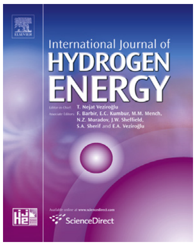
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 1874–1881

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



Laminar burning velocities of rich near-limiting flames of hydrogen

V.V. Zamashchikov [a], V.A. Alekseev [b,*], A.A. Konnov [b]

[a] Institute of Chemical Kinetics and Combustion SB RAS, Institutskaya 3, 630090 Novosibirsk, Russian Federation
[b] Division of Combustion Physics, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden

ARTICLE INFO

Article history:
Received 13 September 2013
Received in revised form
11 November 2013
Accepted 15 November 2013
Available online 15 December 2013

Keywords:
Hydrogen
Flame
Burning velocity
Stretch correction

ABSTRACT

In the present work, near-limiting hydrogen flames were investigated both experimentally and numerically. Very rich hydrogen + air flames were studied in a constant volume bomb equipped with a pressure sensor and a Schlieren system for optical registration of the flame front movement. The mixtures contained 70% and 75% of hydrogen, the rest being air. The measurements were conducted at pressures from 1 to 4 atm for 70% H_2 + air mixture and from 0.7 to 1.4 atm for 75% H_2 + air mixture. Two methods for determination of the laminar burning velocity were used: from the temporal evolution of the flame front movement and from the pressure records at nearly constant pressure. These methods were compared and discussed in terms of accuracy and implicit assumptions behind them. Markstein lengths were also extracted and compared with the literature by using different extrapolation models. An important role of the critical radius for extraction of the burning velocity and Markstein length is demonstrated. New experimental data are compared with three models for hydrogen combustion to elucidate the need for their further development.

1. Introduction

Laminar burning velocity is a critical characteristic of any combustible mixture, varying with its composition, pressure and initial temperature. Idealized 1D burning velocity can nowadays be easily calculated employing detailed kinetic mechanisms and, therefore, it is used for their validation whenever experimental data are available. Measurements of the burning velocity of hydrogen have a long history and showed significant spread until it was realized that apparent burning velocity is largely affected by the flame stretch and curvature [1]. Recent measurements in hydrogen flames possess good consistency from moderately lean to moderately rich mixtures. Moreover, contemporary models for hydrogen combustion [2–4] accurately reproduce burning velocities of these flames.

The situation is essentially different for near-limiting (very lean and very rich) mixtures. Significant spread of the laminar burning velocities in rich mixtures of hydrogen and hydrocarbons is a quite common problem that hampers validation of kinetic models at these conditions. Burke et al. [5] studied $H_2/CO/O_2$/diluent flames at low flame temperatures from atmospheric pressure up to 25 atm and compared their measurements with several contemporary kinetic models. They found that “large disparities are apparent among model predictions themselves at fuel-rich conditions, with variations of nearly a factor of three in predicting burning rates”.

---

* *Corresponding author*. Tel.: +46 462223208; fax: +46 462224542.
E-mail addresses: albor@kinetics.nsc.ru (V.V. Zamashchikov), vladimir.alekseev@forbrf.lth.se, hedgefog@gmail.com (V.A. Alekseev), alexander.konnov@forbrf.lth.se (A.A. Konnov).

http://dx.doi.org/10.1016/j.ijhydene.2013.11.054

Fig. 1 presents stretch-corrected burning velocities of rich (equivalence ratio $\phi \geq 5$) H_2 + air flames at atmospheric pressure. Older results (not shown here) are mostly of historical interest, yet it is remarkable that Scholte and Vaags [6] managed to burn a very rich mixture containing 80% of hydrogen though its upper flammability limit is close to 76% ($\phi = 7.54$). Most recent measurements in rich hydrogen + air flames performed during the last decade [7–10] look systematically higher than earlier results [11–13], although similar approaches for stretch correction were implemented. This makes the validation of the model predictions (also shown in Fig. 1) rather ambiguous.

In the present work, rich near-limiting hydrogen flames were investigated both experimentally and numerically. Spherical hydrogen + air flames in the range of pressures from 0.7 to 4 atm were studied in a constant volume bomb equipped with a pressure sensor and a Schlieren system for optical registration of the flame front movement. Two methods for determination of the laminar burning velocity were used: from the temporal evolution of the flame front movement and from the pressure records at nearly constant pressure. New experimental data are compared with the recent models for hydrogen combustion [2–4] to elucidate the need of their further development.

2. Experimental

Schematic of the experimental rig is shown in Fig. 2. The experiments were conducted in a stainless steel spherical chamber with the volume of 10 L. The chamber had two optical windows of 9 cm in diameter, a pressure gauge and two steel electrodes of 4 mm in diameter ended with 1 mm tungsten wires. The mixture was spark-ignited at the center of the chamber. The spark was obtained with a conventional capacitive discharge ignition system.

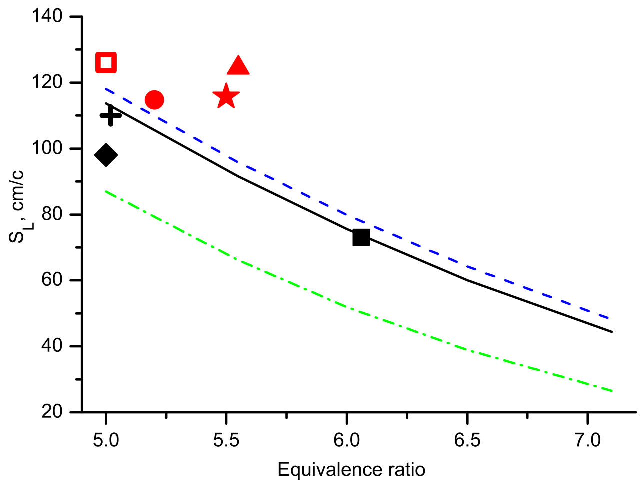


Fig. 1 – Burning velocities of hydrogen + air flames at atmospheric pressure. Symbols: experiments, lines: modeling. Cross [11], solid square [12], diamond [13], circle [7], open square [8], star [9], triangle [10]. Solid line: mechanism of Konnov [2], dashed line: mechanism of Burke et al. [4], dash-dot line: mechanism of Hong et al. [3].

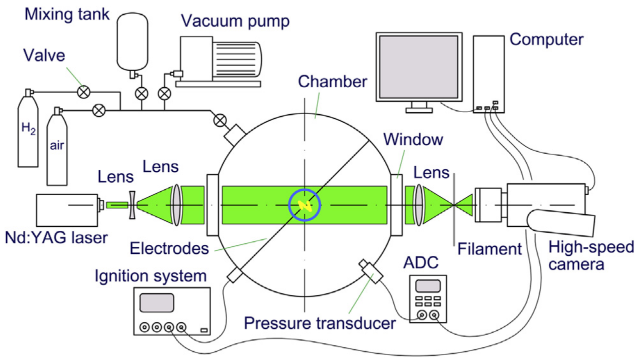


Fig. 2 – Experimental setup (not to scale).

An optical setup was built for the registration of the flame front movement, which consisted of a frequency-doubled Nd:YAG laser LS-3-N-532/2000, a lens system and a high-speed video camera AOS X-PRI. A laser beam was expanded and then collimated again to a parallel beam, which was directed through the chamber. After that it was focused on a 0.3 mm filament. The camera was placed after the filament, so that only the part of light dispersed due to refractive index gradient could reach the camera. Since the gradient is the highest in the flame front, the camera recorded its position.

The pressure inside the chamber was measured with an inductive pressure transducer (DD-10), which allows to register the changes in pressure with a frequency up to 10 kHz. The electrical signal from the transducer was read by an ADC. Prior to experiments, the pressure sensor was calibrated.

The mixtures were composed by the partial pressures of its components and contained 70 ± 0.5% and 75 ± 0.5% of hydrogen, the rest being air. Prior to the experiments, the chamber was evacuated and filled with the mixture to the desired pressure. The initial pressure in the chamber was measured with standard manometers. The signal from a computer triggered the ADC, the camera and the ignition system, the latter after a certain delay. The data from the camera and the ADC were recorded by the computer.

Mixtures containing 70% of hydrogen (equivalence ratio = 5.55) were ignited without problems over the entire pressure range from 1 to 4 atm. The distance between the electrodes in these experiments was set to about 1 mm. However, with this experimental configuration the flame kernel extinguished after ignition in the mixtures of 75% H_2 + 25% air (equivalence ratio = 7.1). In order to overcome the extinction, the distance between the electrodes was extended to 5 mm. At pressures close to atmospheric, these near-limiting flames propagated without signs of cells or cracks, as shown in Fig. 3. The laminar burning velocity decreased with the increase of the initial pressure starting from 0.7 atm, and at $p_i = 1.6$ atm the flame kernel could either extinguish or propagate over the chamber. Fig. 4 shows the flame front radius as a function of time for two cases: flame propagation (circles) and extinction (squares) at the same initial conditions. It can be seen that at first the flame front slows down, and then, in case of no extinction, the flame speed rapidly increases. Note that similar behavior was observed in rich hydrogen mixtures by Kelley et al. [14]. They attributed the