LAMINAR BURNING PROPERTIES OF LEAN CH_4-H_2-AIR MIXTURES AT HIGH PRESSURE

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Abstract
Experimental evaluation of laminar burning characteristics of gaseous fuels has been carried out, analyzing spherical expanding flames. Tests were performed within the framework of the DHARMA (Device *for* Hydrogen-Air Reaction Mode Analysis) initiative at Istituto Motori - CNR. Based on a high-pressure, constant-volume bomb, the project is aimed at populating a systematic database on the burning properties of CH_4, H_2 and other species of interest, in conditions typical of i.c. engines and gas turbines.
High-speed, high-resolution shadowgraph is used to record the flame growth and to infer laminar burning parameters. Details are given of the experimental apparatus and of the data analysis. Experimental results are presented for the combustion in air of CH_4-H_2 mixtures, with a H_2 percentage of 0% and 20% (vol.). All the tests were performed in the same conditions of initial pressure (0.6 MPa) and temperature (298 K). The lean part of the flammable range was scanned, varying the (global) equivalence ratio between 1.0 and the lower flammable limit. Data analysis yielded the (unstretched) laminar burning velocity and the Markstein length. The variation of these parameters was reported as a function of the equivalence ratio: the positive effect of H_2 addition to CH_4 was verified and quantified, in terms of decreased LFL and increased burning velocity.

Introduction
CO_2 reduction represents the main driver to the development of heat engines. As far as the specific case of internal combustion engines is concerned, one of the options is the application of gaseous fuels, like CH_4, the lower C/H ratio of which represents an immediate advantage over other hydrocarbon fuels. Essential to the development of dedicated systems is the knowledge of fuel combustion characteristics, which can be ultimately expressed through laminar burning properties. While the amount of experimental and/or numerical data on the flame characterization of gaseous fuels is noteworthy [1-3], literature still lacks a systematical approach, allowing a well-defined frame of reference for the performance analysis and design of i.c. engines. A further dimension to the problem is added by the possibility of enhancing the combustion properties of CH_4 by H_2 addition: a promising solution, which is still asking for clear assessment in engine-like conditions.

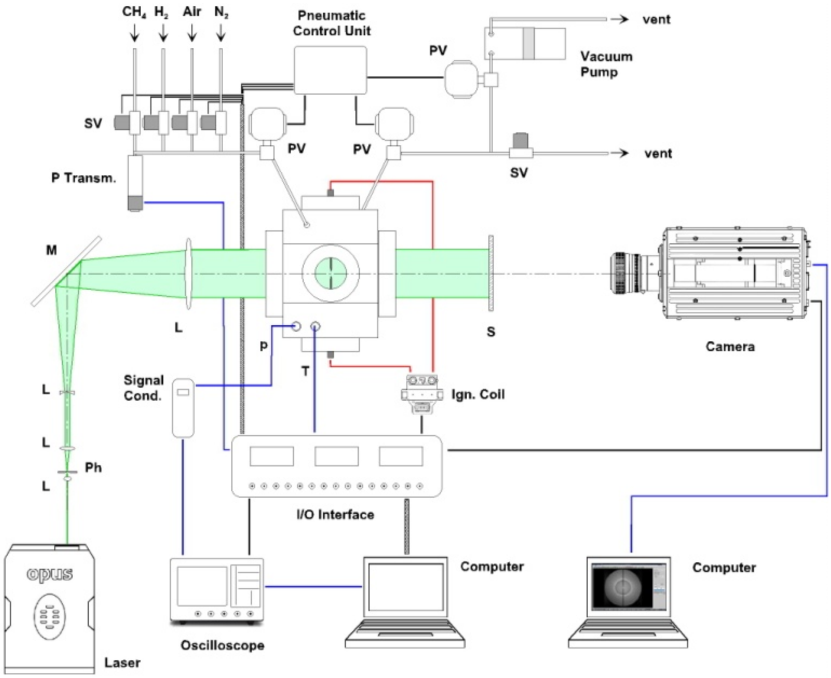

Figure 1. Experimental apparatus.

Experimental setup and procedures

The general arrangement of the experimental layout is shown in Figure 1: a detailed description is given in [4]. The DHARMA laboratory is built around an optically-accessible, constant-volume bomb, made of stainless steel (AISI 316). The cylindrical test chamber (i.d. = 0.070 m, h = 0.090 m) can withstand a maximum pressure of 20 MPa (static). A total of 6 optical accesses are available: the larger viewports are normal to the chamber axis, providing nearly full access to chamber bore; smaller viewports are positioned on the chamber side, along two orthogonal axes. A total of 4 additional service ports are available for the intake and the exhaust of the gases.

The mixture is ignited with an automotive inductive ignition system (energy ≤ 60 mJ): the spark discharge takes place in the center of the chamber between two pointed-tip tungsten electrodes (0.001 m diameter), with a 0.001 m gap.

Pressure signal during the combustion events is detected by a pre-amplified high-frequency dynamic transducer (res. freq. ≥500 kHz, rise time ≤1 μs, sensitivity 14.5 mV/mbar), coupled to a matching signal conditioner (1 MHz, 1:1 gain). Temperature of the gases is measured with a metal-shielded, type K thermocouple.

Mixture is prepared from high purity gases (CH_4: 99.9995%, H_2: 99.999%, dry air: 99.999%, N_2: 99.9995%) relying on the partial pressures method: the amount of gas is metered by solenoid valves and the pressure is monitored by a high-accuracy pressure transmitter. After each test, the system is pumped down to 10^{-2} mbar. All

the systems operate with a high degree of automation, to maximize safety and repeatability of the tests.
A parallel-beam direct shadowgraph diagnostic scheme [4] has been implemented to analyze spherical expanding flames and infer the laminar characteristics of fuels. Light source is a c.w. DPSS laser (2W @532nm); high-speed, time-resolved visualization is accomplished by means of a CMOS camera (*Photron SA-5*, 1024x1024 pixel, 1000000 fps, shutter time ≥ 368 ns).

Theoretical Background

The shadowgraph images of the spherical expanding flame allow to evaluate the laminar burning parameters, according to a well-known approach [2-4]. The time evolution of r_u (the flame radius on the *unburned* gas side) is obtained through frame-by-frame analysis; the *stretched* flame speed V_s can then be evaluated as:

$$V_s = \frac{dr_u}{dt} \tag{1}$$

The obtained speed includes the stretch effects associated to the propagation of a flame surface, undergoing curvature and flow dynamic strain [5]. The flame stretch is defined as the relative rate of change of the flame area: for a spherically expanding laminar flame it can be expressed as:

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{2}{r_u}\frac{dr_u}{dt} = 2\frac{V_s}{r_u} \tag{2}$$

As originally suggested by Markstein, the relationship between flame speed and stretch is linear; it can be expressed after Clavin [5] as:

$$V_s = V_{s0} - L_b \cdot \alpha \tag{3}$$

where V_{s0} is the unstretched flame speed and L_b is the burned gas Markstein length, which indicates how and to what extent the flame is influenced by the stretch.
In the hypothesis of constant pressure, the unstretched flame speed V_{s0} is related to the unstretched laminar burning velocity u_{l0} through the following relation:

$$u_{l0} = V_{s0}\frac{\rho_b}{\rho_u} \tag{4}$$

where ρ_b is the density of burned gases and ρ_u the density of unburned gases.

Results and Discussion

The combustion behavior of lean CH_4-air and CH_4-H_2-air (20% H_2) mixtures has been compared. The results were obtained at initial temperature T_0 = 298 K and initial pressure P_0 = 0.6 MPa. The equivalence ratio ϕ was varied from 1.0 to the LFL. Spark energy was 20 mJ: being delivered by an inductive ignition coil, only a small fraction of this energy is released in the breakdown phase, which governs the early kernel growth [4]: the extent of the ignition disturbances can be expected to be accordingly limited.

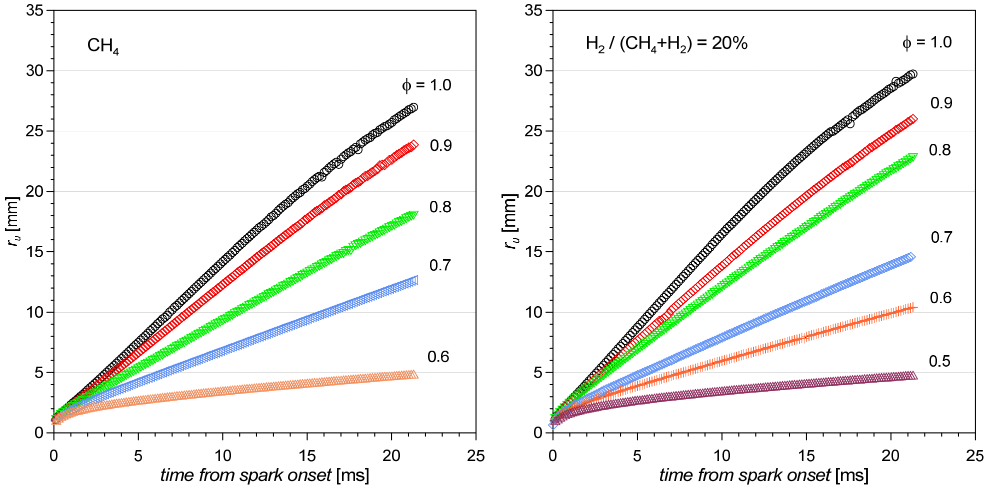

Figure 2. Measured flame radii. P_0 = 6 bar, T_0 = 298 K.

An image processing routine has been implemented to infer the flame radius r_u from the shadowgraph data: for each frame, the flame contour is traced and the enclosed area is evaluated; the radius is estimated as that of a circle of equal area to the flame. In Figure 2 the evolution of the flame radius r_u is reported, for CH_4 and CH_4-H_2, at different equivalence ratios: each set of data correspond to a single, time-resolved combustion event, which has been selected as representative of the test conditions (P_0, T_0, % H_2, ϕ). For each case, all the measured radii are reported, spanning from the spark inception up to the largest traceable front.

As stated earlier, laminar flame parameters can be meaningfully inferred as long as pressure keeps constant. Moreover, as stated by Bradley et al. [1], the early stages of the flame kernel growth are affected by the spark energy release, and cannot be taken into account in the evaluation of laminar flame properties.

In the current series of measurements, data analysis was limited to the range ~2.5mm to ~9.5mm (corresponding to ~27% of the chamber radius): the stretched flame speed V_s was evaluated from derivation of a polynomial fit of the above-defined data subsets [3].

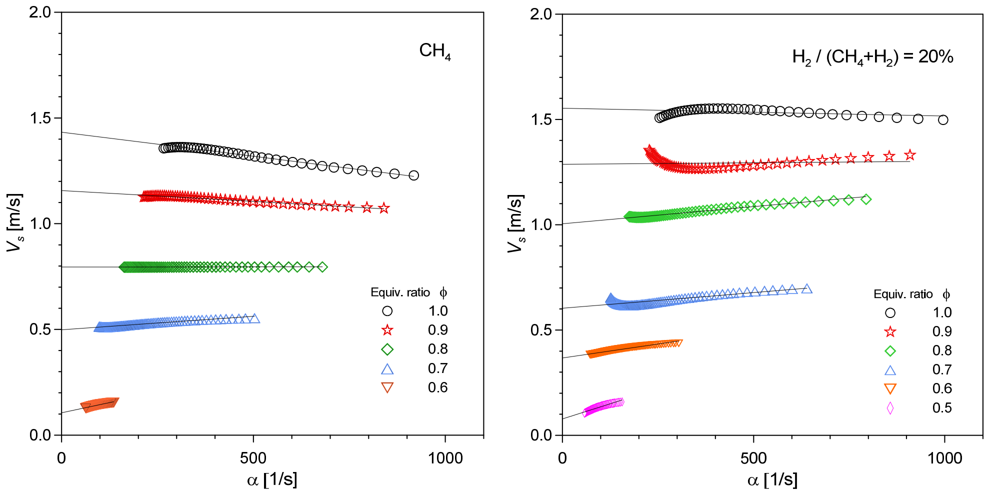

Figure 3. Stretched flame speed vs. α. $P_0 = 6$ bar, $T_0 = 298$ K.

Knowing V_s and r_u, the stretch rate α was evaluated after equation (2): the plot of the stretched flame speed against α is shown in Figure 3.
According to equation (3), linear-fit extrapolation of the flame speed to $\alpha = 0$ gives the unstretched flame speed V_{s0}, while the slope of the fit allows to estimate the burned gas Markstein length L_b.

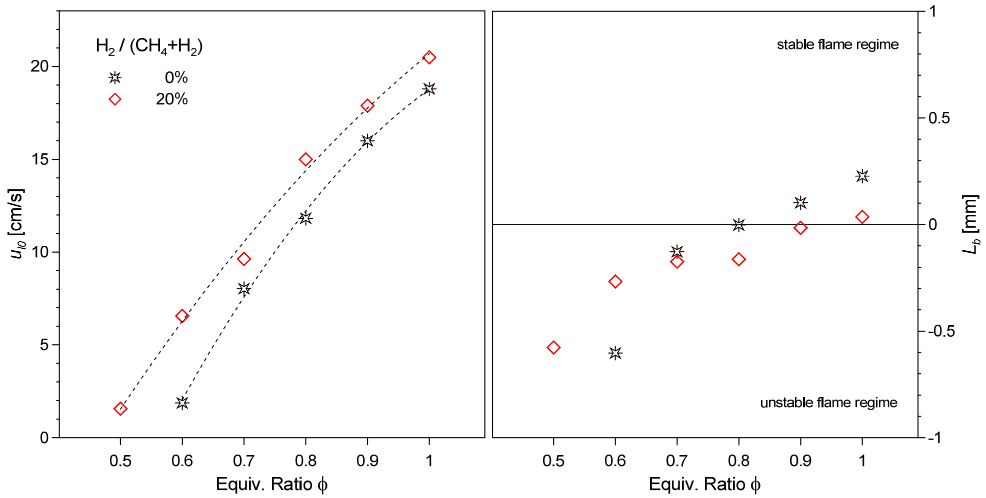

Figure 4. Laminar flame speed (left) and Markstein length (right) as a function of ϕ. $P_0 = 6$ bar, $T_0 = 298$ K.

The unstretched laminar burning velocity u_{l0} was obtained through equation (4), where the expansion factor ρ_b/ρ_u was evaluated from the properties of the reactant species and of equilibrated adiabatic products. The u_{l0} and L_b values are reported in Figure 4 as a function of the equivalence ratio, for pure and H_2-enriched CH_4.
The addition of 20% H_2 to CH_4 increases the laminar burning velocity, which is proportionally higher for leaner mixtures: the observed gain ranges from 10% @ ϕ=1.0 to >20% @ ϕ=0.7. The overall effect is the extension of the flammable range of at least 0.1 (in terms of ϕ). As the mixture is leaned, the flame gets more and more unstable, as confirmed by the decreasing Markstein length: in the case of CH_4, L_b assumes a negative value after ϕ=0.8; the addition of 20% H_2 shifts the L_b values of CH_4 of ~ -0.15mm, making almost all the CH_4-H_2 flames to fall in the unstable regime. This behavior confirms the findings of Hu et al. [6], who show that a clear relationship exists between flame front instability and hydrogen percentage.

Summary
Experimental evaluation of the laminar burning characteristics of lean CH_4-H_2-air mixtures has been carried out in the DHARMA lab, at P_0 = 6 bar, T_0 = 298 K. Unstretched laminar burning velocity and Markstein length were reported as a function of the equivalence ratio ϕ: the effect of H_2 addition to CH_4 was assessed in terms of increased u_{l0}, reduced LFL and increased flame instability (negative L_b).

References

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