Measurements and Data Analysis Review of Laminar Burning Velocity and Flame Speed for Biofuel/Air Mixtures

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Abstract. Precise measurement and prediction of flame speed and laminar burning velocity are essential for premixed combustion properties characterization, turbulent combustion models validation, progress, and validation of chemical kinetic models. Besides, the problem of lack of fossil fuel, planet pollution, and production of several fuel alternatives led researchers to reexamine the process of combustion and optimize fuel consumption. So, it would be necessary to know the change of laminar burning velocity and flame speed with thermodynamic conditions to understand the impression of practical applications in all combustion systems as working pressures and temperatures are extensively higher than the atmospheric conditions. Several investigations work regarding flame speed and laminar burning velocity had been achieved. However, a detailed literature review of methods and techniques used to measure these two parameters and the effect of operating factors for different fuels focusing on biofuels is presented in this paper for ease of reviewing.

Keywords. Biofuels, Flame speed, Fundamental and characteristic of flame parameters, Laminar burning velocity.

1. Introduction

Recently, biomass fuels (biofuels) as alternatives to fossil fuels have obtained much consideration. Biofuels are sustainable and less damaging than fossil fuels to the environment, mainly those created from the 2nd generation biofuels, which lingo cellulosic is utilized as feedstock (Sims et al., 2010, [1]). Biomass may be processed into a gaseous, liquid, or solid fuel depending on the conversion process and the feedstock. Liquid or gaseous biofuels can be utilized in different combustion systems like burners, boilers, automobiles engines, etc. (Sequera et al., 2008, [2]). Solid biomass fuel is used with coal in power generation plants. Biofuels can be derived from biomass through thermochemical or biochemical reactions (Demirbas, 2007, [3]). Biomass pyrolysis is a thermochemical operation utilized to generate liquid biofuels (Lupandin et al., 2005, [4]). The pyrolysis treatment is a process of applying heat to the organic substances without the presence of O₂ to create hot fuel vapors that can be condensed into bio-oil to utilize in gas turbines and engines work with diesel fuel (Damstedt et al., 2007, [5]), but it has a high viscosity which needs to modify the existing fuel delivery equipment. It is listed that the three fossil fuels; coal, oil, and natural gas, dominated the global energy economy and covering above 80% of the whole energy supply (Jin et al., 2011, [6]), while combustible renewable and waste resources covered approximately 9.8% of the gross essential energy supply in 2007, as shown in Table 1. Even for the 9.8% renewable energy where biomass is part of it, about one-third of
biomass energy was used in different industrial applications, such as heat, power, road transportation, and heating purposes in the personal section. The remaining two-thirds of biomass were utilized for cooking and warming. In fact, just about 2% of overall transport consumption was from biofuels, which means there is a considerable potential to use biofuels in transportation and other applications.

Table 1. Primary energy sources of the world (Jin et al., 2011, [6]).

| Source                                | Share (%) |
|---------------------------------------|-----------|
| Oil energy                            | 34        |
| Coal energy                           | 26.5      |
| Natural gas energy                    | 20.9      |
| Nuclear energy                        | 5.9       |
| Hydro-power energy                    | 2.2       |
| Combustible renewable and waste energy| 9.8       |
| Other energies include geothermal, solar, wind, heat, etc. | 0.7       |
| Total                                 | 100       |

This paper investigates works related to flame speed and laminar burning velocity to view various methods and techniques used in this field and view the influences of operating factors for different fuels focusing on biofuels to present it in this paper for ease of reviewing.

2. Fundamental and characteristic of flame parameters

The adiabatic flame temperature is defined as the temperature obtained at the end of the burning process of a homogeneous mixture at the initial conditions, in which it obtains chemical equilibrium during an isobaric and adiabatic process (Egolfopoulos et al., 2014, [7]). It is influenced by some parameters like initial temperature and pressure, equivalence ratio, and mixture composition. In reality, it is greater than the flame’s actual temperature because of the losses in heat, which affect the laminar burning velocity, engine performance, and emissions (Egolfopoulos et al., 2014, [7]).

Laminar burning velocity \( S_b \) is the speed of propagating a steady, adiabatic, one-dimensional, laminar premixed flame relative to unburned mixtures. It is a crucial and essential physicochemical parameter of burnable mixtures. Which is describes the exothermicity, diffusivity, and reactivity of the related mixtures. Practically, it influences the fuel consumption in internal combustion engines in addition to its performance and emissions. Fundamentally, the burning velocity is an essential objective for the progress and validation of the kinetic mechanism. Moreover, \( S_b \) knows as the volume of consuming unburned mixture per unit area in unit time of the flame wave at its temperature and pressure. It is unaffected by burner size, flow rate, and flame geometry.

The burning velocity is necessary for flames stabilization and for locating the rates of releasing heat. The primary trouble in measuring burning velocity is that it is only under unique conditions the flame wave plane can be obtained because the flame wave may be either curved or not normal to the direction of gas stream velocity. The surface of the expanding flame is exposed to strain and curvature impact causing variations in the flame area. The overall flame stretch rate results from a combination of the curvature stretch rate and that which is due to the flow field aerodynamic strain. It is available for well-defined stretch rate flames to determine the un-stretched laminar burning velocity \( (S_b)_a \), which can be compared with numerically determined data where no stretch effect is present (Bradley et al., 1996, [8]). The relation of flame speed to the rate of flame stretch had been illustrated by \( S_b \) and Markstein length \( L_b \), which are input parameters in numerous turbulent combustion styles in the flame field (Peters Norbert, 2000, [9]).

The ignition temperature of a specified matter is the lowest temperature obtained at which the matter ignites, with the absence of an external ignition source, like a spark.

The flammability limits characterize the domain of fuel concentration in the mixture at given initial conditions that permit ignition to start and flame to expand and maintain. It is mostly influenced by the
type of fuel, temperature, pressure, the direction of flame expanding, and the combustion vessel geometry (Hagos et al., 2013, [10]).

Flame stabilization means that a flame can adjust its position, direction, and arrangement flexibly in an irregular, temporally changing flow field (Egolfopoulos et al., 2014, [7]). Flame stability is characterized by three primary parameters: flame flashback, flame liftoff, and flame blowout.

Flashback and liftoff are important undesired design criteria for gas burners. Flashback takes place when flame propagates through the tube of the burner without quenching, while liftoff is the case where the flame is separate from the port of the burner, it is stabilized at a space from the port, and this distance will increase with increasing the velocity of unburned gases until the flame blow out (Stephen R. Turns, 1996, [11]). Flashback is not only a disturbing thing, but it can be a safety hazard as well. The flame propagation through the burner port can ignite the fuel vessel, which might result in an explosion. On the other hand, flame propagation from the pilot flame through a flash tube to the burner is used for ignition. In practical burners, flame lifting can lead to escape some of the unburned mixtures or cause imperfect combustion. Moreover, ignition is not easy to attain above the lifting limit. Perfect control of the location of a lifted flame is hard to achieve. Thus, poor heat transfer characteristics can be produced. Also, lifted flames can be noisy.

3. Experimental apparatuses employed for measuring laminar burning velocity

The methods of measuring $S_n$ are categorized into two major types: stationary and nonstationary flame methods. It will be summarized below because burning velocity has been found using different methods, and an understanding of these methods is essential.

3.1 Stationary flame

In this category, a flow of premixed combustible mixture flows into a constant flame with a speed equivalent to $S_n$. It can be created by flowing a continuous combustible mixture into a burner at a constant velocity. It will be formed at the rim of the burner, from which burning velocity can be taken. There are many measuring techniques used for this type of flame.

3.1.1. Bunsen burner method

The simplest method is the Bunsen burner; it forms a flame with cone-shaped, shown in Figure (1). It is used by Brown et al. 2008, [12], and Oh and Noh 2012, [13]. From the flame cone angle, and the velocity of the coming combustible mixture burning velocity can be estimated (Hinton and Stone, 2014, [14]). Although it is a simple approach, it had a significant problem, as explained by (Rallis and Garforth, 1980, [15]). The difficulty in determining the cone edge may be the most significant of these problems, making the $S_n$ not fixed along the flame plane’s cone because of the non-uniform flame shape and curvature, and the quenching at the rim of the burner are causing a non-adiabatic flame. Therefore different methods are used. Each one produced a distinct edge, Figure 2.

A more precise calculation of ($S_n$) can be detected by obtaining a uniform outlet velocity profile by employing an aerodynamically surrounded nozzle. This leads to approximately straight cone edges achieved. Therefore, if the nozzle outlet velocity is $u_o$, and the cone angle is $2\alpha$ equal to $2\alpha_{in}$, the flame speed is calculated by (Chung K. Law, 2006, [16]):

$$S_n = u_o \sin \alpha$$  \hspace{1cm} (1)
3.1.2. Flat flame burner method. In this method, a flow of combustible mixture flows into a constant flat flame; therefore, the speed at which the unburned gas enters the stable flame burner is equivalent to the \( S_u \) of that mixture. The flat flame burners use many vertical channels to ensure the flames are flat. Chan et al. (2015), [19], and Liao and Roberts (2016), [20], used this method. Flat flame burners typically lack consistency in burning velocity data results depending on the flame’s location. It is also restricted to a low burning velocity range (\( \geq 0.20 \) m/s) (Z. Wang, 2016, [21]). Moreover, energy losses from the flame to the burner reduces the total precision of measuring \( S_u \).

L.de Goey et al. (1993), [22] modified this method by proposing the flat flame-based heat-flux method. The burner rim exposed to external heat can cancel the loss of heat from flame to the burner and achieve an adiabatic condition to find the laminar burning velocity, which simplifies data processing since the stretch does not influence it. Many researchers used this technique, such as Sileghem et al. (2013), [23], Goswami et al. (2014), [24], and Alekseev et al. (2016), [25], Figure 3.
3.1.3. Slot burner method. This method obtains a flat side inverted “V” flame with a constant velocity profile by employing a long rectangular nozzle. Which is eliminate the effect of flame curvature. This method is used by Pareja et al. (2010), Cardona and Amell (2013), and Ashrafi et al. (2015).

3.1.4. Nozzle burner method

It utilizes Bunsen burner type flames that are conical in shape. Moreover, they suffer from mostly the same problems as flat flame burners do. This method used by Zhang et al. (2013) and Wang et al. (2015).

3.1.5. Annular step-wise and diverging channel method. Mullins BP (1953), proposed and demonstrated flame stabilization inside a diverging tube and used typically to study ignition delays for various fuels. Nevertheless, it was employed for measuring burning velocity (Miyajima and Sakamoto, 1971). Recently, the approach has been developed to annular step-wise and diverging channel techniques, which is used by G. T. Kim and Nam Kim (2011), Liu et al. (2013), Z. Liu, and Kim (2014), and Jung et al. (2016). In this system, a multi-step arrangement leads to stabilizing flame at a particular position. This method had some disadvantages due to the heat loss and flame stretch effect, Figure 4.

Figure 3. Flat flame with the heat-flux method (Walter et al., 2020).

Figure 4. Development of annular step-wise diverging tube (ASDT) burners, a- Annular diverging tube (ADT) (G. T. Kim and Kim, 2011), b- Annular step-wise diverging tube (ASDT) (Z. Liu et al., 2013), c- Assembled ASDT with a cavity (Jung et al. 2016; and Z. Liu and Kim, 2014).
Akram et al. 2012, [38]; and Katoch et al., 2018, [39], proposed an externally heated diverging channel technique to determine the $S_u$ of different mixtures at high temperatures. The flame will stabilize for a given flow condition due to the wall temperature gradient along the mixture stream direction. Conservation of mass across the flame leads to calculating $S_u$ at a specified condition. This method leads to creating planar flames even for the mixture at non-unity Lewis number. Nevertheless, different problems associated with the planarity of the flame in the direction of the depth (Aravind et al., 2016, [40]; Singh et al. 2015c, [41]), the influence of heat loss to the walls of the channel (Akram et al., 2012, [38]) and extent of hydrodynamic stretch influencing on $S_u$. Thus, it needs more attention from investigators to enhance the precision of the method, Figure 5.

3.1.6. Stagnation flame method. Simmons and Wolfhard (1957), [42], proposed the stagnation/counterflow flame method. It was obtained either by the collision of a flow on a wall or by a collision of two identical flows, as shown in Figure (6). Due to flame symmetry, conductive heat losses are eliminated downstream of the stabilized flames in the double flame method, and there is only an insignificant radiative heat loss. Thus, it is preferable and had reliable results as compared to the stagnation flame method.

3.2 Nonstationary flame
In this category, the flame propagates through a quiescent combustible mixture. Many techniques are available to study the flame propagation speed of this type of flame.

3.2.1. Tube method. In this method, a flame propagating through a length of the tube. It was used by Karim et al. (1985), [43], Odgers J (1980), [44], Quinard et al. (2012), [45], Almarcha et al.
This method is the easiest; however, it has related problems such as heat loss to the tube walls.

3.2.2. Constant volume bomb method. It is also known as the spherical flame method, which is broadly applied to measuring burning velocity $S_\infty$ with reliable experimental results (Egolfopoulos et al., 2014, [7]). Furthermore, this method is applied to a broad range of pressure (0.01 - 6 MPa), which is usually impossible by using other methods, Figure 7.

![Constant volume combustion chamber](image)

**Figure 7.** Constant volume combustion chamber (Z. Wang, 2016, [21]).

In this method, a confined vessel containing a premixed combustible mixture at specified conditions. It is then ignited at the center of the chamber and propagating a spherical flame through the combustible mixture (Figure 8).

![Outwardly expanding spherical flame](image)

**Figure 8.** Outwardly expanding spherical flame (Konnov et al., 2018, [48]).

Hopkinson B. (1906), [49], reported the first experiment for flame propagation inside a constant vessel by central electrical spark ignition. Flam L (1917), [50], suggested a relationship between the quantity of mixture burnt and the pressure for spherically expanding flames. This method is still influenced by several factors, regardless of the simplicity of the experimental configuration and flame geometry, involving radiation heat loss, spark ignition, chamber confinement, flame instability, and flame stretch (Egolfopoulos et al., 2014, [7]; Chan et al. 2015, [19]; and Lipatnikov et al., 2015, [51]). Therefore, to achieve precise $S_\infty$ measurements, the impact of the above factors on flame propagation must be accurately minimized. The interior design of a constant volume chamber can be a cylindrical or spherical cavity with dimensions changed from apparatus to another. Adel M. Saleh and Dr. Mohammed N. H. AL-Fattal (2006), [52] used a cylindrical shape vessel with an inner diameter and 305 mm length. Galmiche et al. (2011), [53], conducted their experiments in a stainless steel cylindrical vessel with a 24.32 L inner volume. Hinton and Stone (2014), [14], used a spherical
combustion chamber with an internal diameter of 160 mm. Mannaa et al. (2015), [54], used a spherical stainless steel combustion vessel with a 330 mm internal diameter. Yasiry and Shahad (2016), [55], used the cylindrical constant-volume combustion vessel with a length of 250 mm and an internal diameter of 190 mm. Yao et al. (2017), [56] used CVCC, a cylindrical cavity with a bore of 80 mm and 268 mm in depth. Bao et al., 2017, [57] used the spherical constant-volume combustion vessel with an inner diameter of 350 mm. Oras K. O. Khudayer and Shahad. (2018), [58], used an iron cylindrical vessel with 190 mm internal diameter, 250mm length, and a volume of 7.084 L. Lhuillier et al. (2019), [59], carried out the experiments in a 4.2 L spherical stainless steel vessel. Linteris and Babushok (2019), [60], used a spherical chamber (3.05 L volume). Duva et al. (2020), [61], used a cylindrical stainless steel vessel with a length and internal diameter of 305 mm, and a wall thickness of 89 mm to resist 130 bar at 523 K.

$S_0$ in the constant volume vessel can be obtained in two different ways: constant pressure method (CPM), which was first proposed by (Ellis, 1928, [62]), and constant volume method (CVM), which was initially presented by (Lewis B., 1934, [63]). In the CPM, the experiments were conducted using the Schlieren system and a high-speed camera. Data analysis for the quasi-steady smooth surface of spherical flame at the beginning propagation time. Also, the flame structure can be investigated to find when flame cellularity and instability occur by using Schlieren photographs. The most outstanding flame stretch rates occur through early flame propagation, which caused a difference between burning velocities derived in earlier research (Bradley et al., 1996, [8]). Corrections made for the stretch by linear and non-linear extrapolating the data to zero stretch conditions. However, researches showed that non-linear extrapolations were more precise than linear extrapolation, which may be causing an over prediction of the un-stretched burning velocity, especially at high equivalence ratios (Bradley et al., 1996, [8]). The extrapolation approach is still an issue of investigation and uncertainty related to the CPM (Halter and Tahtouh, 2010, [64]; and Zheng Chen, 2011, [65]). This led to advancement in calculating $S_0$ without utilizing the properties of the mixture (Varea et al., 2012, [66]). In the (CVM), $S_0$ is calculated as a function of combustion pressure ($p$) and the burned gas fraction ($\varphi$) (Lewis B., 1934, [63]). $S_0$ calculated by this method involves some assumptions; so, it tends to be less precise than that calculated by the CPM (Xu et al., 2019, [67]), who studied the spherical propagating flame of biofuel in a constant vessel at initial temperatures of 358-418 K, pressures of 1-4bar, and equivalence ratios of 0.7-1.4. They showed that the difference of $S_0$ between the constant volume and the constant pressure methods is 15%, excepting at the conditions where the flame cellularity occurred. Figure (9) explains the difference of the $S_0$ during the latest decades for stoichiometric CH$_4$-air mixtures with several measurement methods. It is noticed that the measured laminar burning velocity approaching the amount of (36 cm/s) after introducing stretch corrections to the measuring data, and due to the developments in understanding different theoretical aspects like the impact of heat loss, flame stretch, and more precision in measurement methods (Konnov et al., 2018, [48]).

![Figure 9](image_url)  
Figure 9. The laminar burning velocity of stoichiometric methane-air mixtures with different measurement methods (Konnov et al., 2018, [48]).
4. Techniques of measuring laminar flame speed and burning velocity

The reaction region is often called a reaction wave or flame front. In this region, reactions occur rapidly, and usually, light emitted from it (K. Kuo, 1986, [68]). A particular technique is needed to measure flame speed by detecting the flame wave along with a specific space. Hence, several researchers worked extensively to get various techniques to measure the flame speed and the burning velocity. For flame speed, the techniques used were as below:

1- Visual technique: It is the oldest and simplest technique for measuring flame speed, which used transparent channels to be able to see the flame, and by recording the time consumed to pass the flame front between two specified points, flame speed can be calculated. This technique was used by Ziad (1982), [69], Kretschmer et al. (1985), [70].

2- Optical technique: There are different types of optical technique, which are:

   a. Shadow zone photograph: it is a simple technique; however, it is the least favorable method as it is considered unreliable; for example, Verlag et al. (1979), [71], suggested avoiding using this method for flame speed measurements. This technique is applied by Parsinejad et al. (2007), [72], and Tahtouh et al. (2009), [73].

   b. Schlieren photograph: it is the dominated utilized technique in burning investigation because it is more accurate than other methods. Zhang et al. (2013), [74], Ahmed Sh. Yasiry and Haroun Shahad (2016), [55], Mei et al. (2019), [75], and Duva et al. (2020), [61], used this technique.

   c. Visible zone photograph: it is a less precise technique than the other since it is hard to precisely define the visible region. Sreenivasan et al. (2012), [76], used this technique.

3- Thermocouple technique: in this technique, the flame propagates inside the combustion vessel and passes over many thermocouples, which will sense the flame front since it had the highest temperature among burned and unburned gases. This technique was used by Odgers J (1980), [44], Karim et al. (1985), [43], Adel M. Saleh, and Dr. Mohammed N. H. AL-Fattal (2006), [52], Mohamed (2010), [77], and Phylaktou et al. (2011), [78].

4- Ionized probe technique: in this technique, the flame front will be detected since the ionization level is very high at the flame front. This method cannot predict the flame front’s actual location since ionization levels stay high behind it. Iijima and Takeno (1986), [79], Gulder (1984), [80] Ciccarelli et al. (2011), [81], Ciccarelli et al. (2013), [82], and Li et al. (2015), [83], used this technique.

While the methods used to get the burning velocity are:

1- Density ratio method: this method used Equation (2) to calculate the burning velocity:

\[
S_v = \frac{S \rho_b}{\rho_u} \tag{2}
\]

where \(\rho_b\) is the density of the burned gases, and \(\rho_u\) is of that of the unburned gases. Tseng L K (1995), [84], Varea et al. (2012), [66], Galmiche et al. (2012), [85], and Ahmed Sh. Yasiry and Haroun Shahad (2016), [55], used this method.

2- Pressure measurement method: it is used in combustion in a constant volume method, where the change of pressure with the radius of the flame front leading to determine burning velocity using Equation (3):

\[
S_v \propto \frac{dp}{dr} \tag{3}
\]

Iijima and Takeno (1986), [79], Omari and Tartakovsky (2016), [86], and Hinton et al. (2018), [87], used this method.

3- Hotwire method: this method uses Equation (4) to obtain the burning velocity:

\[
S_v = S_i \pm S_g \tag{4}
\]
where $S_L$ and $S_g$ are the flame speed and the unburned gas velocity, respectively. The advantage of this method resets upon the accurate determination of unburned gas velocity. Simultaneously, it is a disadvantage because, in most combustion systems, the high temperature of the burnt gas often causes the wire to fuse. That necessitates the propagation and calibration of new wires for each experiment. The method was used by Bradley (1971), Mazas et al. (2011), Zhang et al. (2013), and Won et al. (2014).

4- Counterflow method: In this method, two synchronized flame fronts are developed and propagate toward each other by placing two burners opposite to each other and measuring $S_u$. This technique was used by Egolfopoulos et al. (1989), Egolfopoulos and Law (1990), Mittal et al. (2012), Lefkowitz et al. (2013), and Safer et al. (2015).

5- Heat flux method: The principle is based on the measurement of the net loss of heat from the flame to the burner to calculate the flame speed by measuring the temperature variation between the inlet and outlet of cooling liquid flew through the burner. Moreover, by varying the flow rate of the mixture to finally reach a zero-heat flux (that is mean the outlet temperature of the cooling liquid is the same as that of the inlet), and the velocity of gas which flows into the burner will be the adiabatic flame speed. This method was used by Bosschaart KJ (2004), Goswami et al. (2016), Han et al. (2019), Zhou et al. (2019), and Rau et al. (2020).

5. Factors Affecting burning velocity and flame speed

5.1. Fuel type
The combustible mixture contains the air as a maximum fraction of it. So, the molecular fuel weight has a little impact on the $S_u$. Furthermore, the much more effected is the combustion enthalpy of the fuel, which influences the adiabatic flame temperature, which has the most considerable impact on burning velocity. The oxidation kinetics reactions are significant too. Various burning velocity can be achieved for some fuels with the same adiabatic flame temperatures (Yasiry and Shahad, 2016). Generally, the burning velocity for hydrocarbon fuels decreases when the carbon atoms in the molecular fuel increases (Kenneth Kuo, 2004). Adel M. Saleh, 2006, investigated laminar burning velocity for some fuels of alkanes family like (Methane, Propane, LPG, and butane) and showed that it is inversely proportional to the carbon’s number in fuel, as explained in Figure (10).

![Figure 10. Variation of burning velocity with carbon’s number atoms in fuel molecule (Adel M. Saleh, and Dr. Mohammed N. H. AL-Fattal, 2006)](image)

Figure 10. Variation of burning velocity with carbon’s number atoms in fuel molecule (Adel M. Saleh, and Dr. Mohammed N. H. AL-Fattal, 2006).
Also, the hydrogen had a higher flame speed than that of hydrocarbon fuels since the thermal and mass diffusivities are much greater than that for hydrocarbons and the reaction kinetics of hydrogen is very fast because of the relatively slow \( \text{CO} \rightarrow \text{CO}_2 \) step that is the main factor in hydrocarbon combustion is absent (Adel M. Saleh, 2006, [52]). Other researchers studied the laminar flame speed and laminar burning velocity for various surrogate fuels, [101]. Meyer et al. (2012) , [102], demonstrated experimentally that the laminar flame speed of soya and canola biodiesel fuels was lesser by approximately 15 percent than the \( S_u \) of diesel fuel. Chong and Hochgreb (2011) , [103], investigated the laminar flame speeds of diesel, Jet-A1, (PME) palm methyl esters, and blends of them. They concluded that the laminar flame speed pure diesel was greater than that of blends of PME with diesel.

5.2. Initial temperature
It is the most crucial factor affecting varying burning velocity. Generally, raising the unburned gas temperature leads to an increase in the LBV and allows a more stable flame propagation. The most common correlation representing the influence of initial temperature and pressure is:

\[
S_u = S_{u,ref} \left( \frac{T_u}{T_{u,ref}} \right)^\gamma \left( \frac{P_u}{P_{u,ref}} \right)^\beta 
\]  

(5)

Where the subscript \( \text{(ref)} \) represent the reference conditions (typically \( T_{u,ref} = 298 \text{ K}, P_{\text{ref}} = 1 \text{ bar} \)). The exponent’s power for temperature, \( \gamma \), and pressure, \( \beta \), are discussed extensively by Konnov et al. (2018) , [48], which are varies as a function of the type of fuel, oxidizer, and equivalence ratio. Varghese and Kumar (2019) , [104], investigated the \( S_u \) of \( \text{H}_2/\text{CO}/\text{CH}_4/\text{CO}_2/\text{N}_2/\text{air} \) mixtures at elevated temperatures and pressures and proposed the following correlation of power-law, as shown below:

\[
S_u = S_{u,0} \left( \frac{T_u}{T_{u,0}} \right)^{\alpha_0 + \alpha_1 \left( 1 - \frac{P_u}{P_{u,0}} \right)} \left( \frac{P_u}{P_{u,0}} \right)^{\beta_0 + \beta_1 \left( 1 - \frac{T_u}{T_{u,0}} \right)} 
\]  

(6)

Han et al. (2019) , [105], drew the laminar burning velocity under various initial temperatures for natural gas at a pressure of \( 0.2 \text{ MPa} \) and showed that on both the lean and rich sides, \( S_u \) increased with the initial temperatures as shown in Figure (11).

![Figure 11. Laminar burning velocity for natural gas under different initial temperatures (Han et al., 2019) , [105].](image)

5.3. Initial pressure
The first verification of the impact of the pressure on burning velocity was showed by L. Ubbelohde (1916) , [106], using the following power-law pressure dependence, which is applied for the pressure range (1 - 4 bar):

...
\[ S_u = S_{u,0} \left( \frac{P}{P_0} \right)^{\beta_1} \]  \hspace{1cm} (7)

Understanding the above equation has its basics in primary theories of flame propagation. The earliest theory of E. Mallard (1883), [107], indicated the adverse dependence of \( S_u \) with pressure by only the heat and mass balance. P.J. Daniell (1930), [108]; W. Nusselt (1915), [109]; Crussard (1914), [110]; E. Jouguet (1913), [111], expanded this theory by introducing a total reaction rate \( \dot{\omega} \) explicitly. J. Zeldovich (1938), [112] further developed this theoretical technique viewing that the mass burning rate \( (\dot{\omega} = \rho S_u) \) is direct proportional to the square root of the total reaction rate \( \dot{\omega} \). Another correlation for pressure dependence is:

\[ S_u = S_{u,0} \left[ 1 + \beta_2 \log \left( \frac{P}{P_0} \right) \right] \]  \hspace{1cm} (8)

which was first suggested by (J.T. Agnew, 1961), [113], with the value \( (\beta_2 = -0.206) \) for a stoichiometric methane-air mixture. S.P. Sharma and D.D. Agrawal (1981), [114], explained their measurements using Equation (5) and suggested that the value of the coefficient \( \beta_2 \) is close to \(-0.2\), for numerous equivalence ratios \((0.8 - 1.2)\). T. Iijima (1986), [115], derived the same relationship with the parameter \( \beta_2 \) dependent linearly on the stoichiometry. D. Smith (1957), [116], suggested another correlation:

\[ S_u = S_{u,0} \exp \left[ b(1 - \left( \frac{P}{P_0} \right) \right] \right] \]  \hspace{1cm} (9)

The parameter \( b \) depends on the oxidizer composition, and the parameter \( x \) depends on the burning velocity at reference conditions. Andrews et al. (1972), [117], reviewed available experimental data before 1972 and suggested the following correlation:

\[ S_u = \frac{43}{\sqrt{P}} \text{ (cm/s)} \]  \hspace{1cm} (10)

where \( P \) is the pressure, which is in the atmosphere unit, for stoichiometric mixtures at pressures higher than 5 atm. Hinton and Stone (2014), [14], studied the \( S_u \) of biogas over a wide range of temperatures and pressures and demonstrated that increasing pressure results in lowering \( S_u \) while increasing the mixture temperature, causing an increase of burning velocity, as shown in Figure 12.

**Figure 12.** Burning velocity for biogas containing 60% CH\(_4\) and 40% CO\(_2\) for (a) \( T_u = (400 \text{ K}) \), \( P_u = (1–8 \text{ bar}) \) and (b) \( T_u = (380–520 \text{ K}) \), \( P_u = 5 \text{ bar} \) (Hinton and Stone, 2014), [14].
Hayakawa et al. (2015), [118], investigated the un-stretched laminar burning velocity of premixed ammonia-air mixtures and showed that it decreased by raising the initial mixture pressure. That tendency is the same as that of hydrocarbon fuels.

5.4. Equivalence ratio

The equivalence ratio ($\Phi$) is the actual to stoichiometric fuel/air ratio

$$\phi = \frac{(F / A)_{act}}{(F / A)_{stoich}}$$ (11)

The relation between burning velocity and equivalence ratio followed between the laminar burning velocity and the adiabatic flame temperature except for vibrant fuel-air mixtures. So, it is maximum at slightly richer than stoichiometry.

Andrews et al. (1972), [117], studied flames for CH$_4$/air mixtures and demonstrated that the $S_b$ peaked at ($\Phi$ = 1.08). Selle et al. (2012), [119], measured $S_b$ for methane-air mixtures as a function of $\Phi$ at 300 K and 1 bar using a slot burner method. They showed that the peak $S_b$ occurs at $\Phi$ = 1.05 and drop for both the lean and rich mixtures. Hayakawa et al. (2015), [118], showed that the maximum $S_b$ for NH$_3$-air flames at all initial mixture pressure examined reaches its peak value approximately at $\Phi$ =1.1. Kumar et al. (2020), [120], used a diverging mesoscale channel with an externally heated to measured the $S_b$ for the mixture at temperatures above its auto-ignition for premixed n-heptane-air mixtures found that the highest value of $S_b$ was obtained for $\phi \approx 1.1$ at all examined temperatures. Kim et al. (2020), [121], demonstrated that the $S_b$ of DIB-air mixtures at 428 K and 1 atm was greatest at an equivalence ratio of 1.07.

5.5. Oxygen enrichment

In some modern advancements of combustion techniques, fuel is not burned in air, such as oxygen enrichment combustion (OEC) or oxy-fuel combustion, which are used by (Zhang et al., 2016; [122]; Kalvakala, Katta, and Aggarwal 2018, [123]; Jalil et al., 2016, [124]; and Cai et al., 2016, [125]) and Moderate or Intense Low oxygen Dilution (MILD) combustion which are used by (Taylor et al., 2000, [126]; Cavigiolo and Galbiati, 2003, [127]; Weber and Smart, 2005, [128]; and Cavaliere and Joannon, 2004, [129]). In oxy-fuel combustion, O$_2$ diluted with flue gas containing mostly CO$_2$ is used instead of air. While in OEC, all or a part of the N$_2$ in the air is extracted, that means the concentration of O$_2$ in oxidizer changes from 21 to 100 percent by volume. This approach is broadly utilized in industrial purposes in some applications such as cement manufacturing, glass, and metal heating and melting because it leads to an increase in flame stability and the efficiency of combustion. In contrast, MILD combustion is used to obtain high efficient and clean energy supply. Hot flue gases are recycled and mixed with air to create a low-temperature gradient, leading to low luminosity low emissions of nitrogen oxides.

5.6. Inert additives

The dilution of different combustible mixtures with chemically inert species led to enhance the characteristics of flame control and quenching, and control the emissions of combustion process because of increased the specific heats, variations in transport properties, and chemical path-way of fuel oxidation (Tang et al., 2008, [130]). The advantages of using inert additives are fire safety, nitrogen oxides emission control, EGR, and oxy-fuel combustion facilitating Carbon dioxide capture and sequestration. On the other hand, it influences the flame reactivity, which causes problems of flame stability in combustion processes. It requires a well knowing of the influence of diluents on flame propagation behavior.

Many investigators studied the effects of the inert additives to the unburned mixture, such as (CO$_2$, N$_2$, He and Ar), on their burning velocities. Galmiche et al. (2011), [131], conducting numerical simulations and experimental investigations on the impacts of dilution on the premixed CH$_4$-air mixture on $S_b$. The experimental part is done at a 393 K and 1 atm, while the theoretical results were achieved by the GRI mechanism and the Premix code of the Chemkin package. The study investigated
the effect of some diluents such as (CO₂, N₂, H₂O, a mixture of the previous three gases representative of exhaust gases, He, and Ar) on laminar burning velocities at a constant equivalence ratio equivalent to stoichiometric. The results showed that Sₐ decreases with increasing dilution percentages, as shown in Figure (13).

![Figure 13. Effect of diluent type and dilution percentage on laminar burning velocity for CH₄/air flame (Galmiche et al., 2011, [131]).](image)

Selle et al. (2012), [119], demonstrated that the presence of vapor water in the fresh gases led to flame velocity drop. This reduction in the case of fresh gases exceeds 50% by increasing humidity in the air from dry to the saturation vapor condition at a temperature of 330 K. The characteristics of the laminar flame of CH₄ and syngas with carbon dioxide and nitrogen dilution have been broadly investigated numerically and experimentally by (Xie et. al, 2013, [132]; Xie et. al, 2014 [133]; Wang et al., 2015, [134]; Thompson et al., 2017, [135]; Koroglu et. al., 2015, [136], Dong and Weiping, 2016, [137]; Zhou et al., 2019, [138]; and Elia et al., 2013, [139]). the focal subjects of these studies were the laminar flame speed and the ignition delay time. Results demonstrated that the presence of carbon dioxide and nitrogen reduced the total reaction rate and increased the time of ignition delay of CH₄ and syngas combustion. (Chan et al., 2015, [19]) used the kinetic model and experimental study to investigate CO₂ dilution’s influence on the laminar flame speed for CH₄/air mixture. Experiments were conducted using a flat-flame burner method at 298 K and 1 atm pressure over the equivalence ratio range (0.8-1.4). The results showed the laminar flame speed inversely proportion with increasing CO₂ dilution. Increasing carbon dioxide led to reduced reactants’ concentrations and reduced the net reaction rate, which reduces the flame speed. Also, the presence of CO₂ is considered a heat sink, resulting in a reduction in the temperature of reaction and, therefore, reduces the capability to overcome the energy of activation for reactions. (Duva et al., 2020, [61]) concluded that utilizing one or a mixture of two of the significant exhaust gases cannot precisely simulate real combustion residuals since the combustion residuals’ chemical reactivity and thermodynamic properties can vary significantly with pressure, temperature, equivalence ratio, and dilution ratio. So, the effect of dilution methane/air mixture with actual flue gas content on laminar burning velocity Sₐ and Markstein length Lₐ values were measured at 473 K and 1 bar over a broad range of Φ. The results showed that Sₐ was reduced by additions of actual flue gases.

5.7 Ignition energy

A shock wave, followed by a less speed thermal wave caused by ignition energy (Bradley et al., 1996, [8]), increases flame speed due to increasing the mixture temperature. The spark ignition helps to develop a small flame kernel and influence flame expanding at a beginning stage. Therefore, skipping small flame kernels can significantly reduce this effect when extracting Sₐ. Bradley et al. (1996;1998, [8,140]) concluded that the impact of spark ignition could be ignored when the flame radius is greater than 6 mm. Nevertheless, the critical radius depends on the energy of ignition, thickness of flame,
Lewis number (Le), equivalence ratio (Φ), etc. as mentioned by (Bradley et al., 1998, [140]; Burke et al., 2009, [141]; Chen et al., 2009, [142]; Kelley et al., 2009, [143]; Z. Chen and P. Burke, 2011, [144]; and Ho et al., 2013, [145]). Ho et al. (2013) found experimentally that the critical initiation radius varied within the range of (10.5-13.5 mm) for n-decane/air mixtures at a high (Le) number between (1.46 - 3.1). The results showed that the critical radius of initiation decreases with pressure and increases with the Lewis number.

Table (2) lists the flame radius range reported by some researchers. It explained the initiation and end radius employed in the experiments to determine the $S_u$ applying various linear and non-linear techniques. Nevertheless, most of the $S_u$ was determined with a constant range of flame radius and various extraction techniques, leading to substantial uncertainty in $S_u$ values. Thus, it is necessary to select a suitable range of flame radius for extrapolating precise $S_u$ under certain conditions and extraction techniques.

Table 2. List of the initiation and end radius for obtaining the Su for several pieces of research

| Year | $r_{ini}$ (mm) | $r_{end}$ (mm) | $r_{w}$ (mm) | Investigators |
|------|----------------|----------------|--------------|---------------|
| 2009 | 6              | 15             | 50           | (Burke et al., 2009), [141] |
| 2010 | 10             | 60             | 180          | (Qiao et al., 2010), [146] |
| 2011 | 6              | 25             | 90           | (Wu et al., 2011), [147] |
| 2011 | 8              | 46             | 152.5        | (Lowry et al., 2011), [148] |
| 2012 | 6.5            | 25             | 100          | (Bénédicte Galmiche, Halter, and Foucher, 2012), [85] |
| 2013 | 6.5            | 19             | 42.5         | (Varea et al., 2013), [149] |
| 2013 | 10             | 18             | 41.28        | (F. Wu and Law, 2013), [150] |
| 2016 | 5              | 35             | 190          | (Yasiry and Shahad, 2016), [55] |

5.8. Fuel blends

Fuels are often a mixture of many chemical components. It is useful to be able to guess the $S_u$ of a mixture of two or more components, each of which has a known burning velocity. Payman and Wheeler (1922), proposed the following Equation to guess the $S_u$ of fuel of more than one component.

$$S_{u,mix} = \sum \zeta_i \cdot S_{u,i}$$  \hspace{1cm} (12)

$\zeta_i$ is the volume fraction of one fuel component and its oxidant concerning the whole mixture.

$$\zeta_i = \frac{\text{volume of (fuel } i + \text{ corresponding oxidant)}}{\text{volume of (total fuels + total oxidants)}}$$  \hspace{1cm} (13)

This was the most straightforward mixing rule. It states that the $S_u$ of the mixture is equal to the burning velocities of the components, weighted by the ratio of their respective volumes. However, (Yumulu 1967, [151]), showed that this rule does not fit the experimental data very well since it does not consider the variations in the fuel flame temperature of the mixture with changes in concentration. Therefore an alternative was proposed by (Spalding 1956, [152]).

$$S_{u,mix}^2 = \sum \zeta_i \cdot S_{u,i}^2$$  \hspace{1cm} (14)

Here $\zeta_i$ relates to a mass fraction and also assumes that the burning velocity of the components all corresponds to the flame temperature of the mixture. This expression also assumed an arbitrary allocation of the oxidant between the fuels. The high $S_u$ of the H2 led investigators to utilize it as a blended fuel to raise the mixture burning velocity and consequently enhance the combustion process. Sarli and Benedetto (2007), [153], conducted a numerical investigation to evaluate the $S_u$ of premixed hydrogen/methane /air flames by the CHEMKIN PREMIX code with GRI kinetic model. They demonstrated that the data extracting values by averaging the $S_u$ of the pure fuels based on their molar proportions were always more significant than those of the actual laminar burning velocities. Broustail
et al. (2011), [154], suggested that the following empirical correlation expects the $S_u$ of ethanol or butanol blend with iso-octane/air mixture.

$$ S_{u,va}^0 = S_{u,CH18}^0 \left( \frac{S_{u,CH18}^0}{S_{u,CH18}^0} \right)^{f_{va}} $$

where $f_{va}$ is the volumetric fraction of alcohol in the blend, $S_{u,CH18}^0$, $S_{u,CH18}^0$, $S_{u,CH18}^0$ are the $S_u$ for iso-octane and alcohol, respectively, under the same conditions of initial temperature, equivalence ratio, and pressure. Selle et al., 2012, [119] showed that the addition of H$_2$ to CH$_4$ caused an increase of laminar burning velocity ($S_u$), and this increment was linear with rising the H$_2$ fraction over the range of examination (0-50% of H$_2$), as shown in Figure (14).

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Ichikawa et al. (2015), [155], utilized experimental and numerical investigation to study the $S_u$ of NH$_3$/H$_2$/air premixed flames at high pressures (1-5 bar) in a constant volume chamber. They explained that the $S_u$ increases non-linearly with the increase in the hydrogen blends and decreases with the initial pressure increase.

5.9. Flame instabilities

“Hydrodynamic and thermal-diffusional instabilities lead to developing the smooth flame front to be cellular flame surface, and the flame propagation speed will be extensively enhanced” (Xie et al., 2016, [156]). Therefore, eliminating the impact of flame instabilities on the determination of $S_u$ can be achieved by processing a small flame radius with smooth surfaces. Law et al. (2005), [157], investigated theoretically and experimentally expanding the cellular instability of H$_2$/C$_3$H$_8$/air spherically flames. They found that when the flame’s radius was beyond a critical value, the flame surface becomes wrinkled. At the instability start, this critical radius was 0.44 to 2.82 cm for lean H$_2$/C$_3$H$_8$/air mixtures at a pressure of 5 bar. The critical radius varied over the range of (0.05 to 0.65 cm) for H$_2$-air flames at pressures range of 5 to 10 bar (Bradley et al., 2007, [158]).

5.10. Buoyancy

The flame is exposed to buoyancy impacts due to the massive density difference between the burnt gases and the unburned gases (Y. Wu, 2017, [159]), which causes the flame to float up, distorting the
initially spherical flame plane and inducing an essential flow in the surrounding reactants. The schlieren photographs were used to measure sideways and vertical flame speeds, which were then converted to burning velocities. The sideways and vertical burning velocities were combined to form an averaged burning velocity. The sideways flame speed indicates the mixture’s actual flame speed since buoyancy will strongly affect the flame kernel propagation in the vertical directions (Sitar et al., 1995) [160].

WANG et al. (2010), [161], experimentally investigated the influence of buoyancy on the flame propagation for the methanol/air mixture by utilizing a constant volume vessel and a schlieren system at the initial conditions of $T_u = 373$ K, $p_u = 2.5$ bar, $\phi = 0.6$. They found that very low stretched flame propagation speed occurs at the initial stage due to the low $S_{in}$ and a large positive value of the Markstein length. So, the buoyancy impact and cooling impact of the spark electrodes greatly influence the kernel of the flame progress and flame expanding. The flame floats upwards because of the influence of buoyancy. Meanwhile, the cooling impact of the electrodes, causing the flame to expand quickly along the vertical axis compared to that of the horizontal axis, as shown in Figure (15).

![Figure 15. Buoyancy and cooling effects of spark electrodes on the flame propagation for methanol-air mixture at $T_u = 373$ K, $p_u = 2.5$ bar, $\phi = 0.6$ (WANG et al., 2010), [161].](image)

Mei et al. (2019), [75], showed that oxygen enrichment increases the speed of spherically expanding flames, leading to reduce the impact of buoyancy on the laminar flame speed of NH$_3$.

6. Flame stretch

It is a local changing of the flame property with respect to time. It is also the area variation rate per unit area of an element of the flame surface, where this element is defined by the surface points moving at the local tangential gas velocity. Since there is no real one-dimensional flame, it is necessary to evaluate the impacts of not one-dimensionality on the burning rate by studying the stretch’s effect.

Since the late 1970s, significant advances had been made on the theoretical description of stretched flames, and as such, there now exists a reasonably mature qualitative knowledge of the structure and response of laminar premixed flames to stretch rate variations. Specifically, it is well established that stretch effects can be manifested through flame curvature, aerodynamic straining, and flame motion, and these effects are mostly large in the presence of mixture non-equidiffusion due to the resulting modification of the flame temperature (Sun et al., 1999, [162]). For the spherical propagation flame technique, the rate of flame stretch is $K = 2S_{in}/r_e$. The stretched flame speed $S_n$ requires to extrapolate to zero stretches to find un-stretched flame speed ($S_{L}$) and Markstein length of burned gas, ($L_{M}$), applying any of the approaches abbreviated in the table (3).

Table (3) list the obtainable schemes of extrapolation to correct the impacts of stretch. Matkowsky (1982), [163], calculated asymptotically the linear relation (LR) between stretched flame speed, $S_n$, and stretch by some hypothesizes like a unity lewis number, and flame speed is un-stretched. Hanson
(1991), [164], P. D. Ronney (1989), [165], and Kelley et al. (2012), [166], obtained a non-linear relation (NR quasi-steady-state style) between $S_n$ and stretched applicable for all $(Le)$. Z. Chen (2015), [167], showed that the selection of extrapolation type listed in Table (3) to correct the influence of stretch depends robustly on Le number and flame radius range for extrapolation. Wu et al. (2014), [168], suggested another style (N3P) and discuss the contrast in results achieved by other extrapolation styles. They demonstrated that at $Le<1$, the examined extrapolation styles cause many errors compared to simulating unstretched flame speed. Liang, Wu, and Law (2016), [169], assumed a finite flame thickness approach (FFT) based method suggested by (M. L. Frankel, 2007, [170]) for extracting the data of $S_l$ for all Le. Lately, Li et al. (2017), [171], proposed a new extrapolation style (NL4), as listed in Table (3) for cases with $Le>1$. The result showed that non-linear styles’ performance is better than the linear style for mixtures with $Le \neq 1$.

Table 3. Brief of stretch extrapolation styles Linear relation (LR), non-linear relation (NR), linear model related to curvature (LC), non-linear style in expansion form (NQ), non-linear style with three fitting parameters (N3P), finite flame thickness expression (FFT), activation temperature (Ta). (Konnov et al., 2018), [48].

| Model name and description | Expression | Ref. |
|---------------------------|------------|-----|
| LR based on stretch       | $S_n = S_L - L_b K$ | (Clavin, 1985, [172]; Wu, 1984, [173]; Law, 1988[174]; Law and Sung, 2000, [175]) |
| NR Quasi-steady           | $\left( \frac{S_n}{S_L} \right)^2 \ln \left( \frac{S_n}{S_L} \right)^2 = -2 \frac{L_b K}{S_L}$ | (Singh et al., 2015, [41]) |
| LC-based on curvature     | $\frac{S_n}{S_L} = 1 - 2 \frac{L_b}{r_f}$ | (Z.Chen, and P. Burke, 2011, [144]) |
| NQ in expansion form      | $S_L t + c = r_f + 2L_b \ln r_f - 4 \frac{L_b^2}{r_f} - 8 \frac{L_b^3}{3 r_f^2}$ | (Kelley, Bechtold, and Law, 2012,[166]) |
| N3P                       | $\frac{S_n}{S_L} = 1 - 2 \frac{L_b}{r_f} + \frac{c}{r_f^2}$ | (Wu et al., 2014, [168]) |
| FFT                       | $\left( \frac{S_n + 2L_b^2}{S_L} \right) \ln \left( \frac{S_n + 2L_b^2}{S_L} \right) = \frac{2(L_b - \delta)}{R_f}$ | (Liang et al., 2016, [169]) |
| NL4                       | $U = 1 - \frac{L_b}{RU} + \frac{2L_b^2}{RU^2} - \frac{2L_b^3}{RU^3} + \frac{2L_b^4}{RU^4}$ | (Li et al., 2017, [171]) |

Figure (16) explains the $S_u$ of the stoichiometric C$_3$H$_8$/air mixture recorded in researches for the last three decades with various measurement methods at the ambient conditions, which shows a considerable variation in the same condition. This variation in data may at least partly because of employing the stretch correction approaches. To reduce the effect of stretch correction, measurements of $S_u$ utilizing non-stretched flames could be significant.
Figure 16. Laminar burning velocity variation of stoichiometric propane-air mixtures with different measurement methods (Zhou et al., 2019, [99]).

Figure (17) summarizes linear and non-linear stretch extrapolation approaches to obtain data of \(S_u\) for stoichiometric methane/air mixtures. It is noted that stretch correction of laminar burning velocity applying linear extrapolation style caused dropping \(S_u\) from (~40 cm/s) to (~37 cm/s) during the last thirty years.

Figure 17. Historical changing in \(S_u\) for stoichiometric CH\(_4\)-air mixtures applying two extrapolation styles (Konnov et al., 2018, [48])

7. Conclusions
Different techniques for measuring burning velocity and flame speed and the factors affecting these two parameters focusing on biofuels have been revised over a wide range of pressure, temperature, and equivalence ratios for different single-component fuels and blends. The following conclusions are conducted from this review:

- The increase of initial pressure causes a non-linear decrease of the un-stretched laminar burning velocity (\(S_u^°\)) and increased mass burning rates.
- The initial temperature is the most significant factor leading to change burning velocity, generally increasing the unburned gas temperature causing an increase in the LBV, and allows a more stable flame propagation.
- Increasing the equivalence ratio leads to an increase in the \(S_u\) in the lean fuel mixture and decreases in the case of rich fuel mixture, and it is a peek at slightly richer than stoichiometry.
generally, the burning velocity for hydrocarbon fuels decreases when the carbon atoms number in the molecular fuel increases.

- the dilution with inert species reduced the laminar burning velocities; nevertheless, it contributes to emission control.
- Oxygen enrichment flames increase the efficiency of combustion and flame stability; thus, it is broadly used in industrial applications.
- The spark ignition helps to develop a small flame kernel and influence flame expanding at a beginning stage. Therefore, skipping small flame kernels can significantly reduce this effect when extracting $S_u$.
- The data extracting values by averaging the $S_u$ of the pure fuels based on their molar proportions were always more generous than those of the actual laminar burning velocities.
- The sideways flame speed is most indicative of the actual flame speed of the mixture since buoyancy will strongly affect the flame kernel propagation in the vertical directions.
- With all the measurement methods, appropriate care should be taken to reduce the effect of the flame stretch.

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