Burning behaviour of selected biogas and syngas mixtures

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Abstract
Experimental evaluation of the combustion characteristics of carbon-neutral, biomass-derived fuels has been carried out. Since these fuels are meant as likely replacement for CH_4, a comparison was drawn with methane in the same operating conditions. Tests were performed in the high-pressure, constant-volume DHARMA reactor at Istituto Motori - CNR. The laminar burning parameters were evaluated analyzing spherical expanding flames. The flame growth was recorded by means of high-speed, high-resolution shadowgraph; image processing and stretch analysis allowed to infer the laminar burning velocity and the Markstein length for each test case. Results are presented for the combustion in air of CH_4-CO_2 (55-45 % vol.), H_2-CO (5-95 % vol.) and a wood gasification product. All the tests were performed at 0.6 MPa and 301 K. The equivalence ratio ranged between 1.0 and the lower flammable limit. The unstretched laminar burning velocity and the Markstein length are reported for each fuel as a function of the equivalence ratio.

Introduction
It is some years that CO_2 reduction got the status of an imperative. Since then the technological development of energy systems has been following a number of paths: CO_2-neutral fuels, higher combustion efficiency, low-carbon fossil fuels. In practice, the efforts aim to the replacement of fossil fuels by biomass/renewable sources, to the retrofitting/re-design of combustion systems, or, typically, to the combination of both approaches [1].
A wide range of fuels has been proposed, deriving from the gasification of biomass, wastes and even fossil fuels: the technological appeal of fuels like *syngas* or *biogas* resides in the potential of CO_2-neutral energy conversion, of waste recycling, of small scale CHP production. Nevertheless, the composition of these gas fuels is strongly affected by the production process and by the feedstock. Therefore the picture emerges of a wide range of eco-friendly gas mixtures, which are asking for characterization as fuels. In order to optimize and/or design i.c. engines and gas turbine combustors, the knowledge is needed of the fuel-specific combustion properties: these can be expressed in terms of laminar burning velocity and Markstein length, and offer the basis for modelling and simulation of flame-turbulence interaction [2,3].

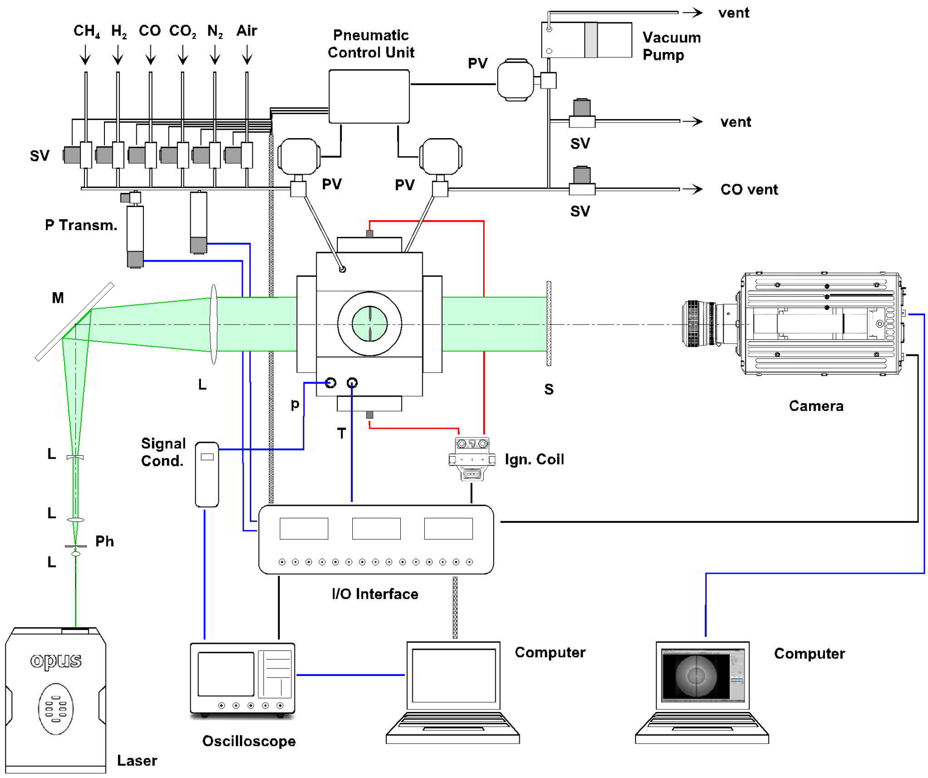

Figure 1. Experimental apparatus.

Experimental setup and procedures

The general arrangement of the experimental layout is shown in Figure 1: a detailed description is given in [3]. The heart of the DHARMA (*Device for Hydrogen-Air Reaction Mode Analysis*) laboratory is an optically-accessible constant-volume test reactor, made of stainless steel (AISI 316): the cylindrical chamber (i.d. = 70 mm, h = 90 mm, aspect ratio = 1.29) is rated for maximum pressure ≤ 20 MPa (static). 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.

The gas handling system allows to prepare combustible mixtures of variable composition with high accuracy, up to 30 bar. The mixtures are obtained from high purity gases with the partial pressures method. 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 [3] has been implemented to analyze spherical expanding flames and infer the laminar characteristics of fuels. It is based on a c.w. DPSS laser and a high-speed CMOS camera (*Photron SA-5*).

Theoretical Background

According to a well-known approach [2,3], the time evolution of r_u (the flame radius on the *unburned* gas side) is obtained through frame-by-frame analysis of high speed recordings; 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. The flame stretch is defined as:

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

The relationship between flame speed and stretch has been thoroughly investigated: its expression depends on the number and nature of the related assumptions [3]. In the present work, following a comparison between linear and non-linear models, a *linear* relationship between flame speed and stretch was found to satisfactorily fit the current data sets. It can be expressed after Clavin [3] 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.

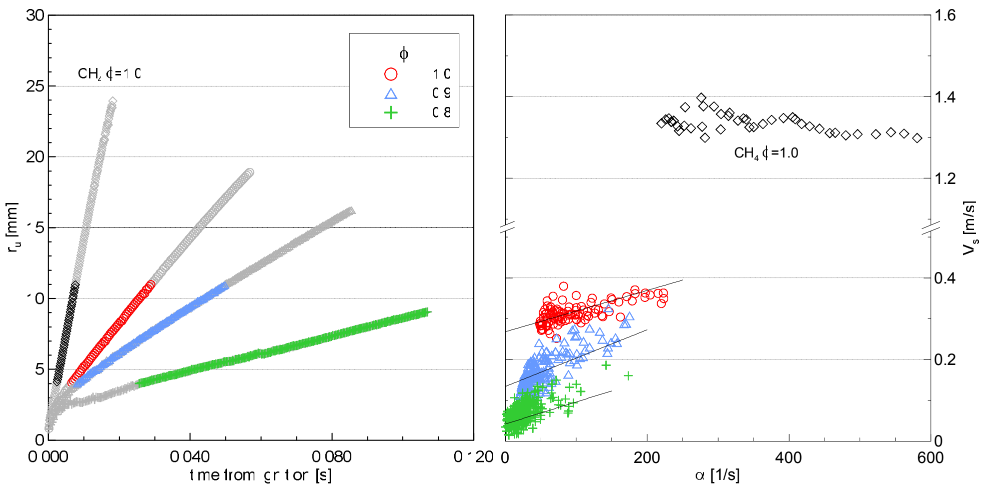

Figure 2. Flame radius and stretched propagation speed for CH_4-CO_2.

In the hypothesis of constant pressure, the unstretched flame speed V_{s0} is related to the unstretched laminar burning velocity u_{l0} through the expansion ratio:

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

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

Results and Discussion

In Fig. 2 the results are reported for the combustion of CH_4-CO_2 mixtures, with a CO_2 percentage of 45% (vol.): this composition is typical of a *landfill gas* [4].

The tests have been carried out at $T_0 \cong 301$ K and $P_0 = 6$ bar (abs.), in the lean part of the flammability range ($\phi = \phi_{min} \div 1.0$). Figure 2 (left) shows the time evolution of the flame radius $r_u = r_u(t)$. Since the early stages of the flame kernel growth are affected by the spark energy release, they must be discarded. Also, the analysis can be carried out until the chamber pressure doesn't show a sensible increment.

In the current tests, the useful data subset was 4÷11 mm: this interval is evidenced with color symbols for each case.

The case of stoichiometric CH_4 combustion is reported as a reference, allowing to appreciate the slower kinetics of CH_4-CO_2 combustion. Fig. 2 (right) shows the stretched propagation velocity as a function of the stretch rate α.

In Fig. 3 the case of stoichiometric H_2-CO combustion in air is reported. The amount of H_2 is 5% (vol.), representative of a typical *syngas* [4,5]. Even with a limited amount of hydrogen, the behavior of this mixture is definitely better than CH_4.

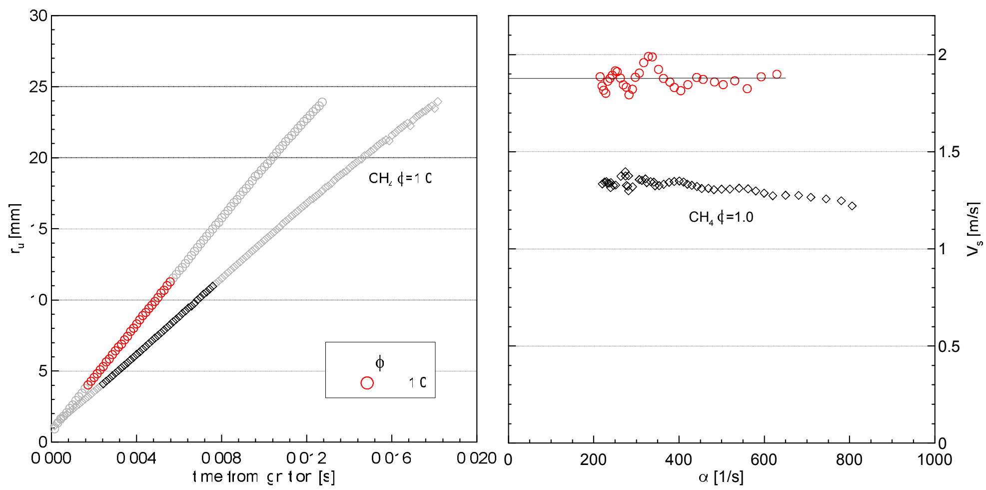

Figure 3. Flame radius and stretched propagation speed for H_2-CO.

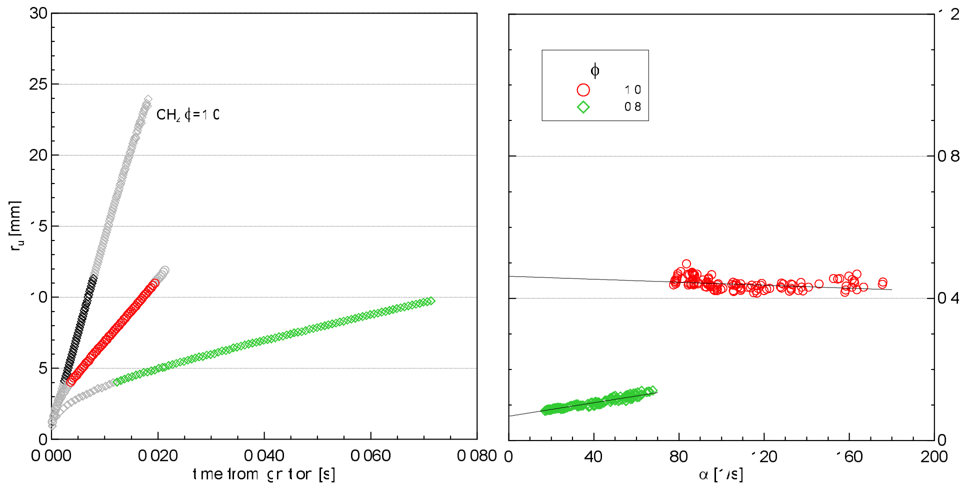

Figure 4. Flame radius and stretched propagation speed for gasification gas.

In order to deal with a more true-to-life fuel, a mixture has been analyzed, which replicates the output of an actual wood gasification plant [6]: details of the composition are shown in Table 1.

Table 1. Volumetric composition of gasification gas (GG).

H_2	CH_4	CO	CO_2	N_2
0.3539	0.0436	0.2792	0.3011	0.0222

Figure 4 reports the results obtained for the gasification gas: the sensible amount of CO_2 stands for a modest performance, if compared to CH_4: propagation speed at $\phi = 1.0$ is 1/3 of methane.
The above-described results allow to obtain the laminar burning parameters for the tested fuel mixtures, namely the unstretched laminar burning velocity u_{l0} and the Markstein length L_b. Figure 5 report the results for u_{l0} (left) and L_b (right) as a function of the equivalence ratio ϕ. The values obtained with CH_4 are reported as a reference. Biogas (CH_4-CO_2) is characterized by laminar burning velocities comparable to very lean CH_4 mixtures ($0.55<\phi<0.65$).
Syngas (H_2-CO) shows u_{l0} values about 30% larger than CH_4 for ϕ=1.0. The case of a H_2-CH_4 mixture (50-50 % vol.) is added, to highlight the role of H_2 as fuel-enhancer. The gasification gas (GG) exhibits laminar burning velocities u_{l0} larger than CH_4/CO_2 but definitely smaller than CH_4. As shown by the values of the Markstein length in Fig. 5 (right), either biogas or GG show larger flame instability than CH_4, being characterized by negative L_b. Anyway, they present a similar trend with the equivalence ratio, since L_b decreases with ϕ. The tested syngas is characterized by a Markstein length close to zero at ϕ=1.0.

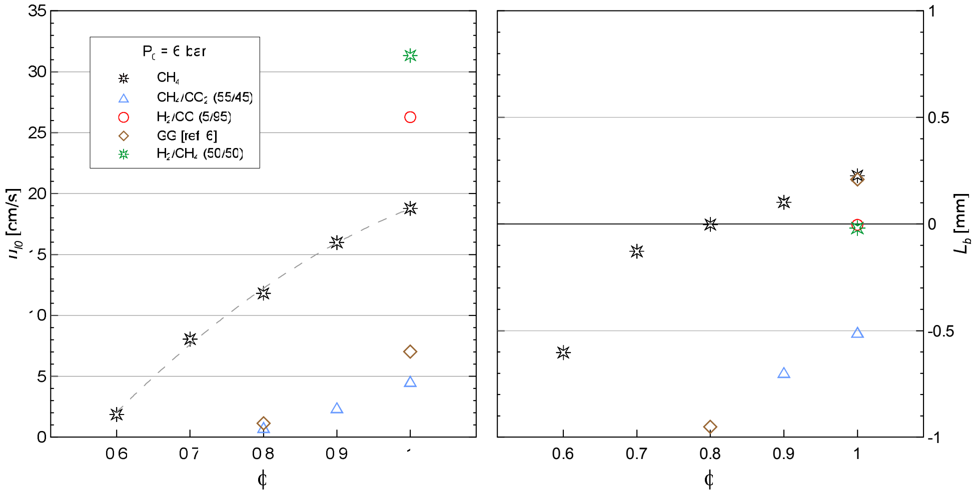

Figure 5. Laminar burning velocity (left) and Markstein length (right) as a function of ϕ. $P_0 = 6$ bar, $T_0 = 301$ K.

Acknowledgments

The research was partially supported by the Italian Ministry of Economic Development within the framework of the Program Agreement MiSE-CNR “Ricerca di Sistema Elettrico”.

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doi: 10.4405/39proci2016.V3