Sci. Bull.
DOI 10.1007/s11434-016-1143-6

www.scibull.com
www.springer.com/scp

Review

Engineering Sciences

The constant-volume propagating spherical flame method for laminar flame speed measurement

Mahdi Faghih · Zheng Chen

Received: 3 April 2016 / Revised: 28 May 2016 / Accepted: 17 June 2016

Abstract Laminar flame speed is one of the most important intrinsic properties of a combustible mixture. Due to its importance, different methods have been developed to measure the laminar flame speed. This paper reviews the constant-volume propagating spherical flame method for laminar flame speed measurement. This method can be used to measure laminar flame speed at high pressures and temperatures which are close to engine-relevant conditions. First, the propagating spherical flame method is introduced and the constant-volume method (CVM) and constant-pressure method (CPM) are compared. Then, main groups using the constant-volume propagating spherical flame method are introduced and large discrepancies in laminar flame speeds measured by different groups for the same mixture are identified. The sources of discrepancies in laminar flame speed measured by CVM are discussed and special attention is devoted to the error encountered in data processing. Different correlations among burned mass fraction, pressure, temperature and flame speed, which are used by different researchers to obtain laminar flame speed, are summarized. The performance of these correlations are examined, based on which recommendations are given. Finally, recommendations for future studies on the constant-volume propagating spherical flame method for laminar flame speed measurement are presented.

Keywords Laminar flame speed · Propagating spherical flame · Constant-volume method · Burned mass fraction · Methane/air

1 Introduction

Laminar flame speed, S_u^0, is an important intrinsic property of a combustible mixture. It is defined as the speed at which an adiabatic, unstretched, premixed planar flame propagates relative to the unburned mixture [1]. Laminar flame speed contains the physicochemical information about the mixture's diffusivity, reactivity, and exothermicity. It affects or even determines the burning rate of fuel/air mixtures in practical combustion systems [2]. Besides, many premixed flame phenomena, such as extinction, flash back, and blow off can be characterized by S_u^0 as a reference parameter [3]. In fundamental combustion research, S_u^0 is an important target for the validation of chemical mechanisms and for development of surrogate fuel models (e.g., [4–6]). Accurate flame speeds measured at high pressures and temperatures are very useful for developing/validating kinetic mechanisms of fuels. Furthermore, S_u^0 is popularly used as a scaling parameter for turbulent flame speed; and it is used in certain turbulent premixed combustion modelling [7].

Due to the importance of S_u^0, great attention has been paid to its *accurate* measurement. As reviewed in Refs. [1, 8, 9], several experimental approaches have been developed to measure S_u^0 using different flame configurations, including Bunsen flame [10], counter flow or stagnation flame [11–14], burner stabilized flat flame [15, 16], and outwardly propagating spherical flames [2, 8, 10, 17–32].

The Bunsen flame method was introduced by Bunsen [33]. This method was very common in the first century of

M. Faghih · Z. Chen (✉)
State Key Laboratory for Turbulence and Complex Systems (SKLTCS), Department of Mechanics and Engineering Science, College of Engineering, Peking University, Beijing 100871, China
e-mail: cz@pku.edu.cn

its introduction due to its simplicity and well defined structure. However, in recent years, it has been realized that Bunsen flame is affected by different factors such as flame instability, stretch, curvature and heat loss [34, 35]. Counter flow flame or stagnation flame was introduced in Ref. [36] and then it was used to measure S_u^0 [12]. The advantage of this method is that the influence of stretch on flame speed can be quantified and extracted by using the procedure proposed by Wu and Law [12]. However, it is difficult to use this method at pressures above 5 atm (1 atm = 1.013 × 10^5 Pa) [9]. The burner-stabilized flat flame method was first proposed by Botha and Spalding [37]. Later de Goey et al. [38] proposed the so-called heat flux method to measure S_u^0 from burner-stabilized flat flame. It has the advantages in circumventing the heat loss issue in burner stabilized flat flame. The drawbacks of heat flux method are the uncertainty of the method due to radiation, boundary condition effect at the burner surface, catalytic effect of the metal surface, flame instability and flow disturbance from the burner holes [9, 39]. It is also difficult to use the heat flux method at high pressures.

According to above discussion, it is difficult to use Bunsen flame, stagnation flame, and burner-stabilized flat flame to measure S_u^0 at high pressures. Currently, the propagating spherical flame method, which will be introduced in the next section, is the only method which can measure S_u^0 at high pressure close to that in internal combustion engines and gas turbines (20–50 atm) [40].

Several excellent review papers [1, 8, 9] have been published on laminar flame speed measurement. However, unlike other methods, the constant-volume propagating spherical flame method has received little attention. As shall be discussed in the next section, the constant-volume propagating spherical flame method is the only available method to measure S_u^0 at simultaneously high temperatures and high pressures close to engine-relevant conditions. Therefore, this review is focused on the constant-volume propagating spherical flame method. It is noted that a thorough review for this method was given by Rallis and Garforth [8]. However, for the constant-volume propagating spherical flame method, there are several correlations in Refs. [29, 41–49] which can be used to obtain S_u^0 during data processing. It is still not clear which correlation is the most accurate and reliable in terms of S_u^0 determination. The present paper is a contribution to examine and review the performance of these correlations and to clarify the strength and weakness of different correlations.

2 The propagating spherical flame method for S_u^0 measurement

Using propagating spherical flame method to measure S_u^0 goes back to 1920s when the soap bubble method was first introduced by Stevens [50]. In this method, a spherical flame propagates outwardly after central spark ignition in quiescent homogeneous combustible mixture [8, 10]. As shown in Fig. 1, the flame front history or pressure history is recorded, based on which S_u^0 can be determined. At the early stage of flame propagation, the flame curvature/stretch effects are considerable; and the pressure rise is negligible. Later the pressure rise rate increases greatly and the curvature/stretch effects become negligible [51]. Depending on the chamber design as well as the pressure rise, there are two different methods for S_u^0 measurement by using propagating spherical flames: one is the constant-pressure method (CPM) and the other one is the constant-volume method (CVM). Figure 1 schematically describes and compares these two methods. As indicated by the dashed ellipses in Fig. 1, flames with small radii (e.g., $1 \le R_f \le 2$ cm) are used in CPM so that the pressure rise is negligible; conversely in CVM since discernable pressure rise is required data corresponding to relatively large flame radii are used.

The constant-pressure propagating spherical flame method (CPM) was first used by Ellis [52] in 1928 who investigated the confinement effect on flame shape in a spherical glass chamber. In CPM, high-speed schlieren or shadow photograph is used to record the flame front propagation [53, 54], from which the evolution of flame radius, $R_f = R_f\,(t)$, is obtained. When the pressure rise is negligible, the burned gas can be assumed to be static and thus the flame speed relative to burned gas is $S_b = dR_f/dt$. Extrapolation to zero stretch rate is conducted to obtain the unstretched flame speed with respect to burned gas, S_b^0. Finally, the laminar flame speed is determined through $S_u^0 = \sigma S_b^0$, where $\sigma = \rho_b/\rho_u$ is the density ratio between burned and unburned gases [55, 56]. There are two main advantages of CPM [51]: (1) direct view from schlieren/shadow photograph helps to identify the flame instability, which thereby can be prevented in data processing; (2) there exists a quasi-steady spherical flame propagation period during which the stretch effect can be eliminated through extrapolation to zero stretch rate. In the literature, there are extensive studies on S_u^0 measurement using the CPM. The readers are referred to Refs. [9, 57, 58] and references therein for more details.

The constant-volume propagating spherical flame method (CVM) was first used in 1934 by Lewis and von Elbe [49]. In CVM, outwardly propagating spherical flames occur in a closed thick-walled spherical vessel and the evolution of chamber pressure rather than flame radius is recorded. Figure 1 shows that the pressure rise is evident only when the flame radius is large enough. The recorded pressure history is then used to determine S_u^0 through correlations between S_u^0, pressure, pressure rise rate, and burned mass fraction. This method has the advantage that S_u^0 for a given mixture over a wide range of pressures and