Laminar Burning Velocities of Typical Syngas Compositions

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Abstract
Syngas is being recognized as a viable energy source worldwide, particularly for stationary power generation due to its availability as a product of bio and fossil fuel gasification. However, there are gaps in the fundamental understand of syngas combustion characteristics, especially at elevated pressures that are relevant to practical combustors. In this work, constant volume spherical expanding flames of three typical syngas compositions resulting from wood gasification have been employed to measure the laminar burning velocity under stoichiometric conditions for pressures ranges between 1 and 20 bar. Over the ranges studied, the burning velocities are fit by the functional formula of Metghalchi and Keck. The influence of stretch rate upon the burning velocity is indicated by Markstein lengths determined at constant pressure by schlieren photography. Conclusion can be drawn that the burning velocity decreases with the increase of pressure. In opposite, an increase in temperature induces an increase of burning velocity. The higher burning velocity value is obtained for the downdraft syngas. This result is endorsed to the higher heat value, lower dilution and higher volume percentage of hydrogen in the downdraft syngas. Small Markstein lengths were obtained for the three syngas compositions, which is indicative of a small influence of flame stretch on burning velocity of syngas flames.

Introduction

Syngas obtained from gasification of biomass is considered to be an attractive new fuel, especially for stationary power generation. The gasification process could be defined as a thermochemical process with partial oxidation of a carbonaceous feedstock at high temperature [1]. The final product is a synthesis gas or "syngas," consisting primarily of hydrogen (H_2) and carbon monoxide (CO), with lesser amounts of carbon dioxide (CO_2), water (H_2O), methane (CH_4), higher hydrocarbons (C_{2+}), and nitrogen (N_2). The considerable variation in the syngas composition is a challenge in designing efficient end use applications such as burners and combustion chambers to suit changes in fuel composition. Designing such combustion appliances needs fundamental understanding of the implications of variation of different constituents of syngas fuel for its combustion characteristics, such as laminar burning velocity.

Laminar burning velocity values for single component fuels such as methane and hydrogen are abundantly available in the literature for various operating conditions. Some studies on burning velocities are also available for binary fuel mixtures such as H_2–CH_4 [2,3], and H_2–CO [4-7]. Prathap et al. [8] study the effect of N_2 dilution on laminar burning velocity and flame structure for H_2–CO (50% H2–50% CO by volume) fuel mixtures. They stated that the dilution with nitrogen in different proportions in H_2–CO resulted in a decrease in laminar burning velocity due to reduction in heat release and increase in heat capacity of unburned gas mixture and hence the flame temperature. Natarajan et al. [9] test an equally weighted, 50:50 H_2-CO, fuel mixture with 0 and 20% CO_2 dilution. They stated that the flame speed decreases with CO_2 dilution. This is not surprising, as dilution with excess air or CO_2 decreases the flame temperature, which reduces the rate of CO and H_2 oxidation reactions and hence flame speed.

Therefore, there is lack of knowledge in the fundamental combustion characteristics of actual syngas compositions where there is a combined effect of N_2 and CO_2 dilution in the H_2-CO-CH_4 fuel gases that composes the actual syngas fuel. This motivated the present work to choose three typical compositions of syngas considered as mixture of five gases (H_2-CO-CH_4-CO_2-N_2) and study its combustion characteristics.

Materials and Methods

The experiments were conducted into two constant volume chambers. The first one is a cubic chamber with two transparent sides in ordinary glass (BK7), which provides optical access to the schlieren photography. The inside size of the chamber is 70 mm of width, 58 mm of length and 120 mm of height. The second is a spherical bomb with inside diameter of 160 mm.

The combustible mixture is prepared within the chamber by adding syngas and air at specified partial pressures. In all cases the purity of the gases is at least 99,9%.The mixture is ignited by centrally located electrodes and a standard capacitive discharge ignition system is used to produce the spark. The pressure is recorded by a piezoelectric Kistler 601A absolute pressure transducer with a resolution of 0,01 kPa. A high-speed digital camera (APX RS PHOTRON) is used to record the flame images during combustion. In the experiments, the initial temperature is 293 K and initial pressures of 0,5 – 5,0 bar.

The three typical syngas compositions under study were obtained from reference [1] and are shown in the

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Table 1. Equivalence ratio has been fixed equal to 1,0 in all tests for all syngas compositions.

Table 1 – Typical syngas compositions

Syngas	Gas composition (% by volume)					HHV (MJ/m^3)
	H_2	CO	CO_2	CH_4	N_2	
Updraft	11	24	9	3	53	5,5
Downdraft	17	21	13	1	48	5,7
Fluidized bed	9	14	20	7	50	5,4

Pressures were recorded in the experiments, where the initial pressure and temperature kept the same value for the three syngas compositions. The initial conditions were strictly controlled in the experiments to realize the same initial pressure and temperature. To avoid the influence of wall temperature on mixture temperature, an interval between two experiments is set, providing enough time for wall to cool down and keeping the same initial temperature. As flame exhibits a spherical pattern, the time flame radius evolution was scaled from flame photos recorded by a high-speed camera.

Burning velocity theory

Constant pressure method

Laminar burning velocity and Markstein length can be deduced from schlieren photographs of the flame [10]. For an outwardly spherical propagating flame, the stretched flame speed, S_n, is derived from the flame radius versus time data as follows:

$$S_n = \frac{dr_u}{dt} \tag{1}$$

where r_u represents the flame radius in the schlieren photographs and t the time.

The flame stretched rate, κ, representing the expanding rate of flame front area, in a quiescent mixture is defined by [11]:

$$\kappa = \frac{d(\ln A)}{dt} = \frac{1}{A}\frac{dA}{dt} \tag{2}$$

where A is the area of flame. In the case of a spherical expanding flame the stretch rate can be simplified as follows:

$$\kappa = \frac{1}{A}\frac{dA}{dt} = \frac{2}{r_u}\frac{dr_u}{dt} = \frac{2}{r_u}S_n \tag{3}$$

A linear relationship between the flame speed and the total stretch exists, and this is quantified by a burned Markstein length, L_b [12], as follows:

$$S_n^0 - S_n = L_b\kappa \tag{4}$$

where S_n^0 is the unstretched flame speed, and L_b the Markstein length of burned gases.

The unstretched flame speed is obtained as the intercept value at $\kappa = 0$, in the plot of S_n against κ, and the burned gas Markstein length is the slope of $S_n - \kappa$ curve. Markstein length can reflect the stability of flame [13]. Positive values of L_b indicate that the flame speed decreases with the increase of flame stretch rate. In this case, if any kind of perturbation or small structure appears on the flame front (stretch increasing), this structure tends to be suppressed during flame propagation, and this makes the flame stability. 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.

When the observation is limited to the initial part of the flame expansion where the pressure does not vary yet, then a simple relationship links the unstretched flame speed to the unstretched burning velocity.

$$\frac{S_n^0}{S_u^0} = \frac{\rho_u}{\rho_b} = \sigma \tag{5}$$

Where σ is the expansion factor and ρ_u and ρ_b are, respectively, the unburned and burned densities.

The same behavior of the unstretched burning velocity regarding the stretch can be observed [14]:

$$S_u^0 - S_u = L_u\kappa \tag{6}$$

where L_u represents the unburned Markstein length, which is obtained dividing the burned Markstein length by the expansion factor.

The normalization of the laminar burning velocity by the unstretched one introduces two numbers which characterize the stretch that is applied to the flame, the Karlovitz number (Ka), and its response to it, the Markstein Number (Ma):

$$\frac{S_u}{S_u^0} = 1 - MaKa \tag{7}$$

$$Ka = \kappa\frac{\delta}{S_u^0} \tag{8}$$

$$Ma = \frac{L_u}{\delta} \tag{9}$$

where δ is the flame thickness defined, in this work, using the thermal diffusivity, α:

$$\delta = \frac{\alpha}{S_u^0} \tag{10}$$

This evolution of the laminar flame velocity with the stretch rate was verified by Aung et al. [15] for moderate stretch rate. As one can see, different definitions of a characteristic flame thickness lead to different Karlovitz and Markstein numbers. Bradley et al. [10] use the kinematic viscosity of the unburned mixture to derive the flame thickness while Aung et al. [15] use the mass diffusivity of the fuel in the unburned gas. However, this effect disappears in Eq. (7) since the flame thickness cancels out.

Constant volume method

In the spherical bomb method, the stretched burning velocity, S_u, of the propagating flame is calculated by the following expression [16]:

$$S_u = \frac{R}{3(P_v - P_i)}\left(\frac{P_i}{P}\right)^{\frac{1}{\gamma}}\left(1 - \left(\frac{P_i}{P}\right)^{\frac{1}{\gamma}}\frac{P_v - P}{P_v - P_i}\right)^{-\frac{2}{3}}\frac{dP}{dt} \tag{11}$$

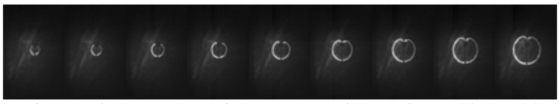
Where P_i and P_v are the initial and adiabatic pressures, respectively. The adiabatic pressure was obtained by the chemical equilibrium calculation at constant volume conditions. γ, is the specific heat ratio of the mixture. P_v and γ were calculated by Gaseq package. R is the radius of the chamber. The propagating flame was supposed spherical and smooth in these procedures.

Results and Discussion

Constant pressure method

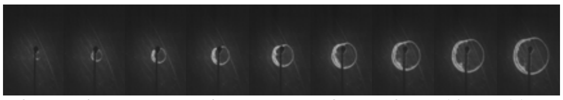
Bradley et al. [10] shown that flame speeds become independent of ignition energy when flame radius is greater than 6 mm. The existence of the critical flame radius was also observed by Liao et al. [13] and Lamoureux et al. [14]. Their studies also gave this value approximately as 6 mm. Thus, the flame radius is analyzed only beyond that radius, at which the spark effects could be discounted.

Figures (1-3) shows schlieren images of updraft, downdraft and fluidized bed syngas flames, respectively.



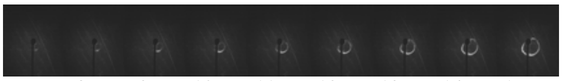
3 ms 4 ms 5 ms 6 ms 7 ms 8 ms 9 ms 10 ms 11 ms

Figure 1 – Schlieren images of updraft syngas flame.



3 ms 4 ms 5 ms 6 ms 7 ms 8 ms 9 ms 10 ms 11 ms

Figure 2 – Schlieren images of downdraft syngas flame.



7 ms 8 ms 9 ms 10 ms 11 ms 12 ms 13 ms 14 ms 15 ms

Figure 3 – Schlieren images of fluidized bed syngas flame.

In the case of updraft and downdraft syngas the time range of the flame images is from 3 ms to 11 ms. It is possible to see that the flame diameter is higher in the case of downdraft syngas, which is indicative of higher flame speed. In the fluidized bed syngas case the figures time range is 7 ms to 15 ms. This is indicative of low flame speed in comparison with the other two syngas cases. Some ignition difficulties were found with the fluidized bed syngas and, due to that, the gap of the electrode was increased from 0,5 to 1,5 mm. Fig. 4 gives the variations of flame radius versus the time for the three syngas typical compositions studied.

The study shows that flame expands spherically after the ignition, and the flame radius will increase rapidly in the subsequent process. There exist a quasi-linear correlation between flame radius and time for all syngas cases.

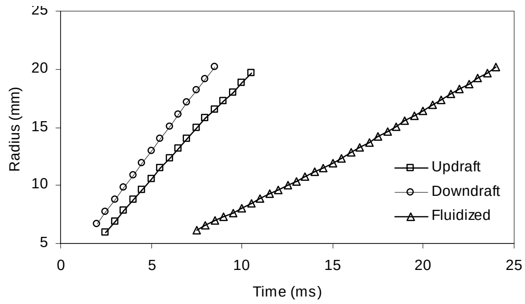
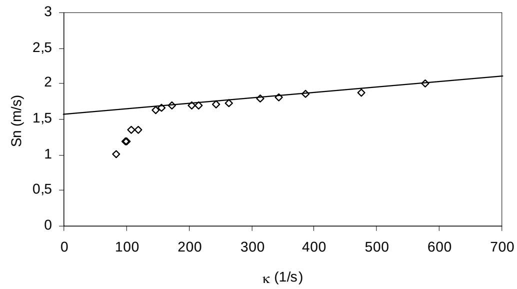


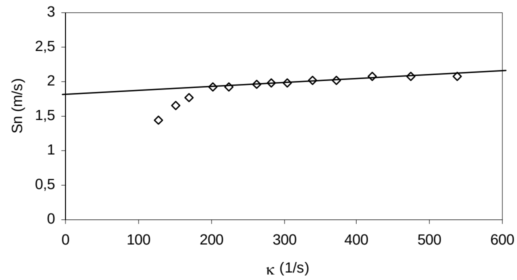
Figure 4 – Flame radius versus time for three typical syngas compositions.

According to the Markstein view, the gradient of the radius-time curve reflects the stretching effectiveness of flame. For an unstable flame, the gradient of the radius-time curve will decrease with the flame expansion, while for a stable flame; the gradient of the radius-time curve will increase with the flame expansion. Therefore, we can conclude that a stable flame is presented for fluidized syngas flames, while the unstable flame is found for updraft syngas.

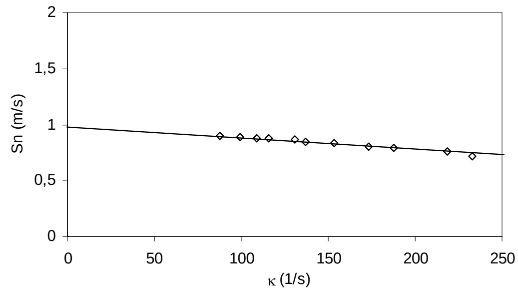
Fig. 5 gives the stretched flame speed versus the flame stretch rate for three typical syngas compositions.



(a)



(b)



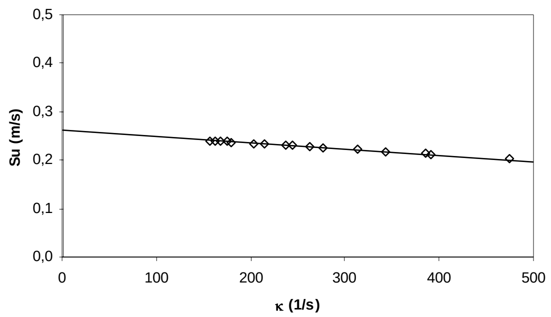
(c)

Figure 5 – Stretched flame speed versus stretch rate for syngas. (a) Updraft; (b) Downdraft; (c) Fluidized bed.

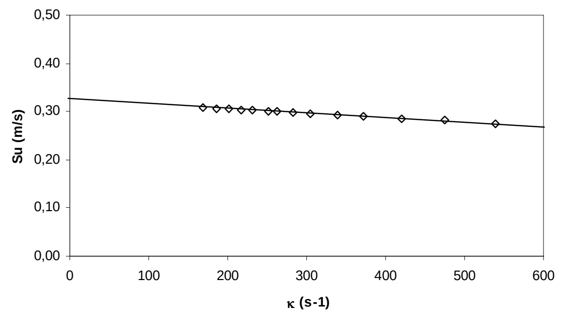
Removing the parts influenced by ignition process and high pressure at late stages of flame propagation, a linear correlation between the stretched flame speed and the flame stretch rate is found. The stretched flame speed increases with the increase of flame stretch rate for the updraft and downdraft syngas cases. In opposite, for the fluidized bed syngas case the stretched flame speed decreases with the increase of flame stretch.

The maximum value of flame speed is obtained for the downdraft syngas following by the updraft syngas being the lower value obtained for the fluidized bed syngas.

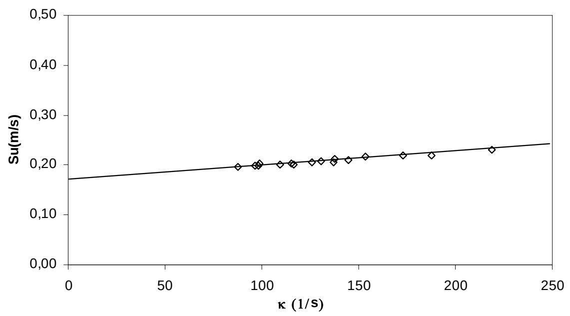
Fig. 6 gives the stretched laminar burning velocity versus the flame stretch rate for three typical syngas compositions.



(a)



(b)



(c)

Figure 6 – Stretched burning velocity versus stretch rate for three typical syngas compositions. (a) Updraft; (b) Downdraft; (c) Fluidized.

The stretched laminar burning velocity S_u, which denotes the rate of mixture entrainment, decreases as the stretch rate increases for updraft and downdraft cases. In opposite, S_u, increases with the increase of stretch rate for the fluidized bed syngas case.

The unstretched laminar flame velocity, S_u^0 is derived from the value of the unstretched flame speed and the expansion factor which is evaluated using the adiabatic flame calculation via the Gaseq code package. Table 2 gives fundamental (unstretched) values of flame speed and burning velocity of syngas flames at atmospheric conditions (1 bar; 293 K). Tendency observed on the unstretched fundamental flame speed is in accordance with the composition of each type of syngas. Flame speed and burning velocity are higher when heat reaction of the syngas increase. Flame speed and burning velocity are higher when hydrogen amount is greater. Flame speed and burning velocity are slightly higher when the combined effect of dilution by nitrogen and carbon dioxide in the fuel gases H_2-CO-CH_4 is higher.

Table 2 – Unstretched flame speeds and burning velocities for syngas-air mixtures.

Syngas	S_n^0	S_u^0
Updraft	1,54	0,26
Downdraft	1,86	0,32
Fluidized bed	1,00	0,17

Table 3 gives the Markstein lengths and Markstein and Karlovitz numbers at atmospheric conditions (1 bar; 293 K).

Table 3 – Markstein and Karlovitz numbers of syngas-air mixtures.

Syngas	L_b	L_u	Ma	Ka
Updraft	-0,0007	$-1,18\times10^{-4}$	-1,39	0,107
Downdraft	-0,0005	$-8,67\times10^{-5}$	-1,17	0,070
Fluidized bed	0,0014	$2,44\times10^{-4}$	2,07	0,096

As it can be seen in Table 3, the Markstein number is negative for the updraft and downdraft syngas indicating an unstable flame. Low Karlovitz numbers indicate a small influence of stretch in syngas flames.

Constant volume method

Workers such as Fiock and Marvin [17] and Rakotoniana [18], who used the constant-volume method for the determination of the burning velocities, have used Eq. (11), respectively, for the regime after the first 25% and 50% of flame propagation, when the pressure could be measured with sufficient accuracy. In this work the criterion was the stretch rate, being the values of burning velocity considered below 50 s^{-1}. For this level of stretch, the stretched burning velocity is close to the unstretched burning velocity.

Based on the results obtained on this study we have determine for updraft, downdraft and fluidized bed syngas cases under stoichiometric conditions empirical correlations like Metghalchi and Keck [19] did. The final expressions are then given by Eq. (12-14).

$$S_u = 0,303\left(\frac{T}{T_0}\right)^{1,507}\left(\frac{P}{P_0}\right)^{-0,259} \quad (12)$$

$$S_u = 0,345\left(\frac{T}{T_0}\right)^{1,559}\left(\frac{P}{P_0}\right)^{-0,156} \quad (13)$$

$$S_u = 0{,}137\left(\frac{T}{T_0}\right)^{2{,}124}\left(\frac{P}{P_0}\right)^{-0{,}518} \qquad (14)$$

Expression (12) is valid for $0{,}75<P(bar)<20$; $293<T(K)<435$. Expression (13) is valid for $0{,}75<P(bar)<20$; $293<T(K)<450$. The correlation for fluidized bed syngas, Eq. (14), is valid only for $0{,}95<P(bar)<10$; $293<T(K)<430$. This is due to the unsuccessful ignition for initial pressures of 0,5 and 5 bar. The minimum initial pressure with successful ignition was 0,8 bar.

In all syngas cases the temperature coefficient is positive and the pressure coefficient negative. This means that the burning velocity increases with temperature increase and decreases with the increase of pressure.

Conclusion

Laminar flame characteristics of three typical syngas compositions were studied in a constant volume chamber under stoichiometric conditions. The influence of stretch rate on flame was also analyzed. The unstretched burning velocities, the Markstein length, Markstein and Karlovitz numbers have been determined for three typical syngas compositions. Markstein and Karlovitz numbers indicates a small influence of stretch in syngas-air flames.

Tendency observed on the unstretched fundamental flame speed is in agreement with the composition of each type of syngas. Flame speed and burning velocity are higher when heat reaction of the syngas increase. Flame speed and burning velocity are higher when hydrogen amount is greater. Flame speed and burning velocity are slightly higher when the combined effect of dilution by nitrogen and carbon dioxide in the fuel gases H_2-CO-CH_4 is higher.

Base on the experimental data some empirical formulations of the burning velocities have been establish for pressure range 0,75-20 bar and temperature range 293K-450K. The ignition difficulties founded in the fluidized bed syngas indicates that this composition is less suitable for engine applications due to problems with the cold start.

Acknowledgments

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References

[1] Bridgwater, A.V., Fuel, 14, (1995) 631-653.
[2] Halter, C. Chauveau, N. Djebaili-Chaumeix, I. Gokalp, Proc. Combust. Inst. 30 (2005) 201.
[3] F.H.V. Coppens, J. De Ruyck, A.A. Konnov, Combust. Flame 149 (2007) 409.
[4] C.M. Vagelopoulos, F.N. Egolfopoulos, Proc. Combust. Inst. 25 (1994) 1317.
[5] I.C. McLean, D.B. Smith, S.C. Taylor, Proc. Combust. Inst. 25 (1994) 749.
[6] M.J. Brown, I.C. McLean, D.B. Smith, S.C. Taylor, Proc. Combust. Inst. 26 (1996) 875.
[7] H. Sun, S.I. Yang, G. Jomaas, C.K. Law, Proc. Combust. Inst. 31 (2007) 439.
[8] Prathap, C., Ray, A., Ravi, M.R., Combust. Flame 155 (2008) 145-160.
[9] J. Natarajan, T. Lieuwen, J. Seitzman. Combust. Flame 151 (2007) 104–119
[10] Bradley, D., Hicks, R.A., M. Lawes, C.G.W. Sheppard, R. Wooley. Combust. Flame 115 (1–2), (1998) 126 –144.
[11] Kenneth k. Kuo, Principles of combustion. 2005. John Wiley & Sons, Inc.
[12] Clavin, P., Prog. Energy Combust. Sci. 11:1 (1985)
[13] Liao, S.Y., Jiang, D.M., Cheng, Q., Fuel 83 (2004) 1247-1250.
[14] Lamoureux, N., Djebaili – Chaumeix,N., Paillard, C.–E. Experimental Thermal and Fluid Science 27 (2003) 385–393.
[15] K.T. Aung, M.I. Hassan, G.M. Faeth, Combust. and Flame 109 (1997) 1–24.
[16] Lewis, B., and von Elbe, G., Combustion, Flames and Explosions of Gases (3rd Ed.), 1987, p. 338. Academic Press Inc. Orlando.
[17] Fiock, E. F. and Marvin, C. F., Chem. Revue 21, (1937), 367.
[18] Rakotoniaina, Jean-Elysée. PhD Thesis. University of Poitiers, 1996.
[19] Metghalchi M, Keck JC. Combust Flame, 38 (1980) 143–54.