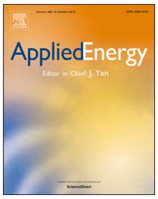
Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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



Assessment of uncertainties of laminar flame speed of premixed flames as determined using a Bunsen burner at varying pressures

S. Hu[a], J. Gao[b], C. Gong[a], Y. Zhou[b], X.S. Bai[a,*], Z.S. Li[b], M. Alden[b]

[a] *Division of Fluid Mechanics, Lund University, 221 00, Sweden*
[b] *Division of Combustion Physics, Lund University, 221 00, Sweden*

HIGHLIGHTS

- PLIF measurements and DNS of methane/air Bunsen flames in high pressures are reported.
- The accuracy of Bunsen burner rig for laminar flame speed measurement is evaluated.
- The mid-height of the flame gives the most accurate flame speed data.
- The flame-area and the flame-cone-angle experimental methods are compared.
- An optimal inlet velocity is found for measurement of laminar flame speed.

ARTICLE INFO

Keywords:
Methane/air
Laminar flame speed
Flame structures
High pressure
Bunsen burner

ABSTRACT

Laminar methane/air premixed flames at different pressures in a newly developed high-pressure Bunsen flame rig are studied using detailed numerical simulations and laser diagnostics. In the numerical simulations, one-dimensional and two-dimensional axisymmetric configurations were considered employing detailed transport properties and chemical kinetic mechanisms. In the measurements, OH PLIF was employed. The aims are to improved the understanding of the structures of the flames at varying pressures, to measure the laminar flame speed at different pressures, and to quantify the accuracy of the Bunsen flame method for measurement of laminar flame speed at different pressures. The stoichiometric and fuel-rich flames were found to exhibit a two-reaction-zone structure: an inner premixed flame in which the fuel was converted to CO and H_2, and an outer diffusion flame in which CO and H_2 were oxidized further to form combustion products. With increasing pressure, the inner premixed flame becomes thinner and the flame as a whole has the tendency to become unstable. Using the numerical and the experimental data, the methods of *flame-cone-angle* and *flame-area* were used to extract the laminar flame speed for different equivalence ratios and pressures. The flame-cone-angle method showed slightly better accuracy than the flame-area method did. The accuracy of both methods became lower under high pressure conditions. The inlet velocity of the burner was shown to affect the accuracy of the extracted laminar flame speed. For a stoichiometric atmospheric flame it was found that the most suitable inlet velocity for the fuel/air mixture was about 6 times the laminar flame speed, yielding a flame length about 7 times the radius of the burner. With appropriate flame length, the mid-height of the flame showed a rather low flame stretch rate, the laminar flame speed being in close agreement with the unstretched laminar flame speed, the error being less than 6% for the flames that were studied.

1. Introduction

The propagation speed of a planar unstretched laminar premixed flame under adiabatic condition, known as the *laminar flame speed* or *laminar burning velocity*, is an important property of the flame. It is widely used, for example, for obtaining a validation data in developing and refining chemical kinetics mechanisms [1–4] or as design data for the analysis of flame instability in premixed flame combustors [5,6]. It also serves as a key scaling parameter for certain important combustion characteristics, such as turbulent flame speed and flame position [7,8]. Laminar flame speed under high pressure conditions is of practical importance in the R&D of high-load combustors, such as internal combustion engines and gas turbine combustors. When unconventional fuels, such as biomass derived fuels or syngas, shall be used in

---

* Corresponding author.
E-mail address: Xue-Song.Bai@energy.lth.se (X.S. Bai).

http://dx.doi.org/10.1016/j.apenergy.2017.09.083
Received 15 January 2017; Received in revised form 6 September 2017; Accepted 12 September 2017
0306-2619/

Please cite this article as: Hu, S., Applied Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.09.083

combustion engines it is desirable to know the laminar flame speed of these fuels at engine relevant conditions. Due to the experimental difficulties, it is a challenge to measure the laminar flame speed at high pressures [9].

A number of recent studies on laminar flame speeds and flame structures have been carried out at different pressure and high temperature conditions, and for different fuels. Bao et al. [10] performed experimental measurements of the laminar flame speed of cyclopentanone, a product of biomass pyrolysis of agricultural waste, using a high-speed Schlieren photography technique in a constant volume combustion vessel. They developed empirical expressions of laminar flame speed for various equivalence ratios and initial temperatures. Using a similar technique and experimental rig, Askari et al. [11] carried out experimental studies and modeling of the flame structure and laminar flame speeds of H_2/CO/air/diluent (syngas) premixed flames at high pressures and temperatures. They reported that without the dilution of exhaust gas to the fuel/air mixture the flame surface became highly wrinkled, and it was then difficult to determine the laminar flame speed. Pugh et al. [12] studied the laminar flame speed and Markstein length of steelworks gas blends, which are mixtures of coke oven gas (COG) blended with four blast furnace gas mixtures (BFG) (containing N_2, CO_2, CO and H_2) using the constant volume combustion vessel rig. Under atmospheric conditions they reported smooth flame surface, which allows them to determine the laminar flame speed and the Markstein length. Munajat et al. [13] carried out meaurements of laminar flame speed of gasified biomass gas (CBG) using a Bunsen burner rig and Schlieren photography. They reported the influence of water vapor and tar component on the flame speed of GBG mixtures. Their work was limited however to atmospheric conditions.

There are various experimental rigs that have been developed for the measurements of laminar flame speed [14,15], such as the constant volume combustion vessel rig discussed earlier [10–12], the planar flame heat-flux burner, the counterflow burner, and the Bunsen burner (used in Ref. [13]). The advantages and drawbacks of these different experimental rigs were discussed in a recent review by Egolfopoulos et al. [15]. The Bunsen flame burner is one of the most widely used rigs for measuring laminar flame speed, due to its simplicity and well-defined flame structure. The flame is easier to stabilize at the burner rim and the shape and length of the flame are less sensitive to disturbances of the burner flow. However, the accuracy of the flame speed as measured using the Bunsen burner is often difficult to assess, due to the heat loss to the burner rim and the high stretch rate at the tip of the flame, where the flame front being highly curved [16–18]. In many previous Bunsen burner experiments, the errors in laminar flame speed introduced by the heat loss and the flame stretch involved were often not known [15].

In a Bunsen burner experiment, the flame front is visualized using different techniques, such as those of planar laser induced fluorescence (PLIF) iamging of CH, CH_2O, and OH radicals [19,20], and Schlieren photography [9]. The flame front of a round Bunsen burner is of conical shape. Two methods can be used for determining the laminar flame speed with use of a Bunsen burner. The first is one based on the apex angle of a conical flame [14]. Assuming that the flame has a perfect right circular cone shape and a height of H, a velocity of U in front of the flame front, and a half apex cone angle of α, the laminar flame speed (denoted as S_L) can be calculated as follows:

$$S_L = U\sin(\alpha) = UR/\sqrt{R^2 + H^2}. \tag{1}$$

where R is the radius of the burner. In reality, the flame is not perfectly right-circular-cone-shaped, due to the non-uniformity of the flow velocity. An alternative method of determining the laminar flame speed is one based on the area of the flame surface,

$$S_L = \dot{m}/A_f = \pi R^2 U/A_f \tag{2}$$

where $\dot{m}$ is the mass flow rate of the burner, and A_f is the area of the flame surface. This method gives an area-averaged flame speed. For both methods, the effects of heat loss from the flame to the burner rim and the effects of flame stretch/curvature on the flame speed are not eliminated. Thus, the measured laminar flame speed using (1) and (2) is not identical to the unstretched flame speed. The flame is also of a certain thickness, which implies that the surface area of the flame and the angle α depend upon the visualization technique employed [14].

Despite the obvious drawbacks of the method referred to above, the Bunsen burner has been used in many recent experiments concerning laminar flame speed [13,21,22], and it is preferred in particular under high pressure conditions [9], due to its simplicity and robustness. We have recently developed a high pressure Bunsen burner that can operate at pressure of up to 36 bar [23]. The rig has a full optical access that permits the PLIF imaging of several species that are found in the reaction zones, such as OH and CH_2O. The present study is aimed at employing the PLIF data for determining the laminar flame speed of a methane/air mixture at varying equivalence ratios and pressures.

The work carried out here particularly concerns with evaluating the uncertainty of the measured laminar flame speed in a Bunsen flame burner. In order to do this, direct numerical simulations (DNS) of the Bunsen flames were carried out, making using of data concerned with the detailed chemical kinetics and the transport properties involved. The DNS data provide the information needed for assessing the effects of flame stretch and of the non-uniformity of the flow on the flame speed. The DNS results are compared with the PLIF results for the flame topology and the reaction zone structures. The numerical results are then used to evaluate the laminar flame speed, using the flame cone angle method, Eq. (1) and the flame area method, Eq. (2). Numerical simulations of one-dimensional planar unstretched adiabatic laminar premixed flames were also carried out in order to be able to compare the results with experiment data and with DNS results obtained for the Bunsen burner. All the tests were performed for methane-air premixed flames at the standard temperature (298 K) over a range of pressures (1–5 atm) and of equivalence ratio (from fuel-lean to fuel-rich conditions). The main aims of this study are to quantify the accuracy of the Bunsen flame method for measurement of laminar flame speed, and to increase the understanding of the structures of the flame near the burner, on the main surface of the flame, and at the burner tip under different pressure and equivalence ratio conditions.

The paper is organized as follows. In the next section the high pressure Bunsen burner rig and the experimental method employed are presented. In Section 3 the DNS method and the computational setups employed are described, the flame stretch rate and the local displacement speed of the iso-surfaces involved also being discussed. In Section 4 experimental and DNS results are presented, this being followed by presentation in Section 5 of the conclusions arrived at.

2. Experimental measurements

A schematic of the burner used in the study is shown in Fig. 1. The high pressure rig is of cylindrical shape and is constructed of stainless-steel. The chamber can operate of a maximum pressure of 36 bar and a maximum ambient temperature of 220 °C. The chamber has an internal volume of 25 l. The cylindrical chamber has an inner height of 500 mm and an inner diameter of 254.5 mm. This high pressure chamber has four viewports positioned at angles of 0°, 90°, 180°, and 270° for full optical access into the chamber with use of various line-of-sight and scattering optical diagnostic techniques. The pressure inside the chamber was kept constant by regulating the exiting gas flow rate electronically with use of back-pressure regulators. The experiments were conducted at steady pressure levels, the deviation of the pressure from the value set being less than 1%. The ambient temperature inside the chamber was monitored by thermocouples. Further details of the high pressure rig are provided in Ref. [23].

The burner is composed of a central inner tube with an inner diameter of 7 mm and a coaxial outer tube with an inner diameter of