Effect of initial laser beam diameter on breakdown and ignition properties of n-decane/air

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1 Introduction

Recent works highlight the use of a focused Gaussian laser beam to possibly replace traditional spark igniters in engine applications [1-2]. The benefits of laser induced breakdown in front of conventional electrical spark plug systems are mainly a better location of energy both in space and time. The time of the laser pulse is generally fixed by the manufacturer while the space location of the laser focused spot is done thanks to a plano-convex lens selected by the user. This lens plays a significant role in the ignition properties because it allows obtaining a tighter focus and consequently a better concentration of the laser energy. This phenomenon is described with the following eq. 1:

$$\omega_0 = \frac{2\lambda}{\pi}\frac{f}{D}M^2 \tag{1}$$

where ω_0 denotes the waist (beam radius at the focal spot with respect to 1/e criterion, orthogonal to the laser beam propagation direction), λ = 1064 nm the wavelength of the laser beam, f the focal length of the lens, D and M^2 are respectively the initial diameter and the quality factor of the laser beam.
Consequently some works have been undertaken about the effect of the focal length [3-4] and one of the common conclusions is that less energy is needed when smaller focal length are used to ignite gaseous mixture. However, looking at eq. 1, there is also the possibility to adjust the wavelength λ or the diameter D of the laser beam before focusing it. Unfortunately tuning λ also implies problems because molecules are sensitive to this parameter for the absorption of the energy send by the laser, so acting on this parameter is not only about geometric purpose. The last parameter available is the initial diameter D of the laser beam which can be tuned using a plano-concave and a plano-convex lens. This parameter D is interesting because laser induced ignition are generally studied in the center of the combustion chamber (to avoid thermal wall losses) and as the focal lens is placed outside the chamber its focal length is upper than the radius of this chamber, so the only way to achieve a smaller radius ω_0 is to increase D. To the authors knowledge's few works adjust one time this parameter [5] (were the beam diameter was expanded from 6 to 36 mm) and very few works has studied several D [6].

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To study the effect of D a gaseous n-decane/air mixture has been elected. This choice has been done considering our previous works [7-8] and also to still study this surrogate of kerosene for aeronautical propulsion topic. Laser ignition for aerospace application is an ongoing topic to increase combustion efficiency to achieve a decrease of pollutant such as CH_x, NO_x and SO_2 [9]. One way to get closer to this goal is to optimize laser induced breakdown with optics.
The aim of this paper is to presents experimental results of the ignition of n-decane/air mixture for several equivalence ratios and several expanded diameter D of the laser beam.

2 Experimental apparatus

A schematic view of the used device is given in fig. 1. Detailed description of the vessel, energy meter and laser and how to use them can be found in [7-8]. The improvement here is the implementation of the beam expander, so only a quick reminder is given here for other elements.

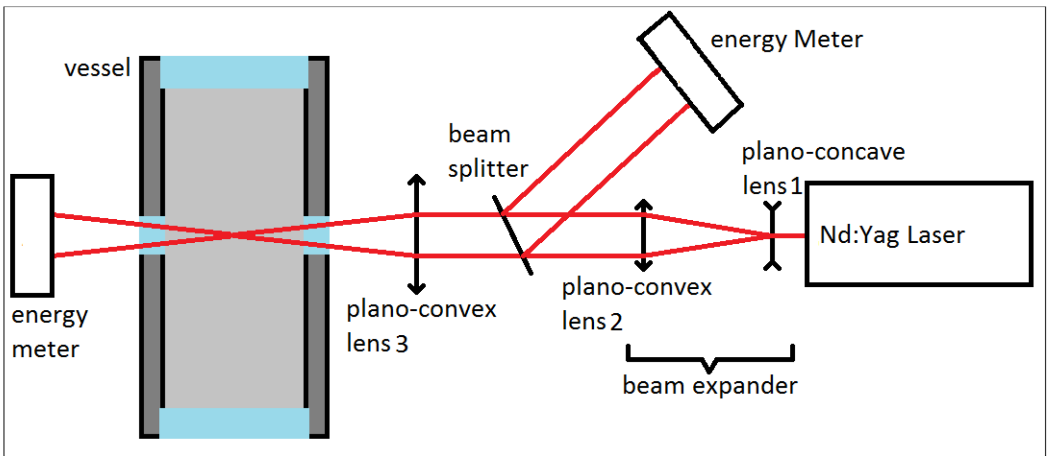


Figure 1. Schematic view of the experimental set-up.

The Gaussian laser beam of the Quantel Brilliant Nd:Yag (λ = 1064 nm, D = 6 mm, M^2 = 1.75, pulse duration τ_{FWHM} = 4.48 ns) is sent to the closed cylindrical vessel (internal length = 200 mm, internal diameter = 80 mm). But prior entering into it, the beam is firstly expanded, secondly a small amount is split to measure the sent energy and thirdly the not split part is focused into the center of the vessel with a focal length f_3 = 150 mm. At the output of the vessel a second energy meter measures the transmitted energy. The beam expander (figure 1) is done with firstly a plano-concave lens f_1 = -50 mm and a plano-convex lens f_2 = {75; 100; 125; 150} mm. The beam expansion ($|f_2/f_1|$) is then BE = {1.5; 2; 2.5; 3} respectively that leads to D = {9; 12; 15; 18}mm respectively. Chosen expansion ratios are still valid regarding the paraxial approximation.
The n-decane and the air used are the same that were used in [8]. The n-decane is provided by Alfa-Aesar under the reference “A14732 n-Decane, 99% » and the synthetic air (20% O2 and 80% N2) is provided by Air Liquid with the reference “ALPHAGAZ 1”.

3 Experimental protocol

In this work five equivalence ratios Φ = {0.65, 0.8, 0.9, 1.1, 1.3} at T = 347 K and P = 1 bar and five initial diameters D = {6; 9; 12; 15; 18}mm were tested by solely adjusting f_2. For testing D = 6 mm the beam expander was simply removed from the apparatus. Note that Φ = 0.65 is close to the lower flammability limit of this mixture (LFL = 0.55). To perform each configuration the Langlie method [10] with a log-normal law has been elected because this statistical approach generally needs only 20-25 shots to provide the ignition probability in front of the incident energy [11]. Basically this method looks for the raw E_{50} (energy needed to obtain 50 % probability of ignition) by a dichotomy approach and also allows calculating a raw standard deviation σ_0 (eq. 2):

$$\text{raw } E_{50} = \frac{X_m + X_M}{2} \text{ and } \sigma_0 = N\frac{\ln(X_m) - \ln(X_M)}{8(n+2)} \tag{2}$$

where X_m is the lowest energy leading to ignition, X_M the highest energy leading to no-ignition, N the total number of shots and n the number of shots lying into [X_m ; X_M].
Then a fitting of experimental results to the cumulative distribution function of a log-normal law whose equation is given here (eq. 3):

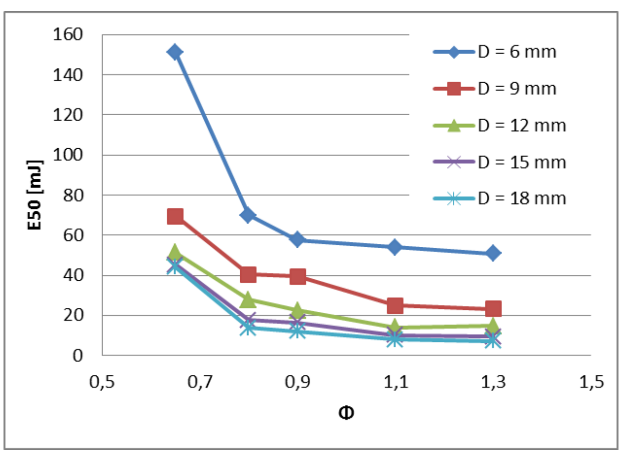
$$F_{\log}(E) = \frac{1}{2}\left(1 + \operatorname{erf}\left(\frac{\ln(E) - \mu}{\sqrt{2}\sigma}\right)\right) \tag{3}$$

where μ and σ are respectively the mean and the standard deviation of the variable's natural logarithm (here the energy).
Then one can deduce the corrected values of E_{50} and standard deviation σ with eq. 4:

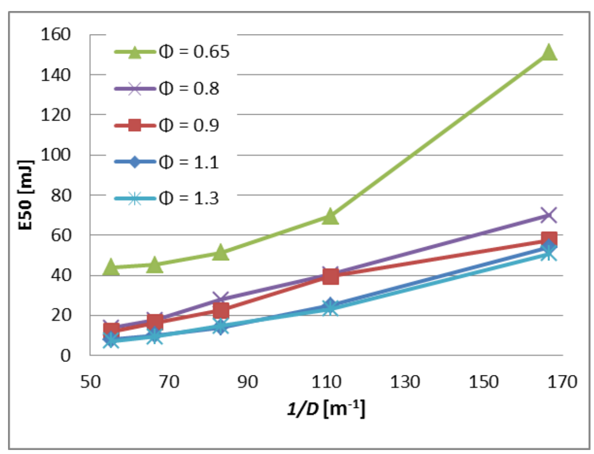
$$E_{50} = \exp(\mu) \tag{4}$$

4 Results and discussions

In those experiments the Langlie method needed 20 to 30 shots to converge to the E_{50} of sent energy.
All the results about the energy contained in D needed to achieve E_{50} for all configurations are given in table 1 and plotted on fig. 2.



(a)



(b)

Figure 2.(a) E_{50} vs Φ for several D, (b) E_{50} vs ω_0 for several Φ.

Table 1: E_{50} [mJ] vs D [mm] for the 5 equivalent ratios Φ.

	Φ				
***D* [mm]**	**0.65**	**0.8**	**0.9**	**1.1**	**1.3**
6	150.88	69.80	57.59	54.01	50.88
9	69.43	40.25	39.33	24.98	23.13
12	51.33	27.74	22.39	14.08	14.69
15	45.29	17.62	16.41	10.16	9.39
18	43.96	13.66	12.00	7.93	7.32

From table 1, fig. 2 (a) and (b) one can note that the effect of the initial diameter D at the exit of the laser as a great influence on the needed E_{50} to reach a 0.5 probability to ignite. Indeed for all tested equivalent ratios increasing D leads to less energy needed to reach E_{50}. This result is consistent with previous efforts on focal length [3,4,8] and can be geometrically explained. The generated plasma spark by the laser shot can be described by eq. 1 and Rayleigh length Z_R (characteristical length of the plasma along the propagation direction of the laser beam) and are proportional to (eq. 5):

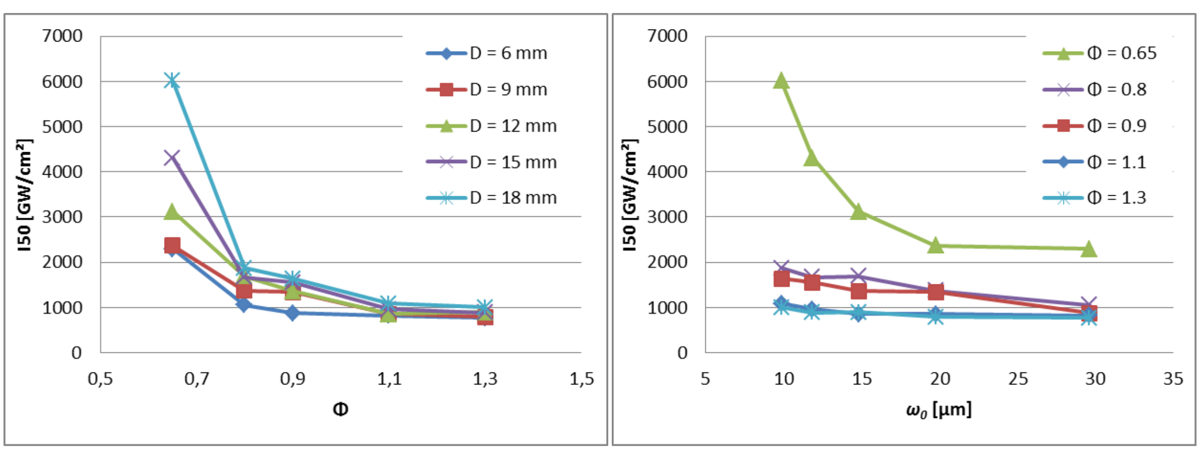
$$\omega_0 \propto \frac{1}{D} \propto f \text{ and } Z_R = \frac{\pi\omega_0^2}{\lambda M^2} \propto \frac{1}{D^2} \propto f^2 \tag{5}$$

Consequently increasing D by a BE factor is equivalent to decreasing f by this BE factor. From this analysis it appears that the tested configuration D = {6; 9; 12; 15; 18} mm and f_3 = 150 mm is equivalent to D = 6 mm and f_3 = {150; 100; 75; 62.5; 50} mm. Note that due to dimension constraints of the vessel it is physically impossible to have f_3 below 100 mm for focusing the beam in its center.

However to characterize the ignition also the intensity at the waist is an important parameter. As the temporal laser pulse is considerd gaussian (manufacturer data) one can express the intensity I_{50} at the center of the waist for 0.5 probability of ignition in [GW.cm^{-2}] (with respect to used variable and units in this paper and calcultions of laser peak power and integration time detailed in [12]) as:

$$I_{50} = \frac{4E_{50}\sqrt{\ln(2)}}{\pi^{3/2}\tau_{FWHM}\omega_0^2}10^5 \tag{6}$$

Calulated I_{50} are presented in table 2 and Figure 3.



(a) (b)

Figure 3.(a) I_{50} vs Φ for several D, (b) I_{50} vs ω_0 for several Φ.

Table 2: I_{50} [GW/cm²] vs ω_0 [µm] for the 5 equivalent ratios Φ.

		Φ				
***D* [mm]**	**ω_0 [µm]**	**0.65**	**0.8**	**0.9**	**1.1**	**1.3**
6	**29.63**	2293.5	1061.0	875.4	821.0	773.4
9	**19.76**	2374.7	1376.6	1345.5	854.4	791.09
12	**14.82**	3121.1	1686.7	1361.4	856.1	893.2
15	**11.85**	4302.8	1674.0	1559.0	965.3	892.1
18	**9.88**	6014.1	1868.8	1641.7	1084.9	1001.4

Surprisingly the I_{50} is not constant in front of ω_0 which means that the geometrical effect of D also seems to impact physical parameters of the gaseous mixture, especially for the leanest ones. Nevertheless those values are in the same range order than the ones reported in [6, 13] for stoichiometric mixtures. Thanks to the energy meters (see fig. 2) the energy sent by the laser, *i.e.* E_{50}, and the energy transmitted E_{tr} through the mixture were recorded. It has been observed that the ratio E_{tr}/E_{50} decreased when D increased. As a consequence the investigation of the absorption coefficient K_{v_50} [cm^{-1}] in table 3 of the n-decane/air mixture is investigated *via* the Beer-Lambert law (eq. 7) considering the length l of the focal volume where the breakdown occurs:

$$\frac{E_{tr}}{E_{50}} = \exp\left(-K_{v\_50}l\right) \text{with } l = \left(\sqrt{2}-1\right)Z_R \tag{7}$$

Table 3: K_{v_50} [cm^{-1}] vs l [cm] for the 5 equivalent ratios Φ.

		Φ				
***D* [mm]**	***l* [cm]**	**0.65**	**0.8**	**0.9**	**1.1**	**1.3**
6	**$615 \cdot 10^{-4}$**	-	2.04	1.12	0.44	0.9
9	**$274 \cdot 10^{-4}$**	25.89	9.08	12.64	5.51	4.72
12	**$154 \cdot 10^{-4}$**	70.07	32.90	30.93	8.31	9.20
15	**$98 \cdot 10^{-4}$**	143.71	58.00	56.00	26.15	16.50
18	**$68 \cdot 10^{-4}$**	246.49	80.46	82.30	36.90	24.80

The K_{v_50} values for l = 154*10^{-4} cm are in the same range [0.1; 100] cm^{-1} than in [13] where a similar geometrical configuration was used (D = 6mm, f = 75 mm and λ =1064 nm). Values for l = 615*10^{-4} cm are in the same range [0.39; 2.74] cm^{-1} than in [14] where a similar geometrical configuration was used (D = 6 mm, f = 150 mm and λ =1064 nm). The K_{v_50} clearly increases when D increases (*i.e.* when l decreases) but not enough to keep I_{50} constant. Note the K_{v_50} of the leanest equivalence ratio is particularly higher than others for any given l.

5 Conclusion and perspectives

The influence of the beam diameter D of the laser on the ignition has been experimentally investigated for 5 equivalent ratios. Results have pointed out a huge reduction of the needed energy E_{50} to ignite the n-decane/air mixture with a 0.5 probability of ignition. This work has highlighted a possible and simple alternative to achieve a smaller waist when it is not possible to reduce the focal length f_3 to focalize the laser beam. However, despite a smaller waist ω_0 a higher intensity I_{50} is needed to ignite due to the absorption coefficient K_{v_50} which not rises fast enough. Nevertheless the very lean mixture Φ = 0.65 was

ignited with an E_{50} three times lower with the highest D (18 mm) than the lowest one (6 mm). It is a noticeable point for achieving greener combustion.
Also the geometrical influences of f and D have been highlighted and allow comparisons with available literature data for different geometric set-up presented in the literature.
Next efforts will focus on deeper analyses of the absorbed energy by the plasma and Schlieren visualizations to better understand how the plasma grows.

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