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# Experimental studies of the fundamental flame speeds of syngas ($H_2$/CO)/air mixtures

Nicolas Bouvet [a], Christian Chauveau [a,*], Iskender Gökalp [a], Fabien Halter [b]

[a] *Centre National de la Recherche Scientifique Institut de Combustion, Aérothermique, Réactivité et Environnement, 1C, Avenue de la Recherche Scientifique, 45071 Orléans Cedex 2, France*
[b] *Université d'Orléans, Institut PRISME, 8 rue Léonard de Vinci, 45072 Orléans Cedex 2, France*

## Abstract

Syngas laminar flame speed measurements have been carried out at atmospheric pressure and ambient temperature using spherically expanding flames. Mixture compositions ranging from 5/95% to 50/50% $H_2$/CO and equivalence ratios from 0.4 to 5.0 have been investigated. Both state-of-the-art linear and non-linear extrapolation methodologies have been tested and extracted laminar flame speeds have been compared to datasets available in the literature as well as computations using two leading kinetic mechanisms for syngas combustion. Syngas flame sensitivities to stretch have been characterized by extracting the corresponding Markstein lengths. In order to explain important disparities found for rich syngas flames among datasets of the literature, computations have been performed to quantify the possible extent of velocity reduction corresponding to small contents of iron pentacarbonyl.

*Keywords:* Laminar burning velocity; Markstein length; Syngas; Spherical expanding flame; Stretch rate

## 1. Introduction

Synthetic gas mixtures, better known as "Syngas", have recently received a particular interest from the combustion community due to the increasing demand of the gas turbine industry to adapt dry low $NO_x$ combustors for $H_2$/CO blend combustion. Among fundamental flame properties required to better understand "syngas burning", the fundamental flame speed is probably one of the most important since it provides detailed information on thermochemical processes governing the fuel combustion. It is therefore extensively used for the validation of combustion models.

Several fundamental flame speed studies of syngas blends have been reported in the literature including measurements performed on conical [1–3], counterflow [4] and outwardly expanding flames [5–9]. If the former configuration is known to suffer from stretch effect, the two latter allow for its systematic subtraction using adapted extrapolation procedures. Recent improvements for the outwardly propagating flame processing algorithm include both robust linear [10] but also non-linear extrapolation methodologies specifically developed for higher hydrocarbon fuels [11]. This non-linear approach provides increased accuracy for flames with strong non-linear answers at higher stretches

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[*] Corresponding author. Fax: +33 238 25 78 75.
*E-mail address:* chauveau@cnrs-orleans.fr (C. Chauveau).

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and by avoiding biasing effects inherent to linear extrapolation procedures.

Although several syngas flame speed investigations have been carried out in the past, just a very few covered a large range of equivalence ratios, including both ultra-lean to very rich mixtures. Among these ones, important scatters are still remaining, as pointed out in a recent syngas combustion kinetics review by Chaos and Dryer [12]. The objectives of the present investigation are therefore to accurately determine fundamental flames speed of various syngas blends using the outwardly propagating flame configuration and both linear and non-linear processing methodologies. The results will be compared to datasets of the literature as well as computations using leading syngas kinetic mechanisms. Discrepancies between results obtained with both linear and non-linear procedures will be characterized. Disparities observed between available flame speed datasets will be numerically analyzed in the light of a potential influence of carbonyl compounds, known to be strong flame inhibitors [12,13].

## 2. Experimental approaches

### 2.1. General configuration and experimental procedure

The experimental apparatus and diagnostic arrangement used in the present investigation are similar to those presented in Ref. [10]; they will be briefly described here. The combustion vessel is a 24.32 l stainless steel cylindrical chamber (160 mm ID, 300 mm height). Two sharpened-edge tungsten electrodes linked to a conventional capacitive discharge ignition system are used to provide the ignition energy. The electrode plane is slightly tilted with respect to the plane of observation to avoid the recording of disturbances inherent to the ignition event. The spark gap can be varied and was usually set between 1 and 2 mm. The volumes of each mixture component ($H_2$/CO/air) are sequentially injected in the combustion chamber thanks to dedicated mass flow controllers digitally piloted via a RS232 serial port. Gas volumes delivered by the flow controllers were periodically checked with wet meters (measuring uncertainty of 0.5%) and were found to be within 1.2% of the input values, allowing an equivalence ratio precision of ±1.4%. The pressure and the temperature inside the chamber are measured using a piezoelectric transducer and a type K thermocouple, respectively. A fan located inside the vessel ensures a homogeneous mixing of reactants prior to ignition. Specific efforts were made to render the entire gas supply network compatible with CO, as further detailed in Section 4.3.

The optical access to the chamber is provided through two opposite portholes. A continuous Stabilite 2017 argon ion laser (6 W, $\lambda = 457.9$–514.5 nm) along with two planoconvex lenses ($f_1 = 25$ mm; $f_2 = 1000$ mm) are used to create the parallel light beam that crosses the combustion chamber. A transparent screen located at its back allows for the display of the shadowgraph images. Shadowgrams of outwardly propagating flames are recorded using a high speed CMOS APX camera operating at 6000 and 15,000 frames/s for 512 × 512 and 256 × 256 pixel size frames, respectively. The spatial resolution achieved is close to 135 μm/pixel in all cases. The entire setup is shown in Fig. 1.

The initial pressure and temperature conditions were kept in the ranges of $1.04 \pm 0.035$ bar and $295.3 \pm 3.7$ K, respectively. Ignition is initiated few minutes after complete chamber filling in order to make sure that quiescent flow conditions were achieved. The ignition sequence was then triggered and the flame front propagation evolution was recorded using the synchronized high speed camera.

During the present investigation, experimental runs were repeated three times in average. The corresponding standard deviations for the flame propagation speed were found to be in a 0.1–7.8 cm $s^{-1}$ range. They are plotted in the form of vertical error bars in the graphs presented herein.

### 2.2. Processing steps

The flame propagation observed on the recorded movies demonstrates a spherical evolution for all flame radii. A conventional assumption to simplify the flame front processing step is that the development of such flames is perfectly spherical and hence, flame fronts can be fitted by the equation of a circle. This approach has been adopted by Tatouh and coworkers in Ref. [10]. Their flame edge detection program is here applied to the present shadowgraph images. This program is successively performing: (i) a background subtraction to enhance the flame front detection;

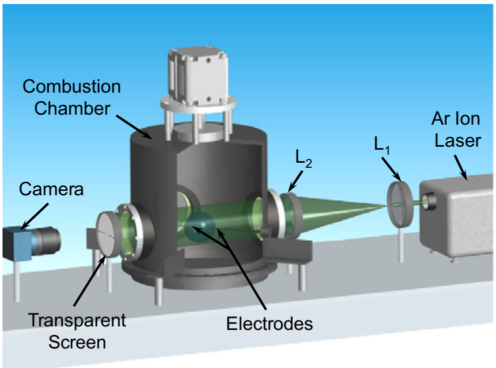

Fig. 1. Schematic of the combustion chamber and shadowgraph system.