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Flame Speed and Laminar Burning Velocity in Syngas/Air Mixtures: A Review

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ABSTRACT

Flame speed and laminar burning velocity (LBV) are important properties of fuel combustion. Both have an impact on how combustion systems are designed and operated. As a result, understanding how LBV and flame speed fluctuate as a function of thermodynamic conditions is critical for understanding the impact of practical applications in all combustion systems. Working pressures and temperatures are far higher than those found in the environment. Several studies on flame speed and LBV have been conducted. This study, however, includes a thorough literature analysis of approaches and procedures used to measure these two parameters, as well as the effects of operational factors for various fuels, with a focus on biofuels, for the sake of review simplicity.

1. INTRODUCTION

Traditionally, coal and oil have traditionally been the main energy sources in recent decades, and they are directly burned to generate electric and kinetic energy in automobiles and power plants. As a result of the increased concern for environmental protection, more stringent emission laws have been enacted for automotive and power plant exhaust gas emissions. Clean combustion research has recently caught people's attention as a possible solution to this problem.

One of the most significant characteristics of a reacting premixed mixture is LBV, and precise data on it is always in demand for combustion applications. Since the late 1970s, scientists have made significant progress in their understanding of the effects of flame stretch on LBV [1]. Syngas is gaining appeal as a cleaner alternative fuel.

Syngas is a gasification product largely composed of H_2, CH_4, CO_2, N_2, CO, and other components, with a small amount of H_2S [2]. Rather than solely in gas turbines, syngas can also be utilized to create power.

However, internal combustion engines are also used. The lack of a consistent fuel supply [3], gas turbine [4], is one of the most critical challenges for syngas-fired IC engines. Fluctuations in the composition of syngas are an issue in this and other combustion systems. Because of the many fuel sources and processing circumstances, syngas composition is quite complex [5]. Hundreds of chemical processes, turbulence vortex patterns, and acoustic field interactions all contribute to the combustion process. Furthermore, because of its complex geometry and operating approach, the combustion process is more difficult to comprehend. As a result, several fundamental study topics have been created, such as laminar flame dynamics, to examine various features of the combustion process [6], flame-turbulence interaction [7], chemical reaction process [8], and so on.

One of the most widely used pieces of equipment is the constant-volume combustion bomb (Figure 1), which ignites the combustible mixture in the domain center and produces a laminar spherically premixed flame that spreads outwardly [9]. One of the most important and well-studied subjects in laminar flame dynamics is the laminar spherically premixed flame of the combustion bomb. This article looks at A variety of factors influence the laminar burning velocity and flame speed for biofuel/air mixtures: a review study. such as initial pressure, initial temperature, flame temperature, initial ignition energy, etc. While the laminar flame speed is the most important parameter for understanding combustion properties. Wrinkled structures may emerge on the flame front when the pressure is increased or hydrogen is introduced to the lean combustible mixture. In this case, the wrinkled structure on the surface of a laminar spherically premixed flame will be looked at.

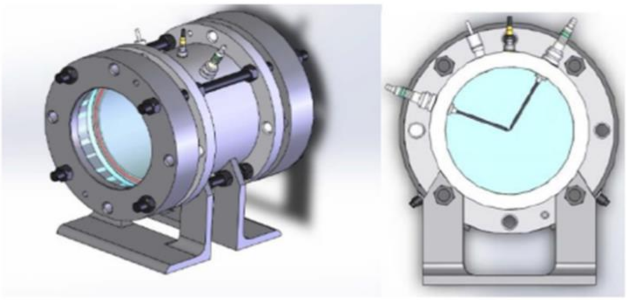

Figure 1. Constant volume combustion chamber [9]

2. FLAME PARAMETER CHARACTERISTICS AND FUNDAMENTALS

A flammable combination's LBV is a critical property. refers to the rate at which an adiabatic, unstretched, premixed planar flame propagates relative to the unburned mixture [10]. The cumulative impact of mixture diffusivity, exothermicity, and reactivity determines the LBV of a premixed fuel-oxidizer mixture [11, 12]. As compared to unburned mixes, the burning velocity in the lamina LBV is the speed at which a steady, adiabatic, one-dimensional premixed flame propagates [9]. A variety of approaches for measuring the one-dimensional LBV have been used for a wide range of temperatures, pressures, and fuels. Some of these methods include stagnation flow flames that are flat or curved, propagating spherical flames in combustion containers, and flat flames stabilized on the burner [13]. When employing any of these methods of measurement, additional attention should be paid to removing the influence of flame stretch, either during the experiment or after the data has been analysed [14]. LBV can be used to characterize a variety of combustion processes, including flame stabilization, flame flashback, flame blow out, and flame extinction [15, 16]. It has an impact on the fuel consumption, performance, and emissions of internal combustion engines in the real world. Fundamentally, a necessity for the advancement and confirmation of the kinetic mechanism is the burning velocity. At the temperature and pressure at which the flame wave occurs, LBV also knows how much unburned mixture is consumed per unit area in a unit period of the flame wave. It is unaffected by the size of the burner, the flow rate, or the flame geometry. Flame stability and estimating the rate of heat release are both dependent on the burning velocity [9]. Although the LBV is not a measurable quantity that must be estimated from other observables using various assumptions or theoretical models, it is an important characteristic for scaling and modelling turbulent combustion flames [17]. The fact that a plane flame front may only be visible under particular conditions makes calculating the LBV one of the most challenging tasks.

The term "flame stability" refers to a flow environment where flames can freely change where they go and how they're organized [18]. It's called flame thickness because it's how far an intermediate species of interest spreads out over the flame front. The flammability limits stated here are the range of fuel concentrations in a mixture that allows ignition to start and a flame to expand and retain specific initial conditions. The type of fuel, temperature, pressure, flame expansion direction, and the geometry of the combustion vessel are all factors [19, 20].

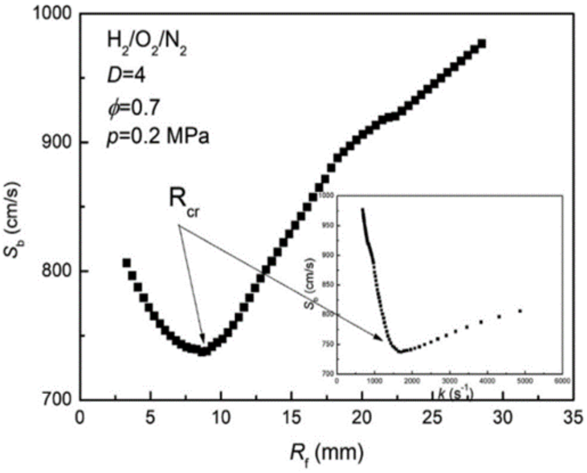

Figure 2. The definition of the critical flame radius [20]

The Radius of Influence (Rcr) The flame propagation speed initially decreases as the flame radius increases, but due to the unstable flame front, it quickly accelerates. For this reason, the critical radius, Rcr, is defined as the start of self-acceleration [20]. Figure 2 shows the definition of the critical flame radius [20]. For gas burners, flashback and liftoff are important drawbacks. When the flame is withdrawn from the burner's port, it stabilizes at a distance from the port, which grows as the velocities of unburned gases rise until the flame blows out [21].

Unburned gas velocity was less important than inlet temperature and pressure in determining flashback propensity [22]. Davu et al. [23] investigated the possibility of syngas flames flashing back. The findings revealed that hydrogen kinetics is the driving force for syngas flame flashback. This is particularly prevalent in syngas mixtures containing more than 5% H_2. Flashback may be both terrifying and harmful. The propagation of flame through the burner port may ignite the fuel vessel, resulting in an explosion. However, flame propagation through a flash tube from the pilot flame to the burner is used for ignition. In practical burners, increasing the flame height can allow unburned mixes to escape or result in poor combustion. Furthermore, above the lifting limit, ignition is difficult to obtain. Maintaining complete control over the location of a raised flame is difficult. As a result, the heat transfer capabilities of the material may deteriorate. Flames that have been lifted can generate a lot of noise.

3. LAMINAR FLAME SPEED AND BURNING VELOCITY: AN EXPERIMENTAL AND THEORETICAL STUDY

Many investigators worked hard to find out the various approaches for measuring flame speed since the detection of flame front arrival in a specific space needs a distinctive approach for measuring flame speed.

Andrews and Bradley [24] proved the principle of the Double Kernel approach. The method's main goal was to fight a pair of flame kernels that had been ignited at the same time. Measurement of flame speed and thickness has also been used to calculate the burning velocity of a hydrogen-air mixture. A new method for accounting for the impacts of finite flame thickness has been devised, which assumes a linear temperature profile through to the flame front. The flow of unburned gas is limited along the line between their centers as they expand towards one another. The flames flatten down, and the two approaching flame surfaces get close to resembling the flat flame geometry. Their relative movement approaches twice the typical burning velocity asymptotically. At the midpoint of the axis of centers, the gas velocity must be zero, and the flame speed somewhere along the axis approaches the burning velocity.

The shape of the flame cone is one of the primary sources of error when evaluating burning velocity with a Bunsen burner. To solve this difficulty, a nozzle is placed directly above the tube end and a cone flame with side lengths is produced. Kobayashi and Kitano [25] employed this technique.

Powling [26] produced a close approach to the idealized one-dimensional flat flame, but were restricted to low burning velocities of 0.15-0.2 m/sec.

Dong et al. [27] used the stagnation flow arrangement to evaluate the laminar flame speeds of an ethane/air combination diluted with helium and nitrogen before the flame transitioned from planar to Bunsen flame.

Oppong et al. [28] studied the combustion characteristics of 2-ethylfuran with a spherical combustion chamber with an interior diameter of 79 mm. The cellular flames were observed at =1.2-1.4 and Pi =4 bar. For the condition where cellularity did not show in the flame, the maximum LBV occurred at 1.1.

Liu et al. [29] measured the LBV by an annular stepwise diverging tube (ASDT). This method was employed to comprehend the features of flames in small combustion spaces based on their flame propagation qualities, and the results were good when compared to the literature. According to Duva et al. [30], the LBV values of CH_4/air mixtures diluted with actual combustion residuals are comparable to those of N_2 and H_2O dilution, but the LBV of CH_4 flames diluted with CO_2 is much slower. Kochar et al. [31] used the Bunsen burner method and the expanding spherical flame method. The mixtures studied varied from pure methane to binary mixes of CH_4 and C_3H_8 and CH_4 and C_2H_6 at pressures up to 10 atm. Over a wide range of temperatures and pressures, the method did a good job of showing how mixture composition affects the speed of the flame. This was a big discovery.

Hinton and Stone [32] investigated the LBV of biogas above a wide range of temperatures and pressures, demonstrating that increasing pressure lowers LBV while increasing mixture temperature raises burning velocity. Ciccarelli et al. [33] used the ionization probes and pressure transducers to determine the explosion front velocity, and high-speed shadowgraph footage was used to illustrate the explosion wave front structure. The flame approaches the speed of sound of the combustion products when it hits a porous, rough surface.

Okafor et al. [34] investigated premixed ammonia-methane flames and discovered that increasing ammonia content results in a non-linear drop in LBV. Safer et al. [35] demonstrated a novel method based on chemi-ionization for measuring flame flickering frequency using the flame's ion creation rate. When compared to standard technologies, the results of ion signals showed some subtle differences. Mannaa et al. [36] investigated different fuels, including iso-octane, n-heptane, toluene, and blends of them, using a spherical stainless steel combustion chamber with an inner diameter of 330 mm. The LBV was calculated using an empirical correlation at pressures as high as 30 bar, which is experimentally impossible to achieve.

Hu et al. [37] studied the effects of different techniques on the Markstein length and LBV of methane-air mixtures. Using a centrally fired ignition system and a constant volume combustion chamber According to the findings, flame radii obtained from a flame area study may be used to calculate flame speed and stretch rate. At an equivalence ratio of 1.1, the burning rate is at its highest. It has a speed of 0.366 m/s.

Yu et al. [38] investigated the impact of carbon monoxide (CO) addition and the barriers placed on the flame propagation of explosions from methane–air mixtures in various circumstances. The findings reveal that an obstruction has a significant impact on the explosion pressure wave's amplification and attenuation. The amount of CO in the air rose from 0% to 2%. This helped the flames spread.

Lhuillier et al. [39] carried out their experiments on NH3/H2/air mixtures in a 4.2-liter spherical combustion chamber. Burning speeds rose as the amount of H2 and the temperature rose, with the fastest speeds found in mixtures that were close to stoichiometry.

Figure 3 depicts the differences in LBV values for stoichiometric CH4-air mixes measured using various methods during the last few decades. After applying stretch corrections to the data, it was found that the measured LBV came close to 36 cm/s, thanks to better understanding of things like heat loss, flame stretch, and better measurement methods [40].

Han et al. [41] investigated flame instability and LBV in a constant volume chamber. The initial temperatures (323 K–423 K), initial pressures (0.1 MPa–0.3 MPa), and dilution rate (0–16%, CO_2 as diluent gas) at a series of equivalency ratios (0.7-1.2) are varied. When the equivalency ratio and CO_2 fraction are fixed, initial temperature and pressure coupling have a clear impact on flame propagation speed, i.e., flame propagation speed can be kept almost constant when the beginning temperature and pressure are both elevated at the same time.

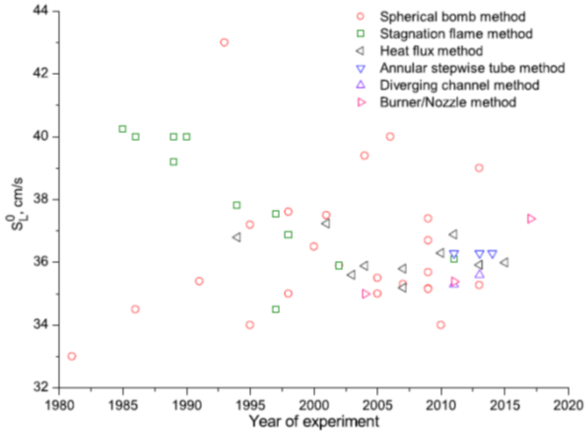

Figure 3. Different measurement methods for LBV of stoichiometric methane-air mixtures [40]

Linteris and Babushok [42] calculated the LBV of saturated C1 and C2 HFC refrigerants using a spherical vessel with a volume of 3.05 l. LBV is predicted for air mixes containing one or two carbon-saturated HCL chemicals.

Kim et al. [43] investigated the effect of modifying the equivalency ratio and ethylene/methane mixing ratio on laminar flame speed in spherically propagating premixed flames at ambient temperature and higher pressures up to 0.8 MPa. The range of flame radius recorded in this experiment was determined to be (13.0 ≤R f ≤31.0 mm). It is discovered by Wei et al. [44] that the LBV in biogas-hydrogen/air mixtures increases linearly with increasing H_2 content.

Hu et al. [45] evaluated Chinese commercial gasoline at various initial temperatures and initial pressures by the outward propagating spherical flame method. Their findings revealed that raising the initial pressure increased the LBV, while raising the initial pressure decreased it, with the peak value occurring at 1.11. Tinaut et al. [46] examined for LBV by a cylindrical constant volume. The results show that the cellularity density of hydrogen-air flames increases as the mixture becomes leaner. As the original pressure or temperature rises, similar patterns emerge.

Some flame speed and LBV measurement methods have been presented in Table 1.

When summarizing previous studies about the LBV, it was noted that the LBV depends mainly on the burned to unburned density ratio. The density of the burning mixture was always less than the density of the unburned mixture. While the LBV increases at lean equivalence ratios to arrive at maximum velocity at 1.1 approximately depending on the type of fuel, the LBV starts decreasing for rich equivalence ratios. It is worth noting that the LBV increases with increasing initial temperature for all types of fuel, and decreases with increasing initial pressure.

Table 1. Some flame speed and LBV measurement methods

Reference	Type of method	Results
Kobayashi & Kitano [25]	Bunsen burner	Obtain a flame that is conical in shape and has straight sides.
Powling [26]	Flat flame burner	Although it comes near to the ideal one-dimensional flat flame, it is confined to modest burning velocities of 0.15–0.2 m/sec.
Dong et al. [27]	Stagnation flow configuration	The results were compared to those of a numerical simulation created with GRI-Mach 3.0. The laminar flame speed of ethane/air/helium was faster than expected, while the ethane/air/nitrogen dilution was more correct.
Liu et al. [29]	Diverging channel	This method was used to understand the characteristics of flames in small combustion spaces.
Duva et al. [30]	Constant volume bomb	The LBV of CH_4 flames diluted with CO_2 is much slower comparison with N_2, H_2O.
Hinton and Stone [32]	Constant volume bomb	LBV increased as the temperature rose, but reduced when the pressure and dilution ratio fell. The diluting methane fuel by 40% CO_2 reduced LBV to 65% for stoichiometric combinations.
Ciccarelli et al. [33]	Ionized	The flame approaches the speed of sound of the combustion products when it hits a porous rough surface.
Mannaa et al. [36]	Constant volume bomb	LBV was determined using an empirical correlation to evaluate critical flame instability of the investigated fuels.
Lhuillier et al. [39]	Constant volume bomb	The burning velocities increased as the H2 fraction and temperature increased.
Konnov and Dyakov [47]	Heat flux	The diffusion flame must be located away from the stagnation plane on the fuel side.

4. CHEMICAL AND PHYSICAL PARAMETERS ON LAMINAR BURNING VELOCITY

The LBV is influenced by a number of factors, both chemical and physical in nature. In the next sections, the impact of various variables is discussed.

4.1 Physical parameters

4.1.1 Initial temperature

It is a significant determinant of burning velocity. In general, increasing the temperature of the unburned gas causes the LBV to increase.

Hu et al. [48] studied hydrogen–air flames at high temperatures. used a constant volume combustion vessel. The rate of laminar burning increases as the initial temperature rises. Kanoshima et al. [49] investigated the LBV of ammonia/air mixtures in a CVC over a range of temperatures (400 K-500 K), equivalency ratios (0.8-1.2), and beginning pressures (1-5 bar). The temperature exponent of the ammonia/air flames was found to be higher than the methane/air flames.

Tang et al. [50] looked at the laminar burning velocities of propane–hydrogen–air mixtures with spherically growing flames at elevated pressures and temperatures, as well as varying hydrogen percentages. The results reveal that when the hydrogen fraction and initial temperature increase, the unstretched flame propagation speed and unstretched LBV increase, but they decrease as the initial pressure increases, as shown in Figure 4.

Boushaki et al. [51] studied the effects of hydrogen enrichment and steam addition on methane-air premixed flame laminar burning velocity. The results reveal that hydrogen enrichment improves LBV and adiabatic flame temperature. Bao et al. [52] studied the laminar flame combustion properties of premixed cyclopentanone/air mixtures at high temperatures and developed empirical formulae for determining LBV for a variety of fuel-air equivalency ratios and beginning temperatures. Reyes et al. [53] explored the burning velocities of methane-air and hydrogen-air mixtures in a spherical constant volume combustion bomb by altering the beginning conditions of pressure, temperature, and fuel/air equivalency ratios. The findings are in good agreement with data gathered by other researchers. The result was that fully laminar combustion at stoichiometry is nearly impossible as pressure rises.

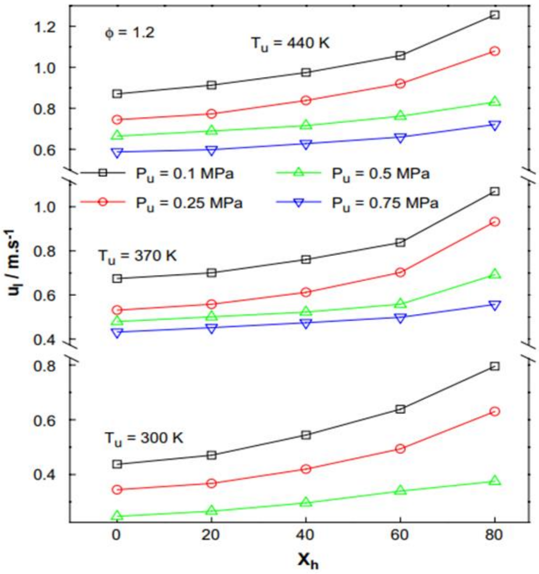

Figure 4. The LBV of C3H8/H2/Air Mixture Variations with Changing Initial Pressure and Temperature [50]

4.1.2 Initial pressure

It is a significant determinant of burning velocity. In general, increasing the pressure of the unburned gas causes the LBV to decree.

Hayakawa et al. [54] studied the un-stretched LBV of premixed ammonia/air mixtures and found that increasing the initial mixture pressure reduces it. The hydrocarbon fuels have the same propensity. Yasiry and Shahad [55] studied LPG/H_2 blends at various beginning pressures and proposed a formula for determining the laminar burning velocity. Halter et al. [56] investigated the effects of pressure and hydrogen addition on premixed methane/air laminar flames. A spherical combustion chamber for beginning pressures of (0.1-0.5) MPa and equivalence ratios of (0.7-1.2). When the mole fraction of hydrogen in the methane+hydrogen combination was changed from 0 to 0.2, the LBV for all mixtures dropped as the pressure was increased. Baloo et al. [57] tested an alternate fuel (a mixture of iso-octane and methane). The temperature, pressure, equivalency ratio, and methane mass percentage of unburned gas were used to propose a LBV correlation. Hu et al. [37] investigated the accuracy of the Bunsen flame method for measuring laminar flame speed at different pressures. The stoichiometric and fuel-rich flames were discovered to have a two-reaction-zone structure: an inner premixed flame where the fuel was transformed to CO and H_2, and an outer diffusion flame. As pressure rises, the inner premixed flame gets thinner, and the flame as a whole is more likely to be thrown off. As seen in Figure 5, the LBV drops exponentially as the starting pressure rises.

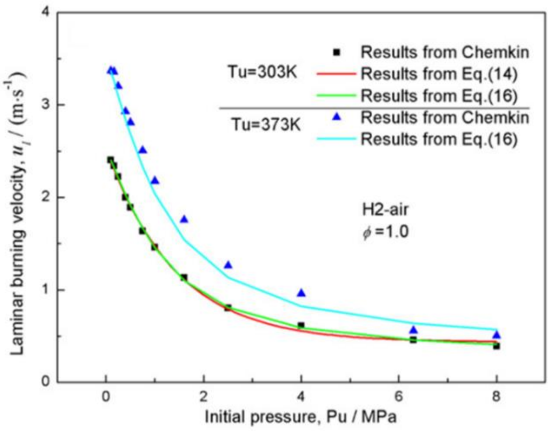

Figure 5. The effect of initial pressure on the LBV of an H2/air mixture

Zhou et al. [58] investigated the impact of modifications in fuel content and initial pressure on the features of premixed H_2/CO/CH_4 flames using the spherical expanding flame method and the CHEMIKIN program. They discovered that when the starting pressure was increased, the LBV dropped, owing to the increasing unburned mixture density and lowering H, OH radical concentrations under the measured equivalency ratio.

Bai et al. [59] discussed pressure rise data acquired from a cylindrical chamber during combustion, a multi-shell thermodynamic model was described to quantify laminar burning speed of biomass/air mixtures with various CO_2 concentrations (0% -60%). Flames start out smooth, but as the pressure and radius of the flame increase, fractures and cells emerge on the surface.

4.1.3 Flame temperature

The greatest burning velocity is determined by the final flame temperature. The reliance on most combinations is quite high. The dissociation of flame temperature occurs much faster than the burning velocity. Some of the programs that can be used to determine the adiabatic flame temperature while accounting for dissociation using equilibrium constants is by Olikara and Borman [60], Gordon [61], and Reynolds [62]. These programs were applicable to any fuel type and alcohol family for a wide range of reactant situations (equivalence ratio, initial pressure, and temperature). Sabdenov [63] demonstrated that the faster the fuel burns, the greater the flame temperature.

4.1.4 Thermal diffusivity and specific heat

Clingman et al. [64] conducted a series of tests to investigate the impact of thermal diffusivity and reaction rates on burning velocity. They measured the speed of methane flame propagation in various oxygen-inert gas combinations where the oxygen to inert gas volume ratio was always 0.21:0.79. Nitrogen, helium, and argon were employed as inert gases. They also discovered that when the thermal diffusivity of the mixture grows, the burning velocity also increases, and that the lower the specific heat of the inert gas, the higher the flame temperature and burning velocity of the combination. Liu et al. [65] studied the effects of diffusional-thermal and hydrodynamic instability on flame destabilization are exacerbated with hydrogen addition in lean and stoichiometric mixtures. The diffusional-thermal instability has a modest effect on flame destabilization as initial pressure rises, while the consequences of the hydrodynamic instability.

4.1.5 Initial ignition energy

Bradley et al. [66] investigated the effects of igniting a stoichiometric mixture on flame growth. Several degrees of thermal energy were used to ignite a stoichiometric mixture. The explosions were numerically generated by hot combustion products within a sphere, and the results revealed that changing the energy between 4.09 and 10.40 mJ has an impact on flame development, as shown in Figure 6. A shock wave followed by a slower thermal wave caused by ignition energy increases the flame speed by raising the mixture temperature, according to Bradley et al. [66]. The creation of a small flame kernel is aided by spark ignition, which has an early influence on flame expansion. As a result, when extracting LBV, avoiding small flame kernels can drastically reduce this effect. when the flame radius exceeds 6 mm. Kim et al. [67] studied the influence of ignition energy on laminar flame speeds for CH_4/N_2/O_2/He mixtures. The data reveals that increasing ignition energy improves initial flame propagation speed and extends the range of flame trajectory impacted by ignition energy, but the rate of development in speed and range slows as ignition energy increases.

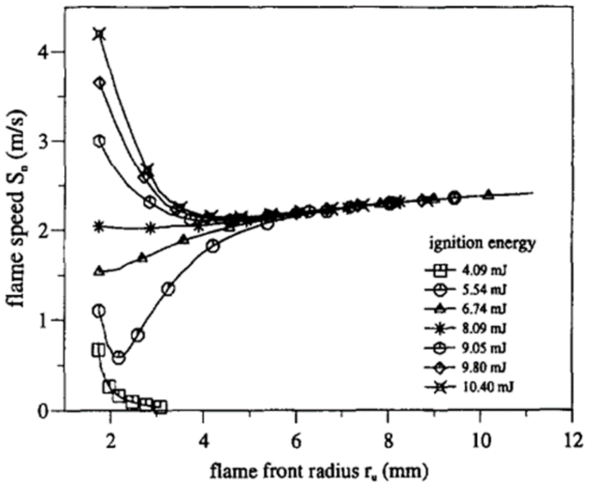

Figure 6. Flame speed vs. radius for various ignition energies [66]

4.2 Chemical parameters

4.2.1 Mixture strength (Φ)

The actual to stoichiometric fuel/air ratio is the equivalency ratio (Ø). Eq. (1) except for exceptionally rich fuel-air combinations, the relationship between burning velocity and equivalency ratio is normally the same as the relationship between LBV and adiabatic flame temperature. As a result, it reaches its peak at slightly richer than stoichiometry.

$$Ø = \frac{\left(\frac{A}{F}\right)\text{act}}{\left(\frac{A}{F}\right)\text{stoic}} \tag{1}$$

Alekseev et al. [68] investigated the effect of temperature on the burning velocity of hydrogen flames for various equivalence ratios using an updated mechanism, validated the mechanism with numerous studies, and discovered that the maximum LBV region is slightly richer than stoichiometric, as shown in Figure 7.

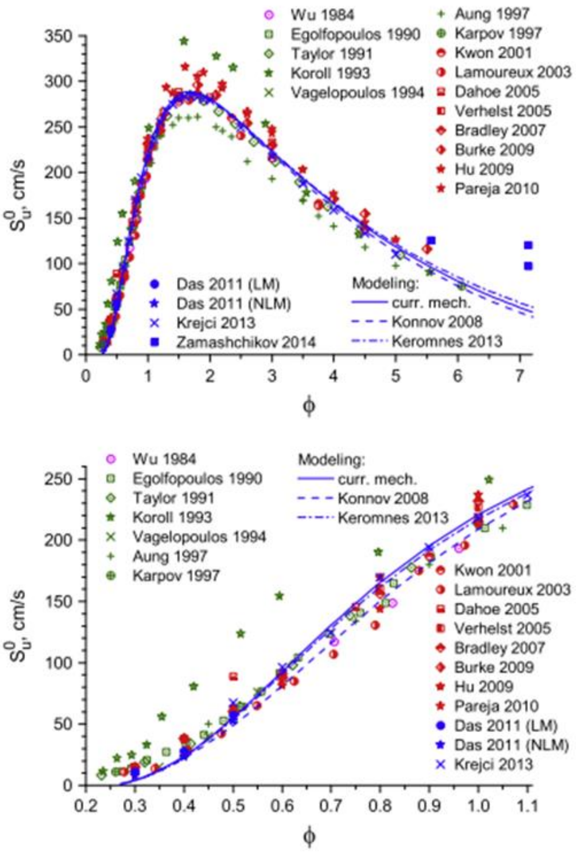

Figure 7. At Standard Conditions, LBV of H_2/Air Flames for ϕ = 0.25–7 (left) & <1 (right) [68]

Huang et al. [69] studied the LBV of an H2-natural gas/air combination in a constant volume bomb at 298 K, 1 atm pressure, and equivalency ratios ranging from 0.6 to 1.4. The findings revealed that there is a linear relationship between flame radius and time for both lean and rich mixture combustion. For natural gas/air, hydrogen/air, and natural gas/hydrogen/air flames, combustion of stoichiometric mixtures revealed a linear relationship between flame radius and time. The flame instability grew as the hydrogen fractions in the mixture rose. Experiments were used to come up with a method for finding the LBV of natural gas, hydrogen, and air flames. Gong et al. [70] investigated the impacted laminar flame speeds of expanding spherical lean syngas/air flames. According to extrapolation, the Mark-stein length rises as the equivalency ratio increases.

4.2.2 Fuel molecular structure

Wei et al. [71] investigated the effects of CO_2 or/and H_2O on instability and cellular structures in order to minimize the intensity of the premixed methane/air flame explosion. CO_2 can decrease the quantity of cellular structures, whereas H_2O can enhance their size. H/O/OH can also be reduced by CO_2 or H_2O. Wang et al. [72] used the spherical flame method to investigate the laminar burning speed, Markstein length, and cellular instability for various types of fuel. The molecular structure of fuels influences laminar flame propagation via the fuel-specific breaking route. Due to the lack of a C–C link in some of the study's fuels, significant oxy-intermediates (CH2O) with high reactivity occur during fuel decomposition.

vom Lehn et al. [73] studied the fuel structure dependence of the LBV LBV using sensitivity analysis and comprehensive fuel comparisons. Unsaturation improves LBV, while methyl substitution has a negative effect on a wide range of fuel structures. This is in line with previous research.

4.2.3 Oxygen as oxidizer

Instead of burning fuel in the air, oxy-fuel combustion is being used in several recent advancements in combustion technology [74]. This combustion removes all or a portion of the N_2 in the air, resulting in an increase in the concentration of O_2 as an oxidant from 21% to 100% by volume. Because it improves the stability of the flame and the efficiency of combustion [75, 76]. This technology is frequently utilized in industries, including cement manufacture, glass production, and metal heating and melting.

Cai et al. [77] investigated the impact. Laminar burning velocities and Markstein lengths of $CH_4/O_2/N_2$ mixes over a wide range of O_2 concentrations Experimental laminar burning velocities increase significantly when the oxygen enrichment ratio is increased in a constant volume combustion chamber. Wang et al. [78] investigated ammonia outward propagation flames at a variety of temperatures, equivalency ratios, and oxygen percentages. The findings showed that increasing the amount of oxygen and the temperature at which it started to burn made the laminar burning speed faster. At pure oxygen and normal temperature (303 K), the LBV reached 125.05 cm/s.

4.2.4 Inert additives fuel

Many studies analyzed the effects of inert additives like CO_2, H_2O, He, and Ar on combustible mixtures' burning velocities. Xu and Jiang [79] studied the effects of adding NaCl to aluminum–methane–air flames over a range of dust concentrations, the LBV, and measured the established by using a modified nozzle burner. As a result, the burning velocity was reduced.

Eckart et al. [80] investigated the influence of N_2 dilution on the LBV of oxymethylene ether in an experimental and numerical investigation (OME1). In the study, it was found that raising the proportion of N2 led to a non-linear decrease in LBV, regardless of the equivalence ratio. Yelishala et al. [81] investigated the influence of CO_2 on the LBV of propane/air mixtures. A cylindrical constant volume bomb was used to test a range of CO_2 concentrations (0-80%), equivalence ratios (0.7-1.2), temperatures (298-420 K), and pressures (0.5-6.2 atm). The addition of CO_2 reduced the laminar burning speed of these mixtures, whereas the increase in gas temperature increased it. It was also discovered that as pressure rises, the rate of laminar burning reduces.

5. ANOTHER ELEMENT THAT AFFECT FLAME SPEED

In spark-ignition engines, flame propagation velocity controls the rate of pressure rise in the cylinder and the type of combustion. Hence, investigating factors that influence flame propagation velocity is critical. A variety of factors influence flame speed to differing degrees. The two most important factors are turbulence and the fuel-air ratio. The following sections go through the numerous factors that influence flame speed.

5.1 Compression ratio

A higher compression ratio raises the mixture's in-cylinder pressure, temperature before ignition and a shorter ignition delay. It leads to improved thermal efficiency and lower fuel consumption. When the compression ratio is increased, the clearance volume is reduced, and the density of the cylinder gases during combustion increases. This raises the peak pressure and temperature while shortening the time of combustion. Faster compression ratio engines provide higher flame speeds [82].

Duan et al. [83] investigated the effect of natural gas composition and compression ratio on thermodynamics and combustion properties. The findings showed that when the heavy-duty spark ignition engine's compression ratio was increased, so did the in-cylinder pressure.

5.2 Fuel-air ratio

A compression ratio raises the working mixture's pressure and temperature before ignition, reducing the first preparation period of combustion and requiring less ignition advance. The second phase of combustion is also accelerated by the high temperatures and pressures in the compressed mixture. When the compression ratio is increased, the clearance volume is reduced, and the density of the cylinder gases during combustion increases. This raises the peak pressure and temperature while shortening the time of combustion. Faster compression ratio engines provide higher flame speeds [84].

5.3 Turbulence

The non-turbulent mixes have a modest flame speed, which increases as turbulence increases. This is due to the physical intermingling of burning and unburned particles near the flame front, which speeds up reaction by increasing the contact rate. Turbulence made up of numerous little swirls appears to speed up the reaction and produce a faster flame than turbulence made up of larger and fewer swirls [85].

Ayache and Birouk [85] used to study the turbulent burning velocity of a premixed biogas-air flame in a spherical combustion chamber. The results showed high turbulence and lowering the methane percentage in the surrogate reduced the mixture's flammability, and as turbulence intensity increased, the peak of turbulent burning velocity migrated away from stoichiometric and toward a leaner equivalency ratio.

6. CONCLUSIONS

The recent advances in fundamental research on laminar spherically premixed syngas flame propagation, particularly laminar flame speed, are discussed in this work. For different stages of flame propagation, there are detailed summaries and discussions. The effects of intrinsic flame instability on laminar flame speed, creased flame front are highlighted, as are the physical and chemical factors that affect the flame speed separately. In addition, this study is a summary of the researchers' studies of a lot of hydrocarbons in this field. Future perspectives on laminar spherically premixed syngas mixture flame propagation are also highlighted:

(1) An increase in the starting pressure of the mixture slows down combustion speed while increasing the amount of mass that is used.
(2) It has been found that raising the temperature of the mixture before it starts to burn speeds up the process and makes the flame more stable.
(3) As the equivalency ratio is increased, the combustion velocity for poor mixtures increases while the combustion velocity for rich mixtures drops.
(4) Hydrogen gas is used to improve laminar burning velocities more quickly.
(5) Diluting with inert materials reduces laminar combustion speeds.
(6) Dilution was used to minimize emissions.
(7) CO_2, in comparison to N_2, H_2O, has a stronger inhibitory effect.
(8) CO_2 performs the most stenography in the LBV because it has a bigger thermal diffusion impact than H_2O and N_2.
(9) A variety of measurement techniques exist for estimating the LBV, but Schlieren's constant-volume combustion chamber approach is considered the most precise.
(10) Addition of oxygen to the flame raises its temperature, increases heat transmission through radiation, and improves the flame's flammability limits while also making it more stable at the same time.
(11) The molecular structure of the fuel the breaking of the fuel affects the spread of the laminar flame. This causes the hydrocarbon fuel's combustion speed to slow down and the number of carbon atoms in the molecule fuel to go up.
(12) Increasing the pressure and temperature both lowered the thickness of the flame, although the effect of temperature on the thickness was less than that of pressure.

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