

Review Article

A Review of Laminar Burning Velocity and Flame Speed of Gases and Liquid Fuels

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Accepted 02 Feb 2017, Available online 12 Feb 2017, Vol.7, No.1 (Feb 2017)

Abstract

Flame speed and laminar burning velocity are two important aspects of fuel combustion characteristic. They both affect combustion system design and performance. A lot of researches work related to flame speed and laminar burning velocity had been carried out, but these work were speared in different journals and conference proceeding. The aim of this paper is to assemble as much as possible of these researches and to present it in this paper for ease of reviewing.

Keywords: *Burning velocity, Bunsen burner, Internal combustion engines, Flame speed*

1. Introduction

The most relevant definition of flames is visible chemical component undergoing highly exothermic chemical reaction takes place in a small zone with the evolution of heat. The flame speed is the measured rate of expansion of the flame front in a combustion reaction [Taylor *et al.*, 1991]. Flames can be produced in two radically different ways depending upon how the reactants are brought together, premixed and non-premixed.

In the premixed flame, the oxidizer has been mixed with the fuel before it reaches the flame front. The reaction creates a thin flame front as all of the reactants are readily available. The pre-mixed flammability limits for most hydrocarbon fuels are $0.6 < \phi < 3$ [Strahle, W. C., 1993].

In a diffusion flame (non-premixed), the reactants are initially separated, and the reaction occurs only at the interface between the fuel and oxidizer, where mixing and reaction both take place. It can also be defined as the flame in which the oxidizer combines with the fuel by diffusion. As a result, the flame speed is limited by the rate of diffusion. Diffusion flames tend to burn slower and to produce more soot than premixed flames because there may not be sufficient oxidizer for the reaction to complete [Taylor *et al.*, 1991].

Laminar burning velocity is one of the fundamental properties of a reacting premixed mixture and its reliable data are constantly needed for combustion applications. So far, several techniques for measuring the one-dimensional laminar burning velocity have been used for a wide range of temperatures, pressures

and fuels. Some of these techniques flat or curved flames in stagnation flow, propagating spherical flames in combustion vessel and flat flames stabilized on burner. With all these measurement techniques proper care should be taken to remove the effect of flame stretch either during experimentation or through further data processing.

Also, Laminar burning velocity contains fundamental information regarding reactivity, diffusivity, and exothermicity. Its accurate knowledge is important for engine design, modeling of turbulent combustion, and validation of chemical kinetic mechanisms. In addition, the determination of burning velocity is very important for explosion protection and fuel tank venting. Laminar burning velocity is highly useful for modeling turbulent burning velocity.

Whereas laminar flame speed embodies the fundamental information on diffusivity, reactivity, and exothermicity of a given mixture and is therefore commonly used to characterize flames. As such, the measurement of laminar flame speed has received considerable attention in the published literature, particularly with regard to the effects of flame stretch on the fundamental (unstretched) laminar flame speed and the attainment of highly accurate, unperturbed measurements.

2. Experimental and Theoretical Investigations of Laminar Burning Velocity

Flat flame burner method due to [Powling and Edgerton, 1949] provided a close approximation to the ideal one-dimensional flat flame, but is limited to low burning velocities of about 0.15 – 0.2 m/sec.

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Heat flux method was based on the earlier work of [Botha and Spalding, 1954] and proposed by [de Goey *et al.*, 1993]. The heat flux method deals with an unstretched, one – dimensional flame at adiabatic conditions. The stabilized adiabatic flame has been used by [Van Maaren and de Goey, 1994] and [Bosschaart and de Goey, 2003]. Many investigators used this method such as [Konnov and Dyakov, 2004 – 2007], [Coppens and Konnov, 2008] and [Naucier *et al.*, 2011].

Hot wire method was a direct measurement of burning velocity from the flame speed and velocity of unburned gas measurements in closed vessel. [Bradley and Hudey, 1971] used hot wire anemometer to measure the gas velocity ahead of the flame front in methane – air explosions. The flame speed may be measured using ionization probes or by flame photography.

[Andrews and Bradley, 1972b] derived burning velocity directly from flame speed measurement in explosions by a method that takes into account the temperature distribution through the flame front. The flame speed is related to burning velocity during the constant pressure period. They have shown that, for (methane-air) mixtures the values were in reasonable agreement with those obtained using both the bomb hot wire anemometer and the nozzle burner track techniques.

[Andrews G.E., 1973] demonstrated the principle of Double Kernel method. The essence of the method was to oppose a pair of simultaneously ignited flame kernels. As they expand towards one another, the flow of unburned gas is constrained along the line between their centers. The flames flatten and the two approaching flame surfaces approximate the flat flame geometry. Their relative movement asymptotically approaches twice the normal burning velocity. The velocity of gas on the axis of centers must be zero at the midpoint, and flame speed along this axis tends to the burning velocity.

[Odger *et al.*, 1980] applied the tube method wherein this method the mixture is ignited at the open end of a tube and the flame front is photographed as propagating towards the closed end. In general, the results obtained from this method were close to those obtained with Bunsen burner.

In constant volume bomb method the flame propagation involves an increase in pressure. The burning velocity was calculated by measuring the pressure variation with the flame front radius. This method was used by [Metghalchi and Keck, 1980].

One of the main sources of error in measuring the burning velocity using Bunsen burner is the curved surface of the flame cone. Then to overcome this problem a nozzle is fitted directly over the tube end to get a conical flame with straight sides. This method was used by [Kobayashi & Kitano, 1989].

[Sher and Ozdor, 1992] used an empirical equation that takes into consideration the effect of addition of hydrogen on the laminar burning velocity of (n-butane-

air) mixture in addition to the effects of equivalence ratio and initial mixture temperature.

[Koroll and Kumar, 1993] found a new technique for measuring burning velocity at high pressure in the final stages of two inward propagating flame kernels in an explosion bomb. The pressure and flame kernel propagation speeds measured by high -speed photography showed that the burning velocities to be elevated above the corresponding laminar burning velocities as a result of developing flame instabilities.

[Arkan F.S., 2000] suggested two empirical equations that takes into consideration the effect of mixture strength, unburned temperature of mixture and number of carbon atoms upon the laminar burning velocity for [(methane, propane, ILPG and butane)- air] mixtures .

Total area method was used to measure the normal burning velocity. The burner's tube should be sufficiently long for fully developed laminar flow to be achieved. This method was used with hydrocarbon-air flames [Ali, R.M., 2000].

[Stanglmaier *et al.*, 2003] reported that the laminar burning velocity of gasoline can be considerably different from that of iso-octane, particularly at higher temperatures and pressures.

[Farrell *et al.* 2004] and [Cruz *et al.* 2009] reported that aromatics have different flame speeds compared to alkanes. Therefore, the laminar burning velocities of primary reference fuel PRF mixtures are different from gasoline laminar burning velocities and may induce errors during flame propagation simulations.

The laminar burning velocity of toluene has not been investigated as extensively as iso-octane and n-heptane with only few measurements having been presented [S.G. Davis,1996], [T. Hirasawa,2002], [R.J. Johnston,2004], [S.P. Marshall,2011] and [C. Ji, E. Dames,2012].

[Al-Shaharany *et al.*, 2005] applied the constant volume bomb method where the combustible mixture was ignited at the center of a rigid spherical or cylindrical vessel, and the rate of propagation of the spherical flame front in space was measured. They found that close to the point of ignition, the high curvature of the flame causes a reduction in the burning velocity, but if a large vessel is used, approximately of more than (250 cm) diameter, then remote from the spark, the flame front approximates a one-dimensional plane.

[Jerzembeck *et al.* ,2009] compared the laminar burning velocity of a commercial gasoline and a PRF mixture with a research octane number of 87. The agreement was very good for lean mixtures but deviations were found for rich and stoichiometric mixtures.

[Hu *et al.* ,2009] used a cylindrical type combustion chamber in experimental work with an inner diameter of (180 mm) and volume of (5.5L) as shown in figure (1). Laminar burning velocities was obtained at the elevated pressures and temperatures . Sensitivity analysis and flame structure were also analyzed.

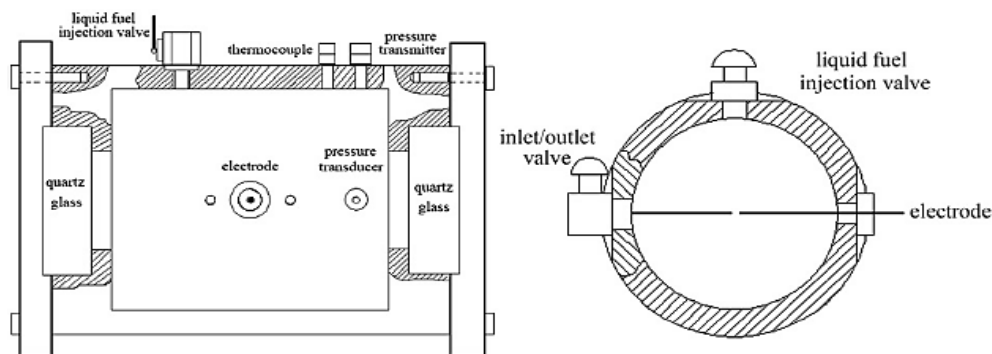


Figure 1: Schematic of CVC Apparatus of Hu *et al.* (2009) [Hu *et al.*, 2009]

Table 1: Results for Some Burning Velocity's Measuring Methods According to their References

Reference	Type of method	Results
Powling and Edgerton , 1949	Flat flame burner	close approximation to the ideal one-dimensional flat flame, but is limited to low burning velocities of about 0.15 – 0.2 m/sec
Konnov and Dyakov, 2004 – 2007	Heat flux	An unstretched, one – dimensional flame at adiabatic conditions provided the stabilized adiabatic flame.
Bradley and Hundey, 1971	Hot wire	The flame speed may be measured using ionization probes or by flame photography
Andrews and Bradley, 1972b	Constant volume bomb	For (methane-air) mixtures the values were in reasonable agreement with those obtained using both the bomb hot wire anemometer and the nozzle burner track techniques
Andrews G.E., 1973	Double kernel	The velocity of gas on the axis of centers must be zero at the midpoint, and flame speed along this axis tends to the burning velocity.
Odger <i>et al.</i> , 1980	Tube method	The results obtained from this method were close to those obtained with Bunsen burner
Metghalchi and Keck, 1980	Constant volume	The flame propagation involved an increase in pressure. The burning velocity was calculated by measuring the pressure variation with the flame front radius.
Kobayashi & Kitano, 1989	Bunsen burner	get a conical flame with straight sides
Koroll and Kumar, 1993	Kernel	the burning velocities will be elevated lead to result of developing flame instabilities
Ali, R.M., 2000	Tube method	fully developed laminar flow
Al-Shaharany <i>et al.</i> , 2005	Constant volume bomb	the high curvature of the flame causes a reduction in the burning velocity
Yang Zhang <i>et al.</i> , 2012	Constant volume bomb	Laminar burning velocities increase with increasing hydrogen fraction due to the high reactivity of H ₂ leading to high production rate of H and OH radicals

Measurements of laminar burning velocities of iso-octane and n-heptane have previously been performed by [van Lipzig *et al.*, 2011] using a similar heat flux setup. The results by [Dirrenberger *et al.*, 2013] are systematically lower than what was reported by [van Lipzig *et al.*, 2011] by a few cm/s. This discrepancy is larger than the stated experimental error. The goal of that work was: first, to provide accurate experimental laminar burning velocity data for a (well characterized) gasoline and the gasoline surrogate components iso-octane, n-heptane and toluene and to compare the experimental data with numerical simulations, previous data from the same setup and data from the literature; second, to investigate the temperature dependence of the laminar burning velocities; and third to find a surrogate that can match the laminar burning velocity of the studied gasoline.

[Liao *et al.*, 2012] suggested an empirical equation for predicting laminar burning velocity of (ethanol– air) mixtures at different initial temperatures, pressures and equivalence ratios.

[Yang Zhang *et al.*, 2012] studied laminar burning velocity of H₂/CO/N₂/CO₂ /air mixtures by using constant volume bomb. Diffusional thermal instability was enhanced but hydrodynamic instability was insensitive to the increase of hydrogen fraction in fuel mixtures. Laminar burning velocities increase with increasing hydrogen fraction due to the high reactivity of H₂ leading to high production rate of H and OH radicals.

[Galmiche *et al.*, 2012] showed that there are significant discrepancies between all the correlations for the laminar burning velocity of iso-octane/air mixtures and that the differences are mainly due to the

different experimental setup and methodologies for data post processing. Laminar burning velocity measurements must still be improved and the influence of temperature, pressure and diluents on the laminar burning velocity has to be investigated in further detail.

Recent measurements of the laminar burning velocity of a commercial gasoline, iso-octane, n-heptane and toluene were performed by [Dirrenberger et al., 2013] using the heat flux method.

[Hartl S. et al., 2014] studied laminar burning velocity for highly N₂ diluted synthetic H₂ and H₂/CO mixtures with low calorific value, burning with air at ambient temperature and atmospheric pressure using heat flux method.

[Christensen et al., 2016] analyzed the influence of different uncertainty factors originating from each part on the setup. Asymmetric heat fluxes and the method for determining flame surface area were found to give an important contribution to the total error. As the result of this, some of the previously published data have been reevaluated.

[Ahmed Shakir, 2016] studied experimentally laminar burning velocity of the premixed Iraqi liquefied petroleum gas (LPG)/ hydrogen/ air flames in a centrally ignited constant volume chamber at different initial pressures (0.1-0.3 MPa) and initial temperature of (308 K). Besides, the tested equivalence ratios of air/fuel mixture range from (0.8 - 1.3), and the investigated blends of hydrogen were 0-80% by volume. Experimental data of laminar burning velocity, flame thickness, stretch rate, and laminar flame speed and combustion pressure of LPG flames with various blends of H₂ have been presented.

3. Experimental and Theoretical Investigation of Laminar Flame Speed

The measuring of flame speed needs a special technique for detection of flame front arrival along a certain space, therefore many investigators worked hard to find out the different techniques of measuring flame speed.

[Dugger G.L., 1952] used optical techniques. The photograph of this method needs that the screen should be close to the flame front. Any increase in distance between the screen and the flame front will increase the separation between the light and dark areas and will be difficult to interpret the image.

[Botha and Spalding, 1954] extended the flat flame method to measure higher flame speed by using a water-cooled porous disk. The cooling effect induces heat loss from the flame and stabilizes the flame closer to the disk. The tests are repeated at different cooling rates so that the values of flame speed S_L can be plotted against the cooling rates. To obtain the adiabatic flame speed S_L , extrapolation of the curve of S_L versus cooling rate back to zero cooling rate is performed. Some uncertainty is associated with this method including the unknown loss of radical species such as H to the porous plate.

[Odger et al., 1980] measurements have been made for propane – air mixtures diluted with nitrogen, carbon dioxide, helium or argon. The results have been used to forecast the laminar flame speed of mixtures, and rates of flame travel for the various mixtures have been correlated with groups representative of reaction rate and gas transport properties

The simplest and oldest method of measurement used a glass or plastic visible channels. Therefore the flame propagation becomes visible and with using a stop – watch to find the time required to pass the flame between any two indicated points. This method used by [Ziad A.K., 1982].

[Gulder O.L., 1983 and 1984] used ionized probe technique since combustion operation is a fast chemical reaction. This phenomenon happens because of the ionization of reaction atoms. Therefore the level of ionization is very high at the flame front. This technique cannot give the real position of the flame front because the ionization levels stay high behind the flame front.

[Odger et al., 1985] used thermocouple technique. The main feature of this technique is that it allows the flame for propagating inside the combustion chamber and for passing over many thermocouple junctions located inside the chamber. The flame temperature is greater than that of the burned and unburned gas, so that, the thermocouple can be used as a sensor probe for this phenomenon.

The flame speed was directly determined when the planar flame undergoes transition from positive to negative stretch region, during which the flame undergoes a near-zero strain rate condition. The minimum velocity at this near-zero stretch state was regarded as true laminar flame speed.

[Mendes-Lopes and Daneshyar, 1985] utilized the wall- jet setup to measure the laminar flame speed of propane/air mixtures and the effect of strain rates on flame speeds.

[Van Maaren et al., 1994] utilized the flat flame method to measure the adiabatic flame speed of methane/air mixtures and good agreement was achieved when compared to the literature. The adiabatic flame speed is determined and based on the measurement of the burner plate temperature profile. The uniform plate temperature profile indicates zero net heat loss of flame and hence the adiabatic flame speed is obtained.

[Vagelopoulos and Egolfopoulos, 1998] measured the unstretched laminar flame speed of methane/air, ethane, propane/air for a wide range of equivalence ratio. The laminar flame speed values were found to be systematically lower than the values that have been determined by using the traditional stagnation flow technique and linear extrapolations to zero strain rate.

[Dong et al., 2002] utilized the stagnation flow configuration to measure the laminar flame speeds of ethane/air mixture diluted with helium and with nitrogen before a flame undergoes a transition from planar to Bunsen flame.

Table 2: Results for Some Flame Speed Measuring Methods According to their References

References	Type of method	Results
Dugger G.L., 1952	Optical technique	Any increase in distance between the screen and the flame front will increase the separation between the light and dark areas and will be difficult to interpret the image.
Botha and Spalding, 1954	Flat flame	The tests are repeated at different cooling rates so that the values of flame speed S_L can be plotted against the cooling rates. To obtain the adiabatic flame speed S_L , extrapolation of the curve of S_L versus cooling rate back to zero cooling rate is performed.
Gulder O.L., 1983 and 1984	Ionized probe	The level of ionization is very high at the flame front. This technique cannot give the real position of the flame front because the ionization levels stay high behind the flame front.
Odger <i>et al.</i> , 1985	Thermocouple	The flame temperature is greater than that of the burned and unburned gas, so that, the thermocouple can be used as a sensor probe for this phenomenon.
Van Maaren <i>et al.</i> , 1994	Flat flame	The adiabatic flame speed is determined and based on the measurement of the burner plate temperature profile. The uniform plate temperature profile indicates zero net heat loss of flame and hence the adiabatic flame speed is obtained.
Dong <i>et al.</i> , 2002	Stagnation flow configuration	The result was compared with numerical simulation obtained from GRI-Mach 3.0. The ethane /air / helium laminar flame speed was over predicted but ethane/air/nitrogen dilution shows closer agreement.
Zhao, J. P. Conley, 2003	Preheating method	Measurements were also performed on the gasoline surrogate fuel consisting of n-heptane and iso- octane mixture at 500 C .
Yash Kochar <i>et al.</i> , 2011	Bunsen burner , an expanding spherical flame method	A significant result was that the effect of mixture composition on flame speed was well captured by the mechanism over the extreme ranges of initial pressure and temperature.
Samahat Samim <i>et al.</i> , 2016	cylindrical bomb capable	Flame speed was measured by analyzing the pressure signals after combustion detected by a pressure transducer mounted on the bomb. The blended fuel has the lowest flame speed at the highest temperature, about 89.7 cm/s at 250 C.

The result was compared with numerical simulation obtained from GRI-Mach 3.0. The ethane /air / helium laminar flame speed was over predicted but ethane/air/nitrogen dilution shows closer agreement.

[Ahmed A.N., 2003] studied the laminar flame speed of Bunsen burner and also studied the effect of insulating the flame from the outside boundary by nitrogen inert gas. The experimental work was for a fuel gas mixture of methane and Iraqi petroleum gas with air for a wide range of mixing rates under conditions ($P_u = 1\text{atm.}$, $T_u = 298\text{K}$).

[Zhao, J. P. Conley, 2003] measured flame speed for gaseous fuels, propane/air and dimethyl ether/air mixtures . A preheating method was used to vaporize liquid fuels of n-heptane/air and n-decane/air mixture to elevated temperatures prior to measurements. Measurements were also performed on the gasoline surrogate fuel consisting of n-heptane and iso- octane mixture at 500 C. The laminar flame speed of the surrogate fuel was compared to actual gasoline and primary reference fuel (PRF) model. The adiabatic flat flame method was further extended to measure the laminar flame speed of ethane, propane, n-butane and isobutene by [Bosschaart and De Goey, 2004].

[Zhao, 2005] measured laminar flame speeds of n-decane /air mixtures at 500 K and atmospheric pressure with and without dilution . The measured flame speeds were significantly different that those

predicated using existing published kinetic models, including a model validated against high temperature data from flow reactor, jet stirred reactor, shock tube ignition delay and burner stabilized flame experiments.

[Natarajan *et al.*, 2007] measured the flame speed of $\text{H}_2/\text{CO}/\text{CO}_2$ mixture for a range of temperatures and compared the strained flame with simulation results Obtained from GRI Mach 3.0 [G. P. Smith] and H_2/CO mechanism of [Davis *et al.*, 2005]. The measurement showed the strained laminar flame speeds for lean mixture of 50: 50 H_2/CO at 700 K. Attention has been placed on obtaining a comprehensive and kinetically accurate model able to predict a wide variety of H_2 - CO combustion data

However, good agreement between the data in [Natarajan *et al.*, 2007] and simulation result was achieved for 5-20 % H_2/CO mixtures at elevated pressure of 5 atm., initial temperature of 300 K and $\phi = 0.6$.

[Yash Kochar *et al.*, 2011] utilized two experimental techniques Bunsen burner method and an expanding spherical flame method. Pressures up to 10 atm. were studied and the mixtures ranged from pure methane to binary blends of $\text{CH}_4/\text{C}_2\text{H}_6$ and $\text{CH}_4/\text{C}_3\text{H}_8$. A significant result was that the effect of mixture composition on flame speed was well captured by the mechanism over the extreme ranges of initial pressure and temperature.

[Samahat Samim *et al.*, 2016] studied the laminar flame speed of gas to liquid (GTL) fuel and its 50-50 % by volume blends with conventional diesel in a cylindrical bomb capable of measuring flame speed at initial temperatures and equivalence ratios at ambient pressure. Flame speed was measured by analyzing the pressure signals after combustion detected by a pressure transducer mounted on the bomb. The blended fuel has the lowest flame speed at the highest temperature, about 89.7 cm/s at 250 C.

4. Effect of Chemical and Physical Variables on Burning Velocity

Many variables affect the laminar burning velocity which can be classified as chemical variables and physical variables. The effect of these variables is discussed in the following sections.

4.1 Chemical Variables

4.1.1 Effect of Mixture Strength (Φ)

Mixture strength or equivalence ratio (Φ) is defined as the ratio of the actual to the stoichiometric air - fuel ratios. It is generally acceptable to assume that a mixture with a maximum flame temperature is also has a maximum burning velocity [Barnard, J.A. and Bradley, 1985]. It is clear that very lean and very rich mixtures fail to support a propagatable flame because there is too little fuel or oxidant to maintain a steady deflagration wave. Thus, there exist upper and lower flammability limits [Turns, R. S., 2000].

[Huang *et al.*, 2006] measured the laminar burning velocity of H₂-natural gas/ air mixture in a constant volume bomb at temperature (298 K), pressure (1 atm.) and equivalence ratios (Φ) from 0.6 to 1.4. The results showed that for lean and rich mixture combustion, there exists a linear correlation between flame radius and time. Combustion of stoichiometric mixture demonstrated the linear relationship between flame radius and time for natural gas/air, hydrogen/air, and natural gas/hydrogen/air flames. Flame instability increased with the increase of hydrogen fractions in the mixture. Based on the experimental data, a formula for calculating the laminar burning velocity of natural gas/hydrogen/air flames was proposed.

[Liao S.Y. *et al.*, 2007] carried out a study on determination of the laminar burning velocities for mixtures of ethanol and air at elevated temperatures. They measured the laminar burning velocities for ethanol-air premixed mixtures at various initial temperature and equivalence ratio. The flames are analyzed to estimate flame size, consequently, the flame speeds are derived from the variations of the flame size against the time elapsed. They also studied the effects of equivalence ratio, initial temperature and pressure on the laminar flame propagation. They studied the premixed laminar combustion of ethanol-

air mixture experimentally in a closed combustion bomb and found that the laminar burning velocity was 58.3 cm/s at initial pressure of 0.1 MPa. and temperature of 358 K.

[Xuan Zhang *et al.*, 2009] carried out a study on measurements of laminar burning velocities and flame stability analysis for dissociated methanol-air-diluents mixtures at elevated initial temperatures and pressures and equivalence ratios. In this study the laminar burning velocities and Markstein lengths for the dissociated methanol-air-diluent mixtures were measured. It was found that the peak laminar burning velocity occurs at equivalence ratio of 1.8. The Markstein length decreases with the increase in initial temperature and initial pressure. Measurements of laminar burning velocities and flame stability analyses were conducted using the outwardly propagating spherical laminar premixed flame.

[Erjiang Hu *et al.*, 2009] carried out a numerical study on laminar burning velocity and NO formation of the premixed methane-hydrogen-air flames. It was found that the unstretched laminar burning velocity is increased with the increase of equivalence ratio and decreased as the mixtures become fuel-rich. Peak value of unstretched laminar burning velocity of methane-air mixture occurs at the equivalence ratio of 1.1 while that of hydrogen-air mixture occurs at equivalence ratio of 1.8. Methane-dominated combustion happens when hydrogen fraction is less than 40%, where laminar burning velocity is slightly increased with the increase of hydrogen addition. When hydrogen fraction is larger than 40%, laminar burning velocity increases exponentially increase with the increase of hydrogen fraction. With the increase of hydrogen fraction, the overall activation energy of methane-hydrogen mixture is decreased, and the inner layer temperature and Zeldovich number are also decreased. All these factors contribute to the enhancement of combustion as hydrogen is added.

[Shuang-Feng Wanga *et al.*, 2010] carried out a study on Laminar burning velocities and Markstein lengths of premixed methane/air flames near the lean flammability limit. Outwardly propagating spherical flames were employed to assess the sensitivities of the laminar burning velocity to flame stretch, represented by Markstein lengths, and the fundamental laminar burning velocities of unstretched flames. Resulting data were reported for methane/air mixtures at ambient temperature and pressure, over the specific range of equivalence ratio that extended from 0.512 to 0.601. Furthermore, the burning velocities were predicted by three chemical reaction mechanisms. Additional results of this investigation were derived for the overall activation energy and corresponding Zeldovich numbers, and the variation of the global flame Lewis numbers with equivalence ratio.

[G. Broustail, 2011] studied the potential of butanol as an additive in iso-octane used as gasoline fuel with respect to laminar combustion, and compared with ethanol.

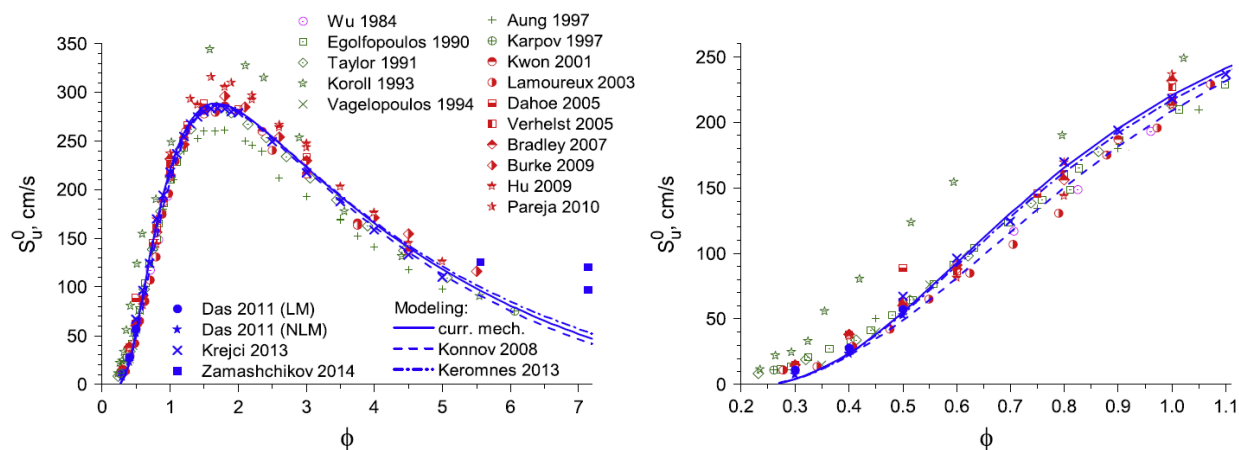


Figure 2: LBV of H₂/Air Flames at Standard Conditions for $\phi = 0.25-7$ (left) and $\phi < 1$ (right) [Aleksseev *et al.*, 2015]

New sets of data of laminar burning velocity were provided by using the spherical expanding flame methodology, in a constant volume vessel. The first results were obtained for pure fuels (iso-octane, ethanol and butanol) at an initial pressure of 0.1 MPa and a temperature of 400 K, and for an equivalence range from 0.8 to 1.4. New data of laminar burning velocity for three fuel blends containing up to 75% alcohol by liquid volume were also provided. From these new experimental data, a correlation to estimate the laminar burning velocity of any butanol or ethanol blended iso-octane-air mixture is proposed.

[Aleksseev *et al.*, 2015] used an updated mechanism to study the effect of temperature on the burning velocity of hydrogen flames for different equivalence ratios and validated the mechanism with many researches and found that the slightly richer than stoichiometric is the region of the maximum LBV as shown in Fig. (2).

4.1.2 Effect of Fuel Molecular Structure

Effect of fuel structure (number of carbon atoms) on the laminar burning velocity had been studied by [Gerstein *et al.*, 1951], [Gibbs and Calcote, 1959]. They found that the laminar burning velocity decreases with the increase in number of carbon atoms.

[Bradley *et al.*, 1991] found that for lean mixtures of the liquid fuel group, the burning velocity varied approximately linearly with the heat of reaction per kilomole of the mixture. They were able to plot different lines for different pressures and functional groups.

[Marshall *et al.*, 2011] investigated LBV of n-heptane, iso-octane, toluene, ethylbenzene and ethanol over a wide range of initial pressures, temperatures and equivalence ratios, along with tests using combustion residuals.

4.1.3 Effect of Inert Additives

Many investigators studied the effects of the inert additives to combustible mixture such as (CO₂, N₂, He and Ar), on their burning velocities.

[Erjiang Hu *et al.*, 2012] studied the effect of diluents on the laminar burning velocity of the premixed methane -air-diluent flames numerically. The mechanisms of diluent, thermal diffusion and chemical effects of diluent on the burning velocity were analyzed at different dilution ratios for different diluents. Results showed that the burning velocity was decreased in the order from helium, argon, nitrogen and carbon dioxide.

[Benedicte Galmiche *et al.*, 2011] investigated effects of dilution on premixed methane /air combustion through experiments and numerical simulations on laminar burning velocities. Laminar burning velocities were determined for several diluents (nitrogen, carbon dioxide, water vapor, a mixture of the three previous gases representative of exhaust gases, helium and argon) and for different dilution percentages. Excellent agreements between experimental data and computed results are obtained.

4.1.4 Effect of Oxygen as oxidizer

Oxygen is one of the more important factors that affecting the measurements and values of laminar flame speed and burning velocity.

[Han *et al.*, 2007] and [Oh and Noh, 2012], determined the burning velocities of methane air and methane oxygen enriched flame for various equivalence ratios by an analysis of the Schlieren image. Modified reaction mechanism showed a good agreement for predicting the burning velocity in methane /oxygen enriched flame as well as methane /air flame.

[Mazas A.N. *et al.*, 2010] investigated effects of water vapor addition on premixed methane oxygen - enhanced combustion through experiments and numerical simulations on laminar burning velocities of CH₄ /O₂/N₂/H₂O (v) mixtures. The tests were carried out at atmospheric pressure and fixed inlet temperature T_u=373 K. The mixture equivalence ratio was varied from 0.6 to 1.5. The oxygen enrichment ratio in the oxidizer, defined as O₂ / (O₂+N₂) (mol.), is

varied from 0.21 (air) to 1.0 (pure oxygen). The equivalence ratio ranges from 0.5 to 1.5 and the steam molar fraction in the reactive mixture is varied from 0 to 0.50. Experimental data yield a linear decrease of the laminar burning velocity when the water vapor molar fraction was increased. For an oxygen enrichment ratio in the oxidizer O_2 (O_2+N_2) (mol.) equal to 0.5, this decrease was found to be independent of the equivalence ratio and a correlation was proposed to decrease the effects of water vapor on the laminar burning velocity.

[Hernando A. *et al.*, 2013] studied the performance of laminar burning velocity of a mixture of H_2 , CO and N_2 (20:20:60 vol.%) using air enriched with oxygen as the oxidizer, varying the oxygen content from 21% up to 35% for different equivalence ratios. The laminar burning velocity increased with the concentration of the oxygen in the mixture due to the increase of the reaction rate for a stoichiometric mixture, the laminar burning velocity increased by almost 25% with an increment of 4% of oxygen in the oxidant.

4.2 Physical Variables

4.2.1 Effect of Pressure

[Lewis in, 1954] studied by constant volume bomb method, the effect of pressure on the burning velocity of various (hydrocarbon-air) mixtures. A power law ($S_L \propto P^{\beta_p}$) was developed, where the exponent (β_p) is referred to as the pressure index. He observed that when ($S_L < 50$ cm/s) the exponent (β_p) is usually negative, implying that (S_L) increases with decreasing pressure, for ($50 < S_L < 100$ cm/s), S_L is independent of pressure, and when ($S_L > 100$ cm/s), S_L increases with increasing pressure.

[Andrews and Bradley, 1973] discussed and described the use of double kernel method of obtaining burning velocities. Experimental results were presented for the variations of methane-air burning velocity with equivalence ratio and initial pressure. Measurement of the higher burning velocities of some hydrogen-air mixtures was difficult with this technique, but some values were presented showing the variation of burning velocity with mixture strength.

[Metghalchi and Keck, 1982] provided flame speed pressure correlation for methane and iso octane fuels. Good agreement with the limited high pressure data for methane and iso octane was obtained for maximum pressure 34 bar.

[S. Jerzembeck *et al.*, 2009] carried out a research on spherical flames of n-heptane, iso-octane and gasoline/air mixtures to determine laminar burning velocities and Markstein lengths under engine-relevant conditions by using the constant volume bomb method. Data were obtained for an initial temperature of 373 K, equivalence ratios varying from 0.7 to 1.2, and initial pressures from 10 to 25 bars. To track the flame front in the vessel a dark field He-Ne laser Schlieren measurement technique and digital image processing

were used. The laminar burning velocities were obtained through a linear extrapolation to zero stretch. The experimentally determined Markstein numbers were compared to theoretical predictions.

[Khizer and Stone, 2004] showed the variation of burning velocity as a function of equivalence ratio and pressure, and found that the burning velocity decreases with the increase in pressure.

[Hu *et al.*, 2009] studied the laminar burning velocity of hydrogen-air flames at different initial pressures and temperatures. Laminar burning velocity decrease exponentially with the increase of initial pressure as shown in figure (3).

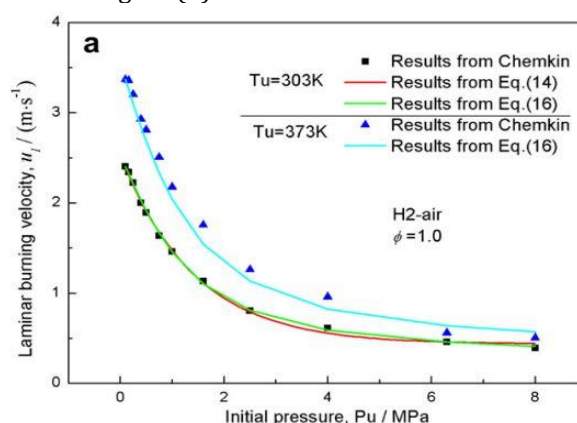


Figure 3: Effect of Initial Pressure on LBV of H_2 /Air Mixture where no. of equation as in ref [Hu *et al.*, 2009]

4.2.2 Effect of Initial Mixture Temperature

[Garforth and Rallis, 1978], [Iijima and Takeno, 1986], also investigated the initial temperature dependence of burning velocity. These studies showed that burning velocity increases with the initial mixture temperature and is mainly due to the preheating effect which increases the heat release rate as a result of increasing the initial enthalpies of reacting materials. Over the temperature ranges studied, it was shown that the burning velocity could be linearly correlated to the initial mixture temperature.

[Marshall S.P. *et al.*, 2011] performed a research on the laminar burning velocity measurements of liquid fuels at elevated pressures and temperatures with combustion residuals. A constant volume vessel (rated at 3.4 MPa.) in conjunction with a multi-zone model was used to calculate burning velocity from pressure and schlieren data, allowing the user to select data uncorrupted by heat transfer or cellularity. n-Heptane, iso-octane, toluene, ethylbenzene and ethanol were tested over a wide range of initial pressures (50, 100, 200 and 400 KPa.), temperatures (310, 380 and 450 K) and equivalence ratios (0.7–1.4), along with tests using combustion residuals at mole fractions of up to 0.3.

[Hu *et al.*, 2009] studied the laminar burning velocity of hydrogen-air flames at different initial temperatures. It was found that the laminar burning velocity increases exponentially with the increase of initial temperatures as shown in figure (4)

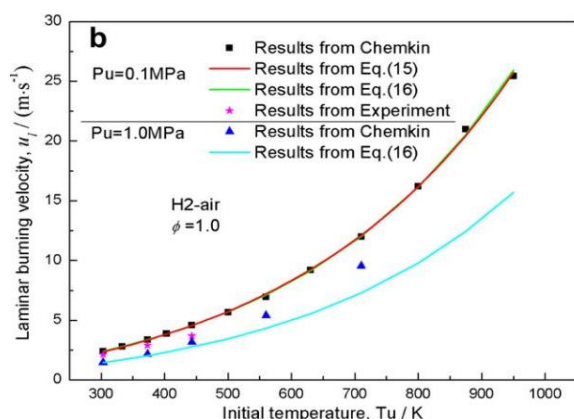


Figure 4: Effect of Initial Temperature on LBV of H₂/Air Mixture where no. of equation as in ref. [Hu et al., 2009]

[Tang et al., 2008] investigated the burning velocity for propane with different hydrogen fractions. The results showed that the laminar burning velocity increases with the increase in initial temperature as shown in figure (5).

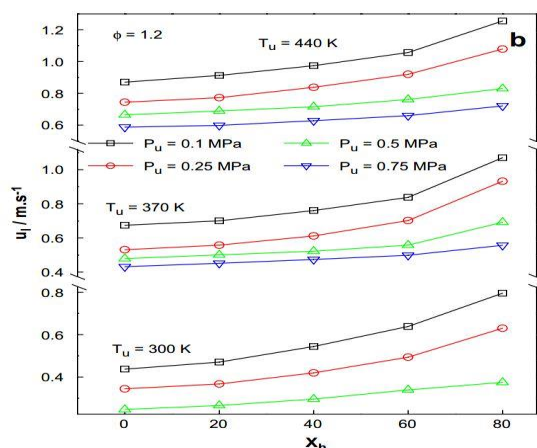


Figure 5: Variations of LBV of C₃H₈/H₂/Air Mixture for Varying Initial Temperature and Pressure [Tang et al., 2008]

4.2.3 Effect of Flame Temperature

The maximum burning velocity is a function of the final flame temperature (T_b). The dependency is very strong for the most mixtures. The burning velocity rises much faster than the flame temperature dissociation reactions.

There are a number of programs available to calculate the adiabatic flame temperature taking into account dissociation through equilibrium constants such as [Olikara and Borman, 1975], [NASA-CEA, 1976] and [STANJAN, 1986]. These programs were applicable to any fuel type and alcohol families for a wide range of reactant conditions (equivalence ratio, initial pressure and temperature).

[T.Lieuwen et al., 2007] measured laminar flame speeds for lean H₂/CO/CO₂ fuel mixtures over a range

of fuel composition (5-95 % for hydrogen and CO and up to 40 % for CO₂ by volume) with reactant preheat temperature up to 700 K. Good agreement with the measurements for medium and high H₂ fuels for preheat temperatures up to 500 K but over predict the measurements at higher temperatures.

4.2.4 Effect of Thermal Diffusivity and Specific Heat

[Clingman et al., 1953] had done a set of experiments to study the effect of thermal diffusivity and reaction rates on burning velocity. They measured the flame propagation speed of methane in various oxygen-inert gas mixtures where the volume rate of the oxygen to inert gas is (0.21: 0.79) always. The inert gases used were Nitrogen, Helium and Argon. Also, they showed that the burning velocity increases with increase in thermal diffusivity of the mixture, and the lower specific heat of the inert gas, the higher flame temperature and burning velocity of the mixture.

4.2.5 Effect of Ignition Energy

The spark discharge causes a shock wave, followed by a slower thermal wave [Bradley, D., Gaskell, 1996]. When there is a voltage difference between electrodes the air in the gap will be ionized and energy will be generated. This energy can increase the temperature of the mixture, hence the flame speed as shown in Fig. (6). For ignition energies below the minimum ignition energy, the flame speed quickly fell to zero.

[Liao et al., 2004] found that burning velocity increased with spark energy for a flame radius less than 6 mm, using ignition system energies of (25, 45 and 65 mJ) to ignite samples of natural gas.

[Huang et al., 2006] studied laminar flame characteristics of natural gas-hydrogen-air in a constant volume bomb at normal pressure and temperature. Laminar burning velocities were obtained at various ratios of hydrogen to natural gas (volume fraction from 0 to 100%) and equivalence ratios from 0.6 to 1.4. They mentioned that flame speeds became independent of ignition energy when flame radius exceeds (6 mm).

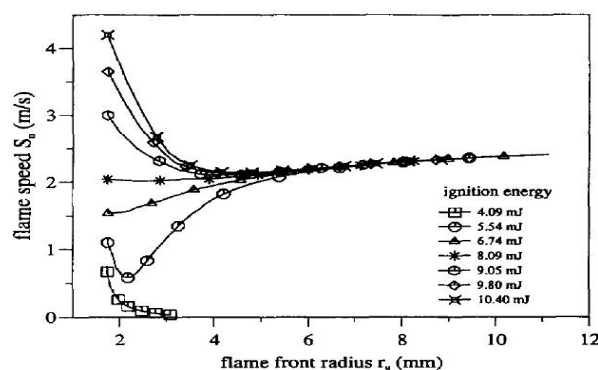


Figure 6: Computations of Flame Speed against Radius for Varying Ignition Energy [Bradley, D., Gaskell, 1996]

5. Factors Influencing the Flame Speed

Studying of factors that affect the velocity of flame propagation is important since the flame velocity influences the rate of pressure rise in the cylinder and the type of combustion that occurs in spark-ignition engines. There are several factors that affect the flame speed, to a varying degree. The most important being the turbulence and the fuel-air ratio. Details of various factors that affect the flame speed are discussed below.

5.1 Turbulence

The flame speed is quite low in non-turbulent mixtures and increases with increasing turbulence. This is mainly due to the additional physical intermingling of the burning and unburned particles at the flame front which expedites reaction by increasing the rate of contact. Turbulence which is supposed to consist of many minute swirls appears to increase the rate of reaction and produce a higher flame speed than that made up of larger and fewer swirls [Esam M.Mohamed, 2010].

[R.G.Abdel- Gayed *et al*, 1985] reported experimental values of turbulent burning velocities for propane, hydrogen and iso octane mixtures with air under conditions of high turbulence and high turbulent Reynolds number. Full quantitative agreement between theory and experiment was not achieved, due to the inherent limitations of theories.

A suitable design of the combustion chamber which includes the geometry of cylinder head and piston crown will increase the turbulence through the compression stroke [Vaishali Katre1, S. K. Bhele2, 2013].

5.2 Fuel-air ratio

The fuel air ratio has a very significant influence on the flame speed. The highest flame velocities are obtained with somewhat richer mixture. When the mixture is made leaner or richer the flame speed decreases. Less thermal energy is released in the case of lean mixtures resulting in lower flame temperature. Very rich mixtures lead to incomplete combustion which results again in the release of less thermal energy [Ganeshan , 2010].

[A. Rashid A .Aziz *et al*, 2014] presented experimental results of the effect of fuel – air ratio on the combustion characteristic of a direct injection spark ignition engine fuelled with a syngas of H₂ / CO composition of equal molar ratio .The effect of fuel – air ratio was more visible on the initial stage of the combustion at lower speeds while it is visible on the rapid burning stage at higher speeds.

5.3 Compression ratio

[Michael D.Gerty *et al*, 2006] used a modern single cylinder 4- valve spark ignition research engine to determine the response of engine efficiency to compression ratio. They found that any increasing in compression ratio will increase flame speed. Also,

efficiency will be improved more with compression ratio at high speeds due to the reduced importance of heat loss.

A higher compression ratio increases the pressure and temperature of the working mixture before ignition which reduce the initial preparation phase of combustion and hence less ignition advance is needed. High pressures and temperatures of the compressed mixture also speed up the second phase of combustion. Increase compression ratio reduces the clearance volume and therefore increases the density of the cylinder gases during burning. This increases the peak pressure and temperature and reduces combustion duration. Thus engines having higher compression ratios have higher flame speeds [Erjiang Hu, Zuohua Huang, 2009].

6. Flame Stretch

The flame stretch rate, which indicates the expanding rate of the flame area [Erjiang Hu, 2009] for a spherically expanding flame, is defined as:

$$\alpha = \frac{d(\ln A)}{dt} = \frac{1}{A} \frac{dA}{dt} \quad (1)$$

where A is the area of flame. For a spherically outwardly expanding flame front, the flame stretch rate can be simplified as

$$\alpha = \frac{1}{A} \frac{dA}{dt} = \frac{2}{r_u} \frac{dr_u}{dt} = \frac{2}{r_u} S_n \quad (2)$$

In respect to the early stage of flame expansion, there exists a linear relationship between the flame speeds and the flame stretch rates; that is,

$$S_l - S_n = \alpha L_b \quad (3)$$

Where S_l is the unstretched flame speed, and L_b is the Markstein number (Markstein length) of burned gases. The unstretched flame speed, S_l , can be obtained as the intercept value at $\alpha = 0$, in the plot of S_n against α , and the burned gas Markstein number L_b is the slope of $S_n - \alpha$ curve.

Markstein number can reflect the stability of flame. Positive values of L_b indicate that the flame speed decreases with the increase of flame stretch rate. In this case, if any kinds of protuberances appear at the flame front (stretch increasing), the flame speed in the flame protruding position will be suppressed, and this makes the flame stable. In contrast to this, a negative value of L_b means that the flame speed increases with the increase of flame stretch rate. In this case, if any kinds of protuberances appear at the flame front, the flame speed in the flame protruding position will be increased, and this increases the instability of the flame.

For a spherically expanding flame in a closed combustion bomb, the stretch imposed on the premixed flame is well defined. The asymptotic

theories and experimental measurements have suggested a linear relationship between the flame speeds and flame stretches.

The stretch rate is a combination of two effects: the flame curvature and the strain rate. Stretch effects induce modifications on the flame front structure and propagation. The sensitivity of the flame speed to the stretch rate is characterized by the Markstein length. Investigations on the laminar burning velocity [Gu X J, Haq M Z, 2000] have shown the importance of local stretch for the local burning speed. Based on an asymptotic analysis, several authors have proposed a linear relation between the stretch rate and the flame speed. This relation is valid when the propagation phenomena are no longer affected by the initial energy deposition needed to initiate exothermic reactions. Moreover, the flame thickness has to remain negligible compared to the flame radius. This linear relation has been extensively applied to outwardly propagating flames [Hermanns R T E, 2007].

Stretch affects the propagation rate by changing the diffusive flux of reactant downstream into the reaction zone and of heat upstream out of it. Since the balance of these fluxes has an influence on the flame temperature and since the reaction rate varies strongly with temperature, flame stretch can affect the reaction rate and, therefore, the burning rate.

7. Flame Thickness

Flame thickness can be represented as the ratio of the maximum temperature difference ($T_b - T_u$) to the maximum temperature gradient (dT / dx) which occurs at the inflection point of the profile [Kanury, A.M., 1975]. This is more relevant definition of flame thickness based on temperature distribution across the flame, where

$$\delta_{\text{slop}} = \frac{(T_b - T_u)}{\max(\frac{dT}{dx})} \quad (4)$$

Figure (7) shows two definitions (δ_{slop} and δ_{total}) of premixed laminar flame thickness. (δ_{total}) represents the distance over which the reduced temperature changes from 0.01 to 0.99. The radial temperature distribution in a spherical kernel method during the pre-pressure period of combustion, in which the increases in temperature due to compression of the burned gases can be neglected as shown in figure (8).

[Andrews and Bradley, 1972a)] measured flame thickness of (ethane-air) mixtures using (thermocouples and Schlieren photograph) and obtained results which contain large differences relative to the total theoretical results. They also calculated flame thickness from measuring flame speed. Some investigators used mathematical relation to represent the relation between flame thickness and burning velocity.

[Blint R.J., 1986], taken into account the temperature effect on flame thickness as

$$\delta_{\text{total}} = 2 \delta_{\text{slop}} \left(\frac{T_b}{T_u} \right)^{0.7} \dots\dots (5)$$

The flame thickness given by eq. (5) does not require a flame computation and is a fairly good estimation of the flame thickness (δ_{slop}) as soon as the adiabatic/ or final temperature (T_b) is known [(Zel'dovich, Frank – Kamenetskii and Semenov (ZFK), 2005)].

[Gottgens *et al.*, 1992], provided accurate analytical expressions for the burning velocity and flame thickness of lean hydrogen, methane, ethylene, ethane, acetylene and propane flames. Starting from a detailed kinetic mechanism of 82 elementary reactions. Significant differences between measured and calculated results are typical. Most of flames are at most only a few millimeters in thickness at room temperature and atmospheric pressure.

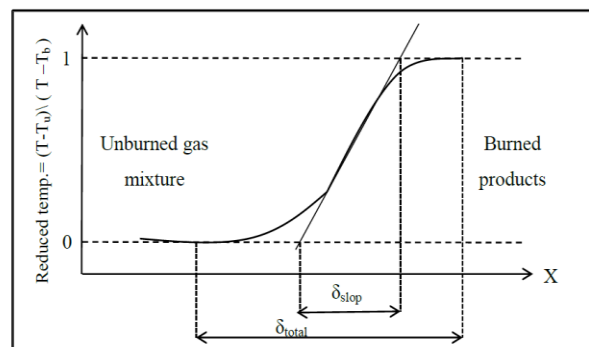


Figure 7: Premixed Laminar Flame Thickness [Kanury, A.M., 1975]

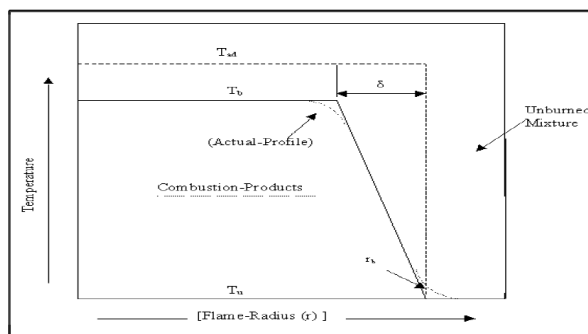


Figure 8: Radial Temperature Distribution in Spherical Flame Kernel [Kanury, A.M., 1975]

Conclusion Based on Literature Survey

1- For lean mixture combustion, flame radius increases with time, but the rate of increase decreases with flame expansion for LPG and for mixtures with low hydrogen fractions, while at high hydrogen fractions, there exists a linear correlation between flame radius and time. For rich mixture combustion, there is also exists a linear correlation between flame radius and time for mixtures with high hydrogen fractions. Combustion at

stoichiometric mixture demonstrates the linear relationship between flame radius and time for LPG-air, hydrogen-air, and LPG-hydrogen-air flames.

2- Hydrogen-air flame gives a very high value of the stretched flame speed compared to those of natural gas-air flame and natural gas-hydrogen-air flames, even for high hydrogen fraction.

3- Enrichment of 25 & 50% hydrogen to LPG-air has very little effect on burning velocities for lean and rich mixtures and remarkable effect on stoichiometric mixtures.

4- Enrichment the mixture with hydrogen expands the equivalence ratio range and makes it wider.

5-Unstretched laminar burning velocities are increased with the increase of hydrogen fraction. Markstein lengths are decreased with the increase of hydrogen fraction, indicating that the flame instabilities are increased with the increase of hydrogen fraction.

6- For a fixed hydrogen fraction, the Markstein length and flame stability increase with the increase of equivalence ratios.

7- With the increase of equivalence ratio, laminar burning velocity increases in the case of fuel-lean mixture combustion and decreases in the case of fuel-rich mixture combustion. Laminar burning velocity decreases with the increase of dilution ratio, and the position of peak value of laminar burning velocity moves slightly to the lean mixture direction with the increase of dilution ratio. With the increase of equivalence ratio, the flame stability is increased. Markstein length increases monotonously with the increase of equivalence ratio and it slightly decreases with the increase of dilution ratio.

8- Laminar burning velocity increases with the increase of initial temperature, and it decreases with the increase of initial pressure. With the increase of initial pressure, advancement of onset of cellular instability is present and Markstein lengths are decreased, indicating the increase of hydrodynamic instability with the increase of initial pressure. Flame instability is insensitive to initial temperature.

9- The laminar burning velocity has the same tendency with the product of thermal diffusion and chemical reaction terms as a function of the dilution ratio for different diluents. The adiabatic flame temperature plays a dominant influence on the laminar burning velocity and thermal diffusivity has a secondary influence on methane-air-diluent flames.

10- The flame thickness was decreased by increasing temperature and pressure, but the effect of pressure was more significant than the effect of temperature on the flame thickness.

11- Decreasing in flame velocity caused by the exhaust gas recirculation can to some extent be compensated for by an increase in the turbulent intensity at a price of increased ignition difficulty.

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