gases and the adiabatic flame temperature. Thus, the ignition transition criterion of this study, corresponding to a constant turbulent Reynolds number (Re_t ~ 360) or to a constant Peclet number (*Pe* ~ 2.1), is consistent with the one obtained by Shy et al., even if the values characterizing the transitions are not the same. This may be attributed to differences in the flow conditions, the turbulence properties and the ignition systems.

4 Conclusion

To analyze the ignition through a spark of lean and highly turbulent premixed flows, laser-induced spark ignition of methane/air mixtures were conducted and the MIE were measured as a function of the turbulence intensity, the equivalence ratio and the volume of energy deposition (focal length). The measurements revealed that a higher MIE is required when the turbulence is more intense, when the focal length of the focusing lens increases and when the equivalence ratio of the lean mixture decreases. These trends are in good agreement with previous studies [4-6]. The measurements also display an ignition transition phenomenon, which is reported for the second time, but for different flow conditions and turbulence properties, and for a different ignition system, than Shy et al. [6]. Indeed, the MIE measurements as a function of *u'* describes linear slopes, with a slope breakdown (for *u'* ~ 1 m/s) which could be due to the transition between two distinct modes of flame structures. Since the MIE is proportional to δ^3 [8], an ignition transition occurs from a certain threshold of turbulence, because the flame kernel would not develop anymore in a flamelet regime, but in a regime where it would be strongly modified by the turbulence: the flame front would undergo a thickening by the small eddies (*Ka* ~ 10) and an intense mixing by all the eddies of the flow (*Da* < 1). The study of the influence of the equivalence ratio and the focal length of the focusing lens reveals that an ignition transition happens for a less intense turbulence, when the mixture is leaner and when the focal length increases. Finally, this study reveals that there is a common criterion of ignition transition: whatever the focal lens of the focusing lens and the equivalence ratio of the mixture, an ignition transition occurs when the turbulent flow reaches a turbulent Reynolds number of the order of 360. This criterion is consistent with that of Shy et al. [6], even if the values characterizing the transitions are not the same, because of differences existing between the flow conditions, the turbulence properties and the ignition systems of these two studies.

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