

Recent Developments in Finding Laminar Burning Velocity by Heat Flux Method: A Review



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Abstract This paper reviews the recent developments in heat flux method to determine the laminar burning velocity of a liquid or a gaseous fuel. Laminar burning velocity is an elementary property in designing the combustion chamber and turbulent combustion model and to validate kinetic simulation. There are numerous methods to find the laminar burning velocity such as Bunsen burner method, flat flame burner method, counterflow method, soap bubble technique, tube propagating technique, and heat flux method. In this paper, some of these methods are discussed in brief and recent developments of heat flux method have been elaborated, as this method is simple and accurate. To find out laminar adiabatic burning velocity, there are two requirements to be satisfied. First is the flame should be one-dimensional, thus flat and stretchless; second is adiabatic which means net heat exchange with the burner is zero. But, satisfying both these conditions at the same time is very difficult. The other methods have failed in satisfying both the conditions. However, heat flux method proved to satisfy these conditions. Results of laminar burning velocity using heat flux technique for methane–air have been compared with other methods of finding laminar burning velocity.

Keywords Laminar adiabatic burning velocity · Heat flux method

1 Introduction

1.1 Laminar Adiabatic Burning Velocity

Laminar adiabatic burning velocity is velocity of unburnt gas through the flame front in the direction normal to flame surface, and complete heat must be transferred to the gas mixture which is generated due to chemical reaction [1]. It mainly dependent on pressure, temperature, and equivalence ratio of the fuel–oxidizer

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mixture. It is a critical parameter which affects many combustion characteristics of a fuel. It is used as input for turbulent modeling, flashback, minimum ignition energy, to test the thermo-kinetic combustion models which can predict characteristics of combustion for various fuels. For analysis and performance predictions of burner and combustion engine, laminar burning velocity is the essential property. Because of these reasons, accurate experimental values of laminar adiabatic burning velocity of the fuel are required [2].

1.2 *Methods of Determining Laminar Burning Velocity*

There are numerous methods of finding laminar burning velocity such as Bunsen burner method, counterflow burner method, spherical bomb method, flat flame burner method, soap bubble technique, slot burner technique, and heat flux method. The problem with determining laminar adiabatic burning velocity is the flame shape which influences the burning velocity [1, 3]. Because of this reason, a lot of early experiments showed complete scattered experimental values when plotted in a single graph. The flame must be flat to the maximum extent to determine laminar adiabatic burning velocity; in other words, flame should be one-dimensional. To stabilize the flame, the flame loses some heat to the burner which implies non-adiabatic state [1, 4]. To obtain accurate value of laminar adiabatic burning velocity, it should satisfy two conditions:

- One-dimensional and thus flat and stretchless.
- Adiabatic and hence net heat interaction with the burner.

Following are some of the general methods of determining laminar burning velocity.

Bunsen Burner Method In finding laminar burning velocity, this is the oldest method. Premixed mixture of fuel and oxidizer is fed into the tube, and flame stabilizes on the rim of the burner tube. Net mass flow coming out of the tube is equal to net mass flow crossing through the flame surface. Now, the fraction of laminar burning velocity and unburnt gas velocity is equal to fraction of area of cross section of exit of the tube and the surface area of the flame. As burner exit area is smaller than conical surface area of the flame, burning velocity will be smaller than the velocity of mixture of unburnt gases as shown in Fig. 1a. Though this method is straightforward and time-saving, the uncertainties in determining the surface area of the flame are high, which can vary up to 10% [4].

Counterflow Method It works on stabilization of flames between counterflow jets. Both the jets deliver premixed mixture of fuel and oxidizer. Since the flame stabilizes in the flow, not on the burner, and does not have heat transfer to the burner, adiabatic state is accomplished. However, the streamlines of the flow of gases are not normal to the flame outer surface which is the reason for strain in the flow as explained in Fig. 1b because of which flame gets stretched. By altering the gap of

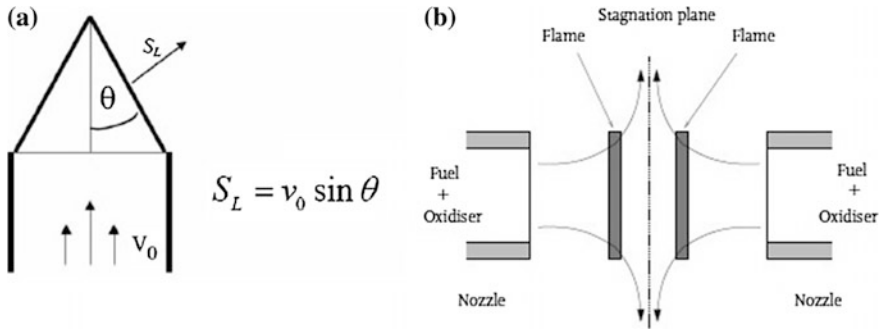


Fig. 1 a Bunsen burner flame [15]. b Counterflow burner setup

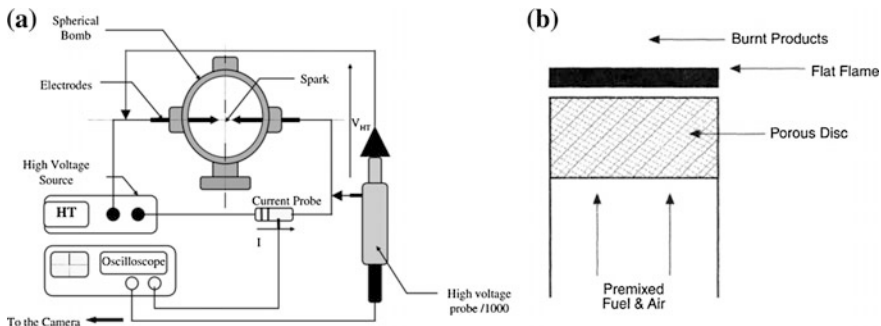


Fig. 2 a Spherical bomb setup [16]. b Flat flame burner setup [8]

separation of the nozzles, the stretch rate can be controlled [5]. A relation is found between strain rate and burning velocity. When it is extrapolated to zero strain rate, laminar burning velocity can be found out.

Spherical Bomb Method In this method, the combustion chamber is filled with the fuel and oxidizer mixture. It is ignited by igniter placed at the center of spherical bomb combustion chamber as shown in Fig. 2a. When the mixture is ignited, the flame expands spherically from the center to the wall. A correlation can be found between the radius of flame and time. Also, the increase in pressure because of temperature rise can be determined from which laminar burning velocity is found out [6, 7].

Flat Flame Burner Method First time, the flat flame was used to determine the laminar burning velocity using this particular method. Flame was stabilized on the porous metal plate which is placed at the end of tube which is water-cooled as shown in Fig. 2b. In further improvement of this method, the metal disk is cooled so that flame comes close to the porous disk. The temperature difference of inlet and outlet of water is measured. The temperature differences are measured at different

cooling rates, and respective gas velocities are also measured. To determine the exact laminar adiabatic burning velocity, the graph is extrapolated to zero cooling [8]. Experimentally achieving zero cooling is difficult because the flame will become instable and blow off. However, the temperature difference between inlet and outlet of water is small and tedious to measure.

Heat Flux Method The extension of flat flame burner method is heat flux technique. It was proposed by de Goey et al. The changes made to flat flame burner are: instead of cooling water supply to porous metal disk, hot water is supplied. Heat loss is measured by knowing the temperature difference of cooling water in flat burner method, whereas in heat flux method net heat transfer is reflected by measuring temperature at different radii of the burner plate [9].

The theory behind this technique is by heating the burner head it will compensate the heat which is lost from the flame to the burner. Heat which is gained by unburnt gases is only when unburnt gas temperature is less than the burner plate. This is facilitated by providing hot water jacket around the burner plate. By doing so, heat is transferred from burner head to porous plate and from burner plate to unburnt gas. The profile of temperature is generally parabolic in nature. Laminar adiabatic burning velocity is calculated when the parabolic coefficient is zero [10, 11]. Heat flux technique is more accurate as there is no requirement of extrapolation to find out laminar burning velocity.

2 Experimental Setup

The experimental heat flux method setup is shown in Fig. 3. The mass flow of unburnt gases is monitored by mass flow controllers (MFCs). The provision of buffering vessel is to reduce the pressure fluctuations within piping. Premixed fuel-oxidizer mixture is fed into the burner. MFCs and thermocouples are monitored by using an interface to PC. Each part of the burner is explained in the next section.

2.1 Plenum Chamber

The plenum chamber is used to supply gas mixture at constant velocity without fluctuation. At the lower end, distributor plate is placed, which has solid part at the center and periphery is filled with holes of 3-mm diameter. The CFD package CFX is used by de Goey et al. to design this [4]. Unburnt gas before entering chamber is premixed; this is ensured by several meters long piping arrangement. This chamber is cooled by a cooling water jacket provided. Because when gas is burnt, heat is transferred to chamber. As laminar burning velocity is depending on temperature, pressure, and equivalence ratio, it will vary with temperature. This water jacket is also useful to determine laminar burning velocity at elevated temperature.

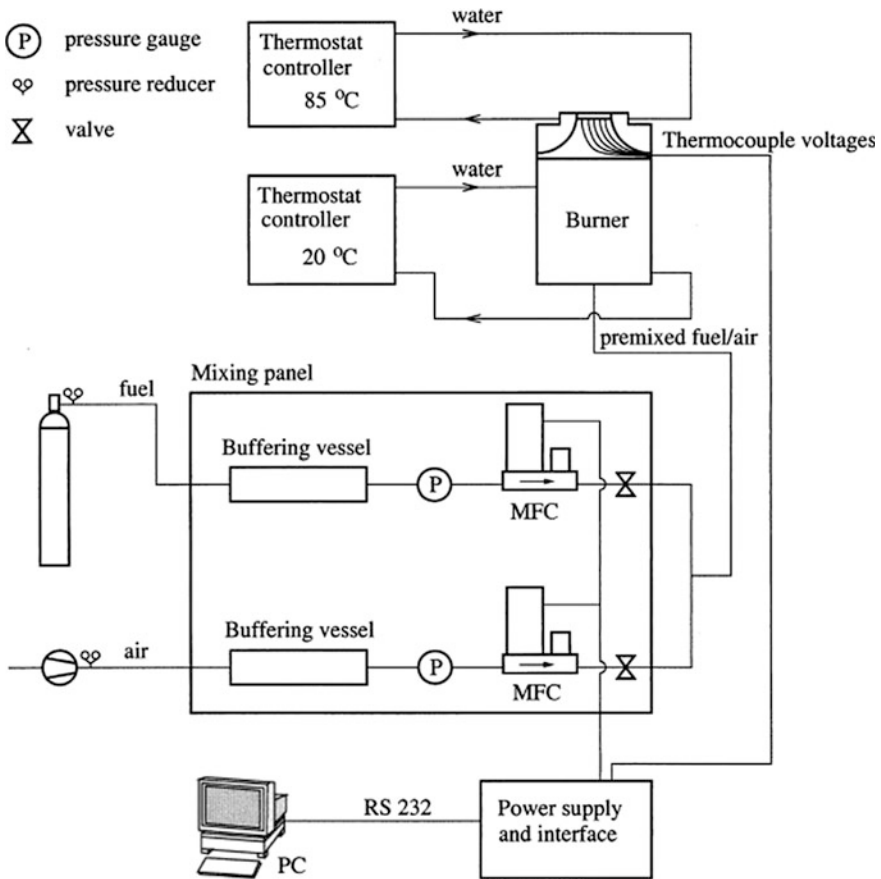


Fig. 3 Skeleton representation of heat flux method setup [4]

2.2 Burner Head

Burner head is designed in such a manner that the outflow of mixture of gases is nearly uniform. The average gas velocity is computed from volumetric mass flow passing through outlet orifice cross section. At the edges of the burner, care should be taken in order to avoid the deviations occurring because of boundary layer formation near the edges of orifice [1].

In this method, the upper head is heated above the room temperature. To facilitate this, separate hot water jacket is provided to the burner head. Figure 4 explains the setup of the burner. To avoid the heat transfer from burner head to chamber, a layer of ceramic insulation is provided [12].

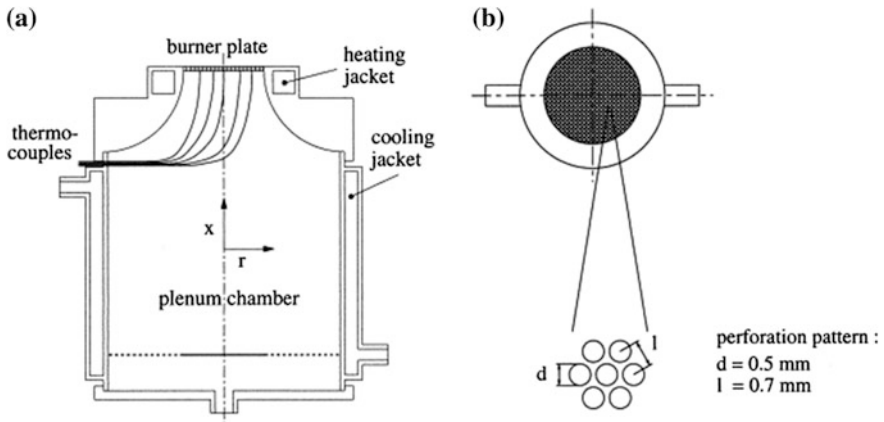


Fig. 4 a Heat flux plenum chamber. b The burner plate with perforation pattern (top view) [1, 4, 10]

2.3 Burner Plate

Brass is used for manufacturing the perforated heat flux burner plate. Thickness of the plate is 2 mm, and it is perforated with 0.5-mm hole diameter and 0.7-mm pitch in hexagonal pattern as shown in Fig. 4. The diameter of hole is calculated by velocity of mass flow through the burner. Numerical simulation was conducted out by de Goeij to find out the dimensions of hole. Previously, the porous plate was fixed inside the head of the burner through tight fit. As an improvement, to increase the thermal contact burner plate is fixed using a press ring [4].

3 Temperature Measurement

The distribution of temperature in the porous plate is measured using K-type thermocouples at different radii. At first, the thermocouples were attached barely to the bottom of the burner plate. It caused systematic deviation. To reduce that, a small cylinder of length 2 mm and diameter of 0.5 mm is drilled a hole of 0.1-mm diameter to a depth of 1.5 mm. The wire of thermocouple is inserted within this hole and glued [1, 10].

3.1 Vertical Temperature Measurement

The energy conservation is applied to the burner plate under the assumption of heat transfer to the perforated uniform plate. The expression shows that the temperature is a function of radius only and it is parabolic in nature

$$T_p(r) = T_c \left(1 - \frac{1}{4} a^2 r^2 \right) \text{ with } C = -\frac{1}{4} a^2 \quad (1)$$

where T_c is the temperature of the plate at $r = 0$ (center). $T_p(r)$ indicates the temperature of the plate at any radius r . α is a constant.

For stoichiometric CH_4 -air gas mixture, distinct temperature profiles are plotted at different inlet unburnt gas velocities. The inlet gas velocity of this mixture is altered about the laminar burning velocity value. For CH_4 -air mixture, the temperature profiles are given in Fig. 5a. The measured temperatures are plotted against the different radii where the thermocouples are mounted on the burner plate. The parabolic coefficient C determines whether a flame is sub-adiabatic or super-adiabatic [13]. Negative C value indicates gas temperature is more than burner temperature and hence burner plate gains the heat. A positive C value signifies that gas temperature is lower than burner plate and hence heat is transferred to the gases [11, 14]. The parabolic coefficient C of different gas velocities is plotted against gas velocity. The gas velocity corresponding to this flat temperature profile is the laminar adiabatic burning velocity which is calculated by interpolation which is given in Fig. 5b.

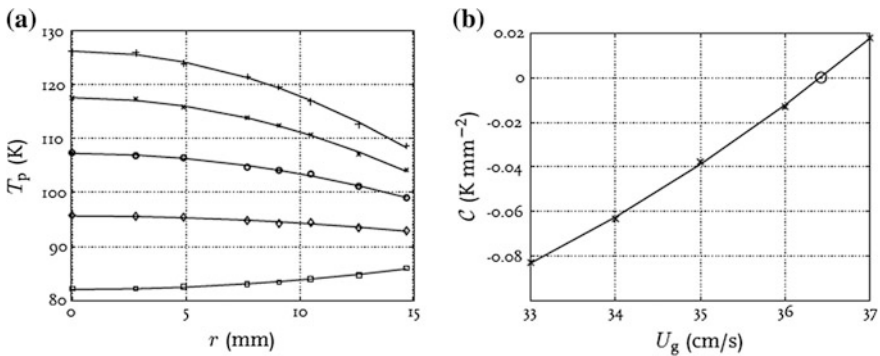


Fig. 5 **a** Plate temperature at different radii versus radius. **b** Parabolic coefficient versus gas velocity

Table 1 Results of burning velocities of CH₄-air mixture (S_L in cm/s) for the three equivalence ratios from different authors

Author	Correlation	$\Phi = 0.8$	$\Phi = 1.0$	$\Phi = 1.2$	Method
Hermanns [17]	$S_L(\phi)$	25.6	36.3	33.2	Heat flux
Coppens et al. [18]	$S_L(\phi)$	25.0	36.7	34.0	Heat flux
Huang et al. [6]	$S_L(\phi)$	31.1	41.7	39.2	Spherical bomb
Rahim [19]	$S_L(\phi, T_u, P_u)$	25.8	38.2	28.3	Spherical bomb
Gu et al. [20]	$S_L(\phi, T_u, P_u)$	25.9	36.0	31.4	Spherical bomb
El-Sherif [21]	$S_L(\phi)$	25.0	36.0	33.7	Counterflow
Stone et al. [22]	$S_L(\phi, T_u, P_u)$	26.5	37.5	30.9	Spherical bomb
Haniff et al. [23]	$S_L(\phi)$	32.4	41.1	38.5	Flat flame
Iijima et al. [24]	$S_L(\phi, T_u, P_u)$	26.4	34.5	35.4	Spherical bomb
Gulder [25]	$S_L(\phi)$	27.6	41.0	40.0	Spherical bomb
Kurata et al. [26]	$S_L(\phi, T_u, P_u)$	26.4	34.5	35.4	Bunsen burner

4 Comparison of Results

In this sub-unit, results of laminar burning velocity of CH₄-air mixture calculated using different methods are discussed. For this mixture, the results of Huang et al. and Gulder and Haniff et al. at stoichiometric condition show a lot of deviation from the exact laminar adiabatic burning velocity values of CH₄-air mixture. Recent experimental results of laminar adiabatic burning velocities draw good agreement that stoichiometric CH₄-air mixture is 36 ± 1 cm/s. According to the results shown in Table 1, heat flux method and counterflow method gave reasonably good results compared to other methods.

5 Conclusion

Overview of heat flux method and comparison of other methods are given in this paper. The setup of this method and experimental procedure are explained as well. This method serves a measurement technique which is advantageous in addition to other techniques, as the results are extrapolated. The methods used for evaluating and rectifying the present setup are quite easy and not complicated physical mechanisms, as stretch models are required. The only technique in which both 1D flame condition and adiabatic state are satisfied is by heat flux technique, and in addition to it, this method facilitates the great way of yielding a specific reference flame.

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