Ignition by Electric Spark and by Laser-Induced Spark of ultra-lean CH_4/air and CH_4/CO_2/air mixtures

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Abstract
This study investigates the Lean Ignition Limit (LIL) of CH_4/air and CH_4/CO_2/air mixtures, using two different ignition devices: Electrical discharge and Laser-Induced Spark (LIS). The experiments were performed for CH_4/air and (0.6 CH_4 + 0.4 CO_2)/air mixtures in ultra-lean conditions ($0.48 \leq \phi \leq 0.67$) at different initial pressures (P= 1–7 bars) and at an initial temperature of 298 K. In these conditions, all observed flames were ascending. The minimum laser pulse energy for ignition (MPE) and the maximum overpressure (MO) were determined. The LIL increases with the initial pressure and with the addition of CO_2.

Introduction
Due to the depletion of fossil fuels, the development of renewable energy is more necessary than ever. In this context, the combustion of biogas from the anaerobic fermentation or from methanization of organic waste is one of the alternatives to the use of natural gas. The biogas is mainly composed of methane and carbon dioxide and thus has a lower calorific value than natural gas. That's why the ignition and combustion of biogas are more difficult to achieve. In order to better control the ignition of biogas, the development of new technology is needed. The LIS ignition is foreseen as a way to achieve a high-energy ignition system.
In recent years, the LIS ignition was the subject of renewed interest [1-10] because of its many potential benefits over conventional ignition systems presented by Ronney [11]. Many laser ignition experiments have been carried out with hydrogen [1,2], with methane [3-7] and with propane and dodecane [8]. However, to our knowledge, Forsich et al. [9] are the only ones to have conducted a study on the laser ignition of CH_4/CO_2 mixtures.
The minimum pulse energy (MPE) has been discerned from the minimum ignition energy (MIE) [2]. The MPE is the total pulse energy needed to obtain the ignition; whereas the MIE is exactly the minimum energy required to ignite the mixture in the combustion chamber. Phuoc and White [4] were the first to propose values of the MIE by LIS ignition. They have studied in a cylindric bomb the ignition of CH_4/air mixtures at atmospheric pressure for a large range of the equivalence ratio ($0.66 \leq \phi \leq 2.0$). Weinrotter et al. [2,7] have studied, at high pressure (5 – 42 bars) the influence of the equivalence ratio on the MPE and the overpressure in ultra-lean hydrogen/air ($0.13 \leq \phi \leq 0.56$), methane/air ($0.52 \leq \phi \leq 0.67$) and methane/hydrogen/air ($\phi = 0.55$) mixtures. Lee et al. [8] have also proposed values of MIE of propane/air and dodecane/air mixtures at low pressure ($0.33 \leq P \leq 1.0$).
Phuoc [10] has made a review on the fundamental aspects and the applications of the laser-induced spark ignition.
Because lean mixtures present a special interest for gas engines the LIL of methane/air mixtures was investigated. This paper focuses on the effect of the equivalence ratio and of the initial pressure on the MPE values and the overpressure. The MPE has been determined in the case of LIS ignition.

Experimental
In the present work, ignitions of different mixtures are performed in a stainless steel spherical combustion chamber, called a Spherical Bomb (SB). This SB has an internal diameter of 250 mm and

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has 4 optical accesses, made of quartz glass. The ignition is initiated at the center of the SB either by LIS or by electric spark discharge between two electrodes. The ignition and the flame propagation are visualized through a classical Schlieren setup with a high speed camera (KODAK, Ektapro 4540 model). Details of the Schlieren setup are explained in Lamoureux et al. [12]. The temporal behavior of the induced overpressure following the ignition is measured with a fast piezoelectric pressure transducer (Kistler).
The mixtures are prepared to achieve the desired equivalence ratio according to the partial-pressure method (Dalton).
In the case of ignition by electric spark, two thin electrodes were used to ignite the mixture. The distance between the electrodes is kept constant (d≈ 2 mm). They are linked to a high voltage power supply. The current and voltage of the electric induced spark used to ignite the mixture were measured, respectively, through a current transformer (BERGOZ, CT-D1.0) and a high voltage probe (Tektronix, P6015A) and acquired on a digital oscilloscope (Lecroy, WS434 – 350 MHz). It was possible thus to measure the amount of delivered energy used to ignite the mixture. However, it was not possible to adjust and minimize this energy. The overpressure signal is recorded on a second oscilloscope (Tektronix, TDS2024B – 200 MHz).

In the case of LIS ignition, the laser used is a CILAS prototype Q-Switched DPSS Nd:YAG laser, working at 1064 nm and with a pulse duration about 13 ns. The laser beam is TEM_{00}, with a diameter of 3.2 mm and a $M^2 = 1.6$. The laser energy delivered per pulse can reach 80 mJ. A variable attenuator, consisting in the combination of a half wave-plate and a Glan-Taylor polarizer, is used to adjust, with good accuracy and repeatability, the laser energy delivered to achieve ignition of the mixture. In order to obtain sufficient energy densities at the focal point, before focusing, the beam diameter is expanded by a beam expander with a 10x magnification ratio. The beam is then reflected on a mirror and focused at the center of the SB with a f = 250 mm spherical lens. A visible laser diode (635 nm) is used to help the alignment of all the optical components of the setup. Two photodiodes (THORLABS, DET10A model) are used to quantify the energy delivered and transmitted through the SB of a single laser pulse. The photodiode 1 (PhD1) detects and measures a part of the weak percentage of laser radiation that is transmitted through the mirror. The photodiode 2 (PhD2) detects part of the radiation diffused by the power-meter sensor placed at the exit of the SB. The amplitudes of the delivered signals by these photodiodes are calibrated in energy through measurements with a laser joule-meter (GENTEC, QE12SP model).

A digital delay generator (BNC, 575 model) is used to trigger the laser shot and the acquisition system of the camera. The photodiode 3 (PhD3) picks up a part of the beam diffused by the variable attenuator and is used to trigger the acquisitions on the two oscilloscopes. The signals of PhD1 and PhD2 are transferred and recorded by the digital oscilloscope (Lecroy). The figure 1 shows a schematic diagram of the experimental setup of the LIS ignition system in the spherical bomb.
In order to estimate with good accuracy the amount of laser energy delivered at the focal point, we need to know and quantify the different sources of attenuation between the laser output and the focal point. All optical components have an AR coating at 1064 nm except the quartz windows. We measured a 12% global attenuation of the laser beam energy.
Moreover, rather than determining the MPE for a given mixture, it is more important to know the instantaneous irradiance I_L (in $W.m^{-2}$) at the focal point, as shown by Kopecek et al. [6]. For a same laser at a given wavelength and for a given mixture, the measured MPE will vary depending on the focal length of the focusing lens. Thus, a determination of I_L will be more representative of the power delivered to ignite the mixture.

I_L can be expressed as follows: $I_L = \frac{E_L}{\Delta\tau \cdot S'} = 2.45.10^{10} . E_L$

with E_L the laser energy delivered per pulse (J); $\Delta\tau$ the laser pulse duration (s); S' the beam cross section at the focal point.

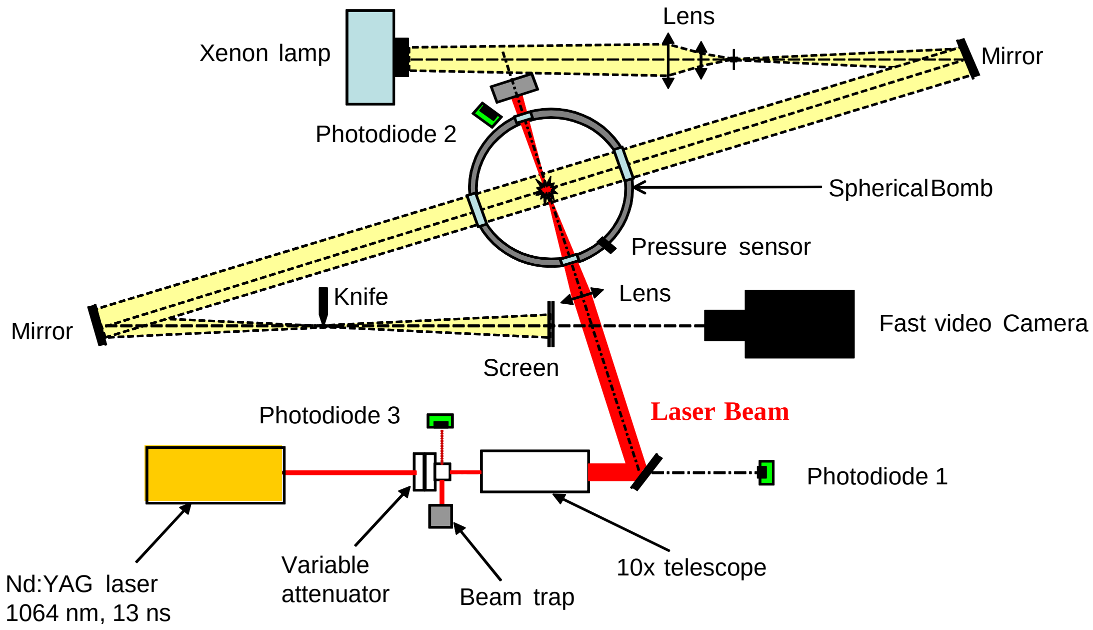


Figure 1. Schematic diagram of the experimental setup for the ignition of mixtures by LIS

Results and discussion

This study concerns the ignition of ultra-lean mixtures of CH_4/air and (0.6 CH_4 + 0.4 CO_2)/air by these two ignition systems in a large range of initial pressure (P= 1-7 bars) at an initial temperature of 298 ±5 K and for equivalence ratio between 0.48 and 0.67. The figure 2 shows the MPE as a function of the equivalence ratio. Below an equivalence ratio of 0.59 for CH_4/air mixtures and 0.63 for CH_4/CO_2/air mixtures, the MPE is a decreasing function of the equivelance ratio. For the richest mixtures, the experiments show that when the initial pressure is higher, the required energy to ignite the mixture is lower.

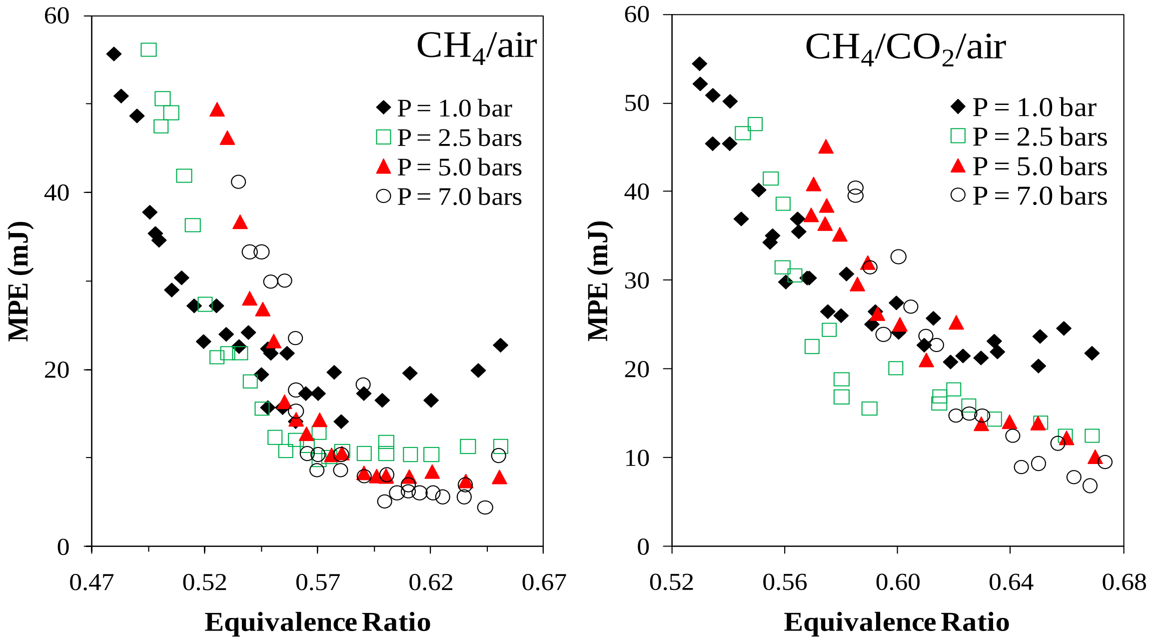


Figure 2. Results by LIS Ignition: Minimum pulse energy (MPE) versus equivalence ratio.

The Figure 3 shows three examples of measured overpressure profiles. Under our experimental conditions, when the equivalence ratio increases, the overpressure also increases. All studied flames spread upward. In this type of propagation, no laminar flame speed can be determined, the maximum overpressure is the only characteristic value of the combustion. That's why in this work, we have studied the evolution of the maximum overpressure (MO) versus the equivalence ratio. Figure 4 shows the evolution of the MO with the equivalence ratio for all CH_4/air and CH_4/CO_2/air mixtures studied by LIS ignition.

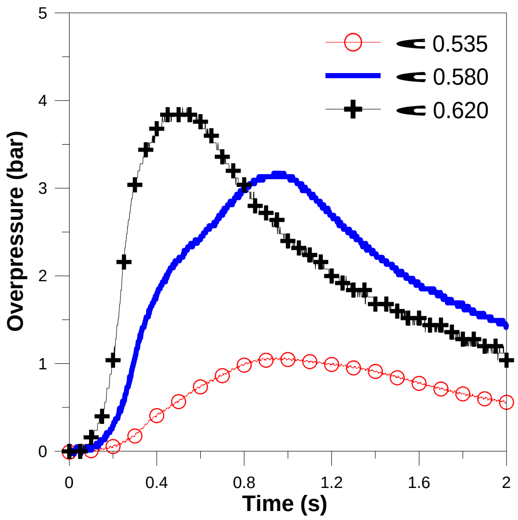


Figure 3. Overpressure signals versus time; CH_4/air with initial pressure = 1.0 bar

For each pressure, we can observe two distinct parts for which the MO is a growing linear function of the equivalence ratio. For the leanest mixtures, the first linear part corresponds to a partial propagation of the flame in the upper part of the SB. Between the two linear parts, the MO increases sharply on a very short range of equivalence ratios.

This increase is even sharper when the initial pressure is high. The second part corresponds to a total propagation of the flame in the SB. For those richest mixtures, the flame is always ascending and not spherical.

The Figure 5 presents a comparison between the MO obtained by electric spark ignition and those obtained by LIS ignition. Despite the intrusive nature of electrodes, this comparison show that the ignition device used does not change the flame propagation because the MO are identical.

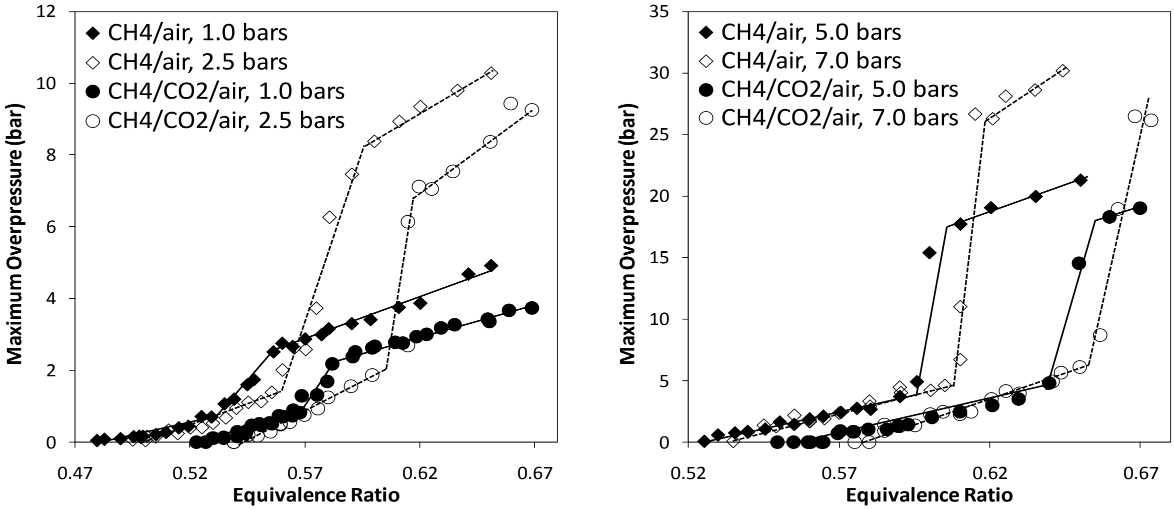


Figure 4. Results by LIS Ignition : Maximum overpressure (MO) versus equivalence ratio – Comparison between CH_4/air and CH_4/CO_2/air mixtures.

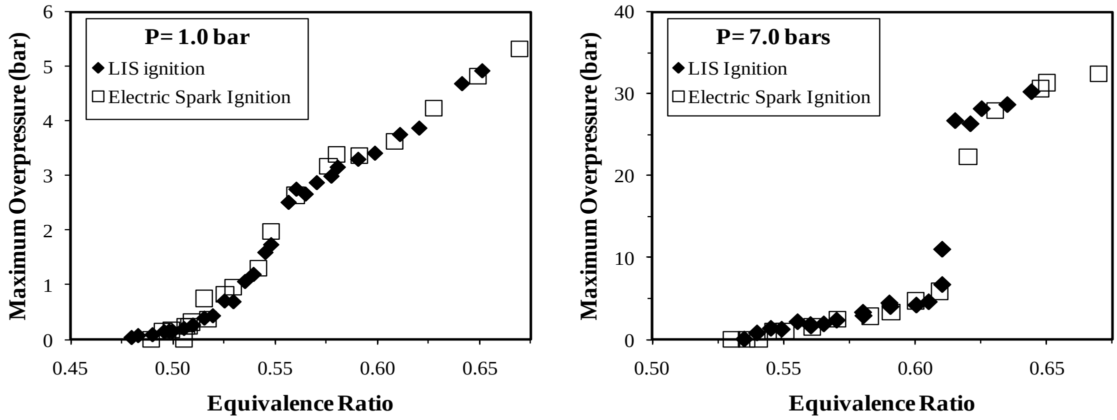
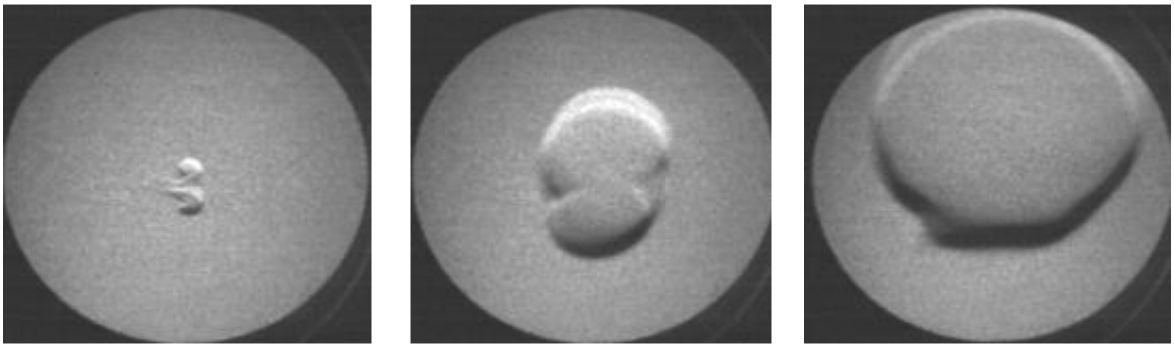


Figure 5. Maximum Overpressure (MO) versus Equivalence Ratio: Comparison between the results obtained by LIS Ignition and those obtained by electric spark ignition.



t = 0 ms t = 32 ms t = 80 ms

Figure 6. Examples of pictures recorded by the fast video camera: CH_4/air mixture; ϕ=0,541; P_i = 1,0 bar; LIS Ignition.

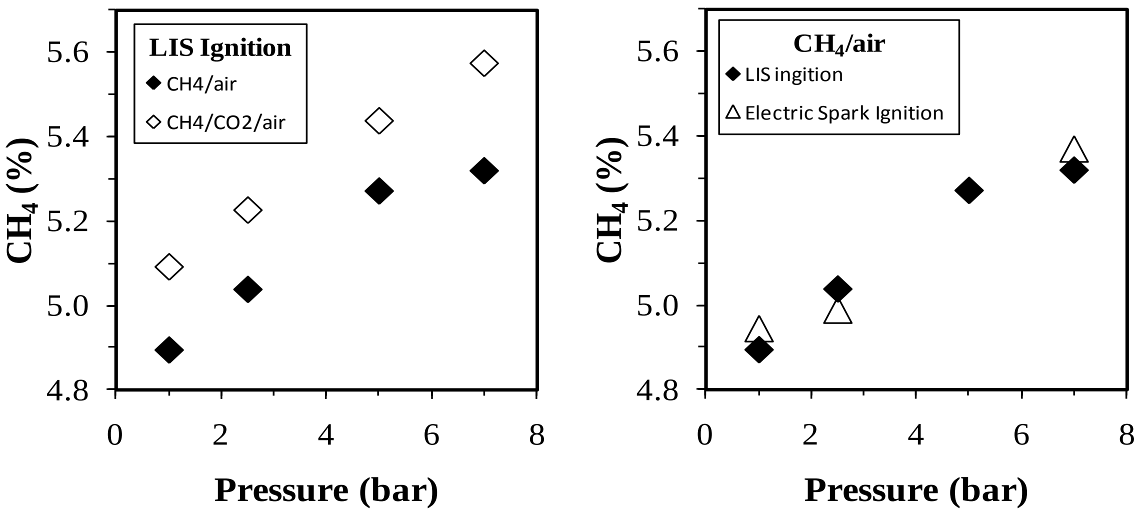


Figure 7. Evolution of the LIL with the initial pressure.

The method used to determine the LIL is based on the observation of the propagation of the flame front or of this extinction. Figure 6 presents an example of pictures in the case of flame propagation. The LIL is the minimum proportion of methane observed for which the flame spreads without extinction. Figure 7 presents the evolution of the LIL with the initial pressure. This limit increases with the initial pressure reducing the flammability limits. Moreover, the introduction of 40% of CO_2 in the fuel mixture increases substantially the LIL. Moreover, the same LIL was found using laser or spark ignition

Conclusion

This work presents a comparison between the ignition by electric spark and by laser induced-spark of ultra-lean CH_4/air and CH_4/CO_2/air mixtures. Lower flammability limits for these 2 types of mixtures have been determined over a wide pressure range and using the 2 different ignition systems. We have shown that the flammability limits, based on the successful flame propagation criterion, are similar using either spark ignition or laser ignition. The main advantage of LIS ignition device is that, when the pressure of the mixture to ignite increases, the laser energy required to for ignition decreases. These results show that the laser represents a good ignition source for high pressure applications in lean conditions.

Acknowledgments
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