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A STUDY ON LAMINAR BURNING VELOCITY FOR METHANE-AIR AND METHANOL-AIR MIXTURES

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Abstract In the present investigation, combustion of methane-air and methanol-air mixtures are studied. Useful correlations for laminar burning velocity are proposed for methane and methanol combustions which are valid over a wide range of combustion. Effects of pressure, temperature, and equivalence ratio on laminar burning velocity are discussed. The results obtained are compared with the observations of other prime investigators.

Keywords : Methane, Methanol, Burning Velocity

INTRODUCTION

Combustions and flames in one form or, other are known since antiquity. Basically, the use of fire marked the beginning of mastery over the forces of nature, and it played a pivotal role in the subsequent development of civilization. Investigations on combustions are fundamentally aimed at the acquisition of a thorough understanding of the mechanism of ignition, flame propagation, species distribution, pressure and temperature developments and energy release of combustible mixtures. The practical results of such investigations are directed towards better control of combustion-related processes in terms of efficiency, safety and environment protection.

Laminar burning velocity (S_u) , sometimes also referred as flame velocity or, simply burning velocity, is considered as one of the most basic parameters in the science of combustion. Laminar burning velocity is defined as the velocity of an infinite flame front normal to itself and relative to the unburnt gas. In general, it is defined as the volume of the unburnt gas consumed per unit time divided by the area of the flame front in which that volume is consumed. The combustion process in a flame involves various physiological processes and is a combination of chemical reactions, diffusion mechanism, all modes of heat transfer and flow pattern. The shape and size of a flame is also governed by all these factors.

In the present study, combustion of premixed methane-air and methanol-air mixtures in a constant volume combustion vessel are studied. Transient pressure rise, gas temperature rise, burning velocity etc. are computed at different initial temperature, pressure and mixture composition. Useful correlations for laminar burning velocity are proposed for methane and methanol combustions which are valid over a wide range of combustion. The effects of mixture composition, mixture pressure and temperature on burning velocity are discussed. A comparative study of burning velocity is also made for methane and methanol. The results obtained are compared with the observations of other prime investigators.

ANALYSIS

In the present analysis combustions of premixed fuel-air are considered to occur at the centre of a constant volume spherical vessel. The basic procedure for computational analysis is logically same as stated in [Bose and Mitra,1997].

In the analysis, it is assumed that no dissociation or preflame reactions occur in the unburnt gas mixture and the combustion products are of homogeneous composition and obey ideal gas laws. The laminar flame is considered to be spherical, smooth and unwrinkled. The pressure at any instant is considered uniform throughout the vessel.

Here, the flame propagation , during constant volume combustion, is taken as the consumption of unburnt gas in small mass decrements, dm_u . This mass at any n-th element, dm_{un} , moves into the reaction zone having finite thickness with an unburnt temperature $T_{u,n-1}$, the vessel pressure being P_{n-1} .
After the consumption i.e., burning of dm_u , the pressure throughout the combustion vessel becomes P_n

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Now, at any instant, Unburnt mass of mixture,
$m_{un} = m_o - \sum dm_{ui}$

Here, $\sum dm_{ui}$ refers to the sum of the mass decrements upto the n-th elements.

The conservation of volume for constant volume combustion vessel gives,

$$V_o = V_{un} + V_{fn} + V_{bn}$$

where,

V_{un} = unburnt gas volume = $(m_{un} . R_{gu} . T_{un})/ P_n$
V_{fn} = volume within flame
= $(4/3).\pi.\{ r_{bn}^3 - (r_{bn} - \delta_n)^3 \}$
V_{bn} = burnt gas volume
= $(1/P_n). \sum \{ dm_{ui} - (m_{f\ i} - m_{f\ i-1}) \}. R_{gbin} . T_{bin}$

Time for decrement of any n-th mass element, dm_u , is given by $dt = dm_u / (4. \pi. r_b^2. \rho_u .S_u)$

Transient pressure, temperature, mass fraction burnt, gas radius, time requirement etc. can be obtained by solving above equations. It is also clear from the above equation that appropriate value of burning velocity (S_u) is required to calculate dt. But burning velocity cannot be measured directly by experiment. Burning velocity values may be obtained by analytical equations with the aid of experimentation or, by appropriate empirical correlations. In the present study, considering combined dependence of various relevant parameters on burning velocity, unified correlations for burning velocity (S_u) for both methane-air and methanol-air have been developed. These correlations are as follow :

I. Methane-air correlations :

$S_{ua} = 38.75 - 220 (\phi - 1.12)^2 - 352 (\phi - 1.12)^3$
$\alpha = 1.60 + 0.22 (\phi - 1)$
$\beta = - 0.42 - 0.31(\phi - 1)$
$S_{u1} = S_{ua} \times (1 + \beta \log_{10} P) \times (T/300)^\alpha$

a) For pressure up to 2 bar,
$S_u = (S_{u1} - 10.\phi - 2.5 P + 9) \times 0.01$

b) For pressure above 2 bar but $0.85 < \phi < 1.15$,
$S_u = (S_{u1} - 33.\{ abs(\phi - 1) \} - 4.5) \times 0.01$

c) For pressure above 2 bar but $\phi \le 0.85$ or, $\phi \ge 1.15$,
$S_u = (S_{u1} - 10.5 \phi) \times 0.01$

II. Methanol-air correlations :

$S_{u1} = 45.80 + 30.(\phi - 1) - 250.(\phi - 1)^2$
$+ 300. \{abs (\phi - 1)^3\}$
$\alpha = 1.47 - 0.90 (\phi - 1)$
$\beta = - 0.31 - 0.80 \{abs(\phi - 1.05)\} \times (438 / T)$
$\times \{P / (P + 1.6)\}$
$S_u = S_{u1} \times (T / 300)^\alpha \times (P)^\beta \times 0.01$

where burning velocity (S_u) in m/s, temperature (T) in Kelvin and pressure (P) in bar.

RESULTS & DISCUSSION

Effect of Equivalence Ratio (ϕ) on S_u

The dependence of S_u for both methane and methanol on mixture composition or , equivalence ratio (ϕ) can be observed from Table-1, Table-2 and Fig.-1. It is observed that burning velocity increases with the richness of mixture strength and it has a peak at slightly richer side of the stoichiometric value (i.e., around ϕ = 1.1). After that S_u decreases with higher values of ϕ. Actually, on the rich side (ϕ >1) burning velocity is reduced due to oxygen starvation and on the lean side (ϕ <1) it is reduced as reaction rate is slowed down due to lack of fuel. Another observation on the dependence of ϕ is that the position of peak values of burning velocities trend to shift from fuel-rich to stoichiometric mixture strength as initial pressure is increased.

TABLE – 1
Effect of equivalence ratio on S_u (m/s)
(T_i = 303 K, P_i = 1.01 bar)

METHANE-AIR			
ϕ	S_u (m/s) [Sharma et al.,1981]	S_u (m/s) [Takeno & Iijima,1981]	S_u (m/s) [Present Study]
0.80	0.2460	0.2410	0.2562
0.90	0.2880	0.2880	0.2978
1.00	0.3270	0.3410	0.3318
1.10	0.3380	0.3690	0.3469
1.20	0.3190	0.3310	0.3217

TABLE – 2
Effect of equivalence ratio on S_u (m/s)
(T_i = 303 K, P_i = 1.01 bar)

METHANOL-AIR			
ϕ	S_u (m/s) [Metghalchi & Keck,1982]	S_u (m/s) [Gulder, 1983]	S_u (m/s) [Present Study]
0.80	0.2862	0.3162	0.3264
0.90	0.3676	0.4098	0.4114
1.00	0.4180	0.4780	0.4638
1.10	0.4368	0.5023	0.4715
1.20	0.3810	0.4056	0.4076

TABLE –3
Values of coefficients of equation(1) for Methane at T_i = 350 K.

P (bar)	A_0	A_1	A_2	A_3
1	3.4267	-10.9766	12.5595	-4.4815
3	-0.4339	-0.14906	2.3364	-1.4444
5	-0.8782	1.30668	0.7087	-0.8713

TABLE –4
Values of coefficients of equation(1) for Methanol at T_i = 350 K.

P (bar)	A_0	A_1	A_2	A_3
1	-3.7224	10.0572	-7.48733	1.7235
3	-3.2022	7.98887	-5.38887	1.0141
5	-2.8099	6.73204	-4.28890	0.6943

The dependence of S_u on ϕ at a particular temperature over a range of mixture pressures may be given by an equation of the form :

$$S_u\ (m/s) = A_0 + A_1.\phi + A_2.\phi^2 + A_3.\phi^3 \qquad (1)$$

,where A_0 , A_1, A_2 and A_3 are calculated constants and given in Table-3 and Table-4 for methane and methanol respectively at T_i = 350 K.

Effect of Temperature on S_u :

The temperature dependence of laminar burning velocity appears to be strong. For both methane and methanol, burning velocity increases with increase in mixture temperature. In fact, rate of reaction increases with temperature. This trend can be readily observed from Fig.2.

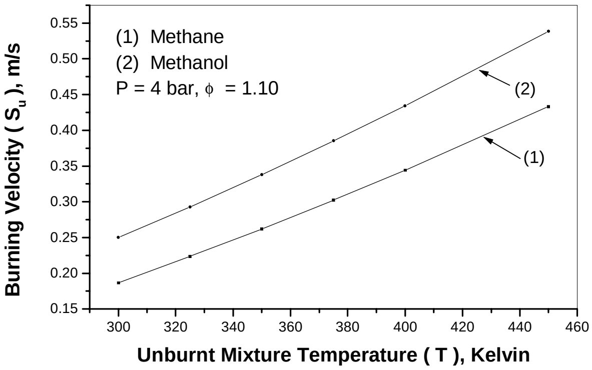

Fig. 2 Effect on temperature on burning velocity

The values of burning velocities may be expressed by an equation of the form :

$$S_u\ (m/s) = B_0 + B_1.T + B_2.T^2 \qquad (2)$$

.where B_0 ,B_1, and B_2 are calculated constants. The values of these constants depend on equivalence ratio for a particular mixture pressure and are given in Table-5 and Table-6.

TABLE –5
Values of coefficients of equation(2) for Methane at P_i = 4 bar.

ϕ	B_0	B_1	B_2
0.80	-0.12767	6.00608e-04	0.90124e-06
1.00	-0.09850	7.01035e-04	1.26021e-06
1.20	-0.17657	6.34546e-04	1.37593e-06

TABLE –6
Values of coefficients of equation(2) for Methanol at P_i = 4 bar.

ϕ	B_0	B_1	B_2
0.80	-0.04948	1.04684e-04	1.90964e-06
1.00	-0.12552	8.19799e-04	1.72607e-06
1.20	-0.13404	9.26495e-04	1.03479e-06

Effect of Pressure on S_u

In general, increase of initial pressure of the fuel-air mixtures, keeping other parameters viz. initial temperature (T_i) and equivalence ratio (ϕ) fixed, reduce the burning velocity. This trend can be observed from Fig.1 and Fig.3. It is also observed that effect of pressure at higher pressure range is comparatively reduced. For example, it is seen that the average reduction in burning velocity in the pressure range of 2 to 4 bar for ϕ = 0.80 to 1.20 in case of methane is about 30% for T_i =303 K. For methanol it is about 35% for the same range. But for the higher pressure range of 4 to 6 bar, those average values of reductions are about 18% for methane and 25% for methanol. Actually, with increasing pressures, the rates of the termination reactions increase at a faster rate than that of the branching reactions and thereby, overall reaction rate and burning velocities are reduced

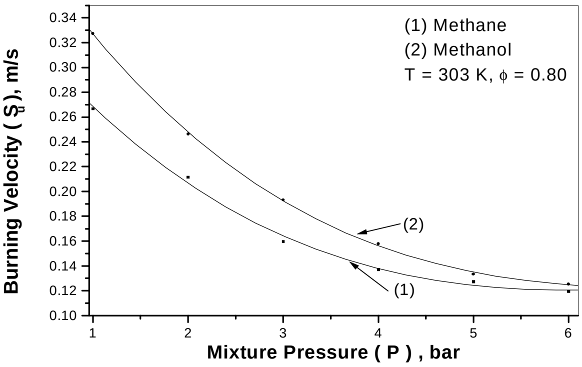

Fig. 3 Effect of pressure on burning velocity

COMPARISON

Table-1, Table-2 and Table-7 compare the burning velocity results of the present study with other available reported values of some prime investigators in this field. The agreements among the results are, in general, good and within reasonable limits. These also highlight the strength and correctness of presently proposed unified burning velocity correlations for methane and methanol. For example, Ryan and Lestz,1981 proposed their correlation for the temperature range of 470 to 600 K and pressure range of 4 to 18 bar and given only for some discrete values of ϕ. Similarly, Metghalchi and Keck,1982 proposed their correlations for some discrete values of equivalence ratio.

TABLE – 7

A comparison of burning velocity (S_u ,m/s)
(T_i = 500 K, ϕ = 1.00 bar)

METHANE-AIR		
P (bar)	S_u (m/s) [Ryan & Lestz,1981]	S_u (m/s) [Present Study[
6.00	0.4871	0.5067
8.00	0.4798	0.4637
10.0	0.4545	0.4303

METHANOL-AIR		
P (bar)	S_u (m/s) [Ryan & Lestz,1981]	S_u (m/s) [Present Study]
6.00	0.6082	0.6290
8.00	0.5916	0.5705
10.0	0.5593	0.5281

CONCLUSION

Unified burning velocity correlations for methane and methanol are proposed in the present study. The proposed correlations are more versatile and accurate compared to other previously proposed correlations. Effects of initial pressure, temperature and equivalence ratio on burning velocity are also studied in the present investigation.

NOMENCLATURE

abs(v)	absolute value of ‘ v ’
m	mass of combustible mixture
P	pressure
r	radius
R_g	characteristic gas constant
S_u	burning velocity
t	time
T	temperature
V	volume
δ	flame thickness
ρ	density
ϕ	equivalence ratio = (actual fuel-air ratio)/(stoichiometric fuel-air ratio)

Subscripts

b	burnt gas condition
e	combustion completed condition
f	condition at flame
n	condition at any n-th element
o, i	condition at initial
u	unburnt gas condition

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