

# Laminar Burning Velocities in Stoichiometric Hydrogen and Hydrogen-Hydrocarbon Gas Mixtures

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Measurements of the laminar burning velocities of hydrogen, acetylene, propane, and methane have been made using a spherical combustion bomb. In addition measurements were also made for mixtures of hydrogen with acetylene, propane, methane, and simulated combustion products in various proportions. All mixtures were stoichiometric with air and pressures and temperatures ranged from 0.5 to 7 atm and 300 to 550K, respectively. The values for the pure gases were in good agreement with previous experimental results from combustion bombs and in reasonable agreement with theoretical calculations by Warnatz. When mixed with hydrogen, propane and methane exhibited a double peak behavior in the burning velocity, as a function of pressure along an unburned gas isentrope.

## 1. INTRODUCTION

The burning velocities of pure hydrogen and hydrocarbon-hydrogen mixtures at high temperatures and pressures are of practical importance in the design and analysis of internal combustion engines and power plant burners [1]. They are also of fundamental importance for developing and testing theoretical models of laminar flame propagation [2].

Although the laminar burning velocities of hydrogen-air mixtures have been extensively studied at room temperature and pressure [2], there is relatively little experimental information available for elevated temperatures and pressures. Also, while burning velocities for several pure hydrocarbon-air mixtures at high

temperatures and pressures have been measured (for example, [3]-[7]), values for blends of these fuels with hydrogen have not been determined. Since there is no established method for calculating the burning velocity of a mixture of combustible gases from the values for the constituent gases, experimental data are required.

This paper presents experimental measurements of the laminar burning velocities of stoichiometric mixtures of air with hydrogen, hydrogen-methane, hydrogen-propane, hydrogen-acetylene, and hydrogen-residual gas. The experiments were conducted in a constant volume bomb and therefore give results which are valid over an elevated range of unburned gas temperatures and pressures.

## 2. EXPERIMENTAL APPARATUS AND PROCEDURE

The combustion bomb used for these experiments has been described previously [3]. In brief it is a spherical bomb of inside diameter 15.25 cm with a central ignition system. A Kistler piezoelectric pressure transducer is fitted flush to the wall, three ionization probes are spaced around the perimeter, and an He-Ne laser shadowgraph system cuts the radius at right angles a distance of 64.47 mm from the center. The spherical symmetry of the combustion front can be checked by comparing its arrival times at the individual ionization probes, while the laser shadowgraph can be used to obtain an internal consistency check on the flame radius computed from the pressure transducer readings. An A/D data acquisition system with 12 bit accuracy is used to transfer readings directly to the computer for analysis.

In setting up the bomb for the experiments, the laser was aligned using a knife edge at the appropriate distance from the center. In addition, laser point images were located on the outer faces of the two windows at their mid-points by using a suitable masking as a screen. These points were checked periodically during the course of the experiments, and it is ensured that the location and normality of the beam to the radius remain unaltered at all times. The Kistler pressure transducer was coated with RTV silicon rubber approximately 15 mils thick to minimize thermal effects. The ion probes were set 0.25 mm from the wall. All gauges were calibrated in their low pressure range against an absolute pressure manometer.

During experiments, the bomb and manifold were pumped to a level of 100 mTorr between fills, this being the practical minimum to avoid excessive pumping time. The test fuel was admitted slowly to the bomb until the calculated partial pressure was reached. The manifold was repumped and air was then admitted to a pressure of 760 or 380 mm-Hg, these being the two base conditions investigated. Atmospheric

air was generally used, although with each gas one or two runs were carried out using a dry bottled air supply for comparison. Any differences using the latter were found to be within the normal experimental variation, and so there was no increase in accuracy obtainable by using bottled air on all runs. When the atmospheric pressure was below 760 mm-Hg, the pressure was made up from the bottled supply.

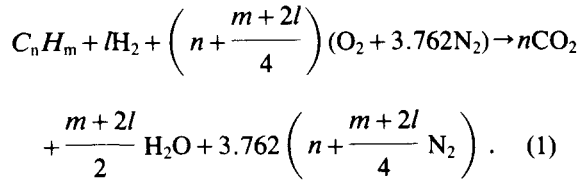
When the combustible gas mixtures were being prepared, the hydrocarbon gas was admitted first, followed by hydrogen and then air, after appropriate pumping of the manifold. Mixing of the gases and/or the settling of any organized motion or turbulence carried over from the inlet process was an occasional problem. This manifested itself as a noticeable difference in ion probe readings. These runs were disregarded in the final analysis. In general, the effect was not thought to be flame buoyancy, as on equivalent runs there was no systematic difference in arrival times at top and bottom ion probes.

Each gas mixture required slight variations in the filling technique and settling time. In general, a slow fill and 5 min settling gave consistent results. Settling times up to 1 h were tried, but no appreciable difference occurred from the results obtained with the standard 5 min. It was therefore assumed that this was adequate to allow the temperature to equilibrate and all turbulence to dissipate. For the hydrocarbon-hydrogen mixtures, a faster hydrogen fill seemed to give more consistent results, probably due to better mixing with the initial hydrocarbon fuel. When this faster fill was used, the settling time was increased to about 8–10 min.

Computations were carried out using the method of Ref. [3] and required accurate properties for the various gases under consideration. Sources of enthalpy coefficients were Martin and Heywood [8] or Gordon and McBride [9], the latter being converted to suit the computer code available. The transport properties of the gases were obtained from calculations using the Lennard-Jones [12–16] potential constants from Svehla [10].

**Partial Pressures of the Gaseous Fuels**

All experiments with either pure or mixed gases were carried out using a stoichiometric fuel/air ratio. In the general case for a hydrocarbon-hydrogen fuel mixture, the fuel partial pressures were determined as follows. Assume that the hydrocarbon is  $C_nH_m$  and that hydrogen is added to give a hydrogen/hydrocarbon ratio  $H_2/C_nH_m = l$ . Then for a stoichiometric mixture (equivalence ratio  $\phi = 1$ ), the overall reaction is



Thus, the total moles of reactants is

$$N_u = 1 + l + 4.762\left(n + \frac{m+2l}{4}\right), \quad (2)$$

the total moles of products is

$$N_b = n + \frac{m+2l}{2} + 3.762\left(n + \frac{m+2l}{4}\right), \quad (3)$$

and the change in the moles of gas during combustion is

$$\Delta N = N_b - N_u = \frac{m}{4} - \frac{l}{2} - 1. \quad (4)$$

The partial pressure of the hydrocarbon in the unburned mixture is

$$x_{HC} = 1/N_u, \quad (5)$$

that of the hydrogen is

$$x_{H_2} = l/N_u, \quad (6)$$

and that of the fuel mixture is

$$x_{FM} = (1 + l)/N_u. \quad (7)$$

The mole fractions of hydrogen atoms in the unburned and burned mixtures are

$$x_{H_u} = (m + 2l)/N_u, \quad (8a)$$

$$x_{H_b} = (m + 2l)/N_b, \quad (8b)$$

and the hydrogen-to-carbon atom ratio is

$$X = (m + 2l)/n. \quad (9)$$

It can be seen from Eqs. (2) and (7) that  $x_{FM}$  increases monotonically from the value  $(1 + 4.76(n + m/4))^{-1}$  for the pure hydrocarbon ( $l = 0$ ) to the value of 0.296 for pure hydrogen ( $l = \infty$ ). In the case of paraffins for which  $m = 2n + 2$ ,  $x_{FM} = (X - 2)/(7.524 + 3.381X)$ , which is only a function of the hydrogen-to-carbon atom ratio for the fuel mixture.

**Residual Gas Fractions**

Since the fraction of residual combustion products in the unburned mixture is known to have a strong influence on the burning rates of hydrocarbons [4, 11], it was of interest to examine the effect of diluting hydrogen-air mixtures with residual gases. This was also important in connection with the interpretation of recent experiments on hydrogen combustion run in the M.I.T. quartz-walled engine [12, 13].

The burning of hydrogen in air produces only water and nitrogen in the complete combustion of a stoichiometric mixture. This may either remain as vapor or condense, depending on the conditions in the cylinders during the power, exhaust, and inlet strokes. When the M.I.T. quartz-walled engine is run on hydrogen, there is no sign of condensation within the combustion chamber, and hence it must be assumed that the residuals are approximately 35% water vapor and 65% nitrogen. Because the combustion bomb was operating at initial conditions of atmospheric temperature and pressure, water vapor in this proportion could not be used. Therefore a mixture of carbon dioxide and nitrogen was substituted. The percentage of  $CO_2$  required in the mixture to match the local specific heat of the real residuals is given in Table 1 as a function of temperature. A mixture of 15%  $CO_2$  and 85%  $N_2$  was chosen as a reasonable approximation over the unburned gas

TABLE 1

Percentage of CO<sub>2</sub> Required in a CO<sub>2</sub> + N<sub>2</sub> Mixture to Match the Local Specific Heat of the Combustion Products of Stoichiometric H<sub>2</sub>-Air Mixtures.

<i>T</i> (K)	Specific Heat <i>C<sub>p</sub>/R</i>			Average <i>C<sub>p</sub>/R</i> Real Products	% CO <sub>2</sub> in Simulated Products
	H <sub>2</sub> O	CO <sub>2</sub>	N <sub>2</sub>		
300	4.04	4.48	3.50	3.69	19.0
425	4.15	5.07	3.53	3.74	14.0
550	4.30	5.40	3.59	3.84	12.6

temperature range 300–550K covered in these experiments. While the use of this simulated residual gas is not ideal, it should give a reasonable assessment of the real residual gas effect.

### 3. MEASURED BURNING VELOCITIES

#### Pure Gases

The four basic gases, hydrogen, acetylene, propane, and methane, used in the experiments were first tested individually in stoichiometric air mixtures. A typical raw result is shown in Fig. 1 for hydrogen initially at  $p_i = 1$  and  $T_i = 298$ K. This is a composite of five identical runs for which the burning velocities were computed using the method of Ref. [3]. Corrections to the data required for heat losses and temperature gradients in both burned and unburned gases were estimated using equations given in the appendix of Ref. [4]. None of the corrections exceeded  $\pm 1\%$  for any of the data included in this report and they were ignored.

The points show an rms scatter of  $\pm 3\%$  about the mean values for a given pressure. This is primarily due to round-off errors in the determination of the time derivative of the pressure  $dp/dt$  required to calculate the instantaneous burning velocity.

A summary of locally averaged burning velocities as a function of pressure along two unburned gas isentropes is given in Table 2 for all the pure fuels studied. These results are also shown on a log-log plot in Fig. 2. The dashed lines connecting points are isotherms for the

unburned gas. The solid lines show the results of a least-squares fit of the relation

$$\log S_u = \log S_{ui} + \epsilon_i \log p \quad (10)$$

to the points. The best fit parameters  $S_{ui}$  and  $\epsilon_i$  are given in Table 3A. Also given are the standard deviations  $\sigma_i$  of the points from the fitted curve. It can be seen that the fits are remarkably good which implies that the isentropic pressure exponent

$$\epsilon = (\partial \ln S_u / \partial \ln p)_s \quad (11)$$

is nearly constant for a given isentrope.

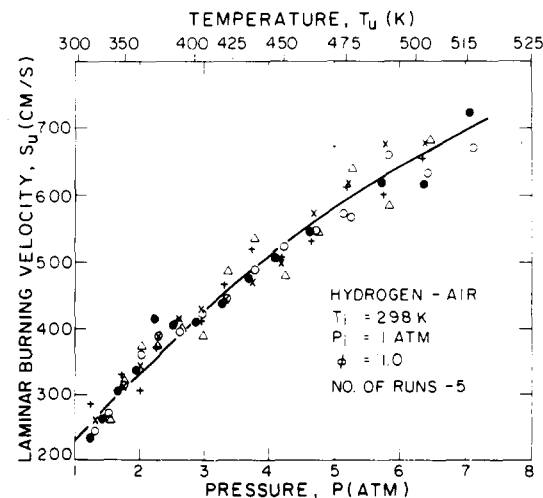


Fig. 1. Burning velocities of stoichiometric hydrogen-air mixtures as a function of pressure for 5 individual runs. Upper scale shows unburned gas temperature for isentropic compression. Solid curve was obtained from Eq. (12) using parameters in Table 3B. The rms scatter of points about the curve is  $\pm 5\%$ .

TABLE 2.

Burning Velocities of Stoichiometric Fuel-Air Mixtures as a Function of Pressure Along Unburned Gas Isentropes

Fuel		H <sub>2</sub>		C <sub>2</sub> H <sub>2</sub>		C <sub>3</sub> H <sub>8</sub>		CH <sub>4</sub>	
H/C = X		∞		1		2.67		4	
Isentrope	p <sup>a</sup>	T <sub>u</sub> <sup>b</sup>	S <sub>u</sub> <sup>c</sup>	T <sub>u</sub>	S <sub>u</sub>	T <sub>u</sub>	S <sub>u</sub>	T <sub>u</sub>	S <sub>u</sub>
U	1	298	230	300	135	300	38	300	35
	2	360	340	360	172	360	43.5	362	39
	3	405	425	400	228	35	49	402	42
	4	440	510	433	250	430	52	435	43
	5	470	580	460	275	455	56	462	45
	6	495	645	482	295	475	60	485	46
	7	512	700	502	312	495	64	505	46.5
	8	—	—	520	325	510	67	—	—
L	0.5	298	200	300	125	300	40	300	37
	1.0	360	275	360	175	360	49.5	362	50
	1.5	405	350	400	205	395	55	402	59
	2.0	440	420	433	237	430	60	435	65
	2.5	470	495	460	265	455	64.5	262	69
	3.0	495	560	482	290	475	68	485	73
	3.5	512	630	502	325	495	70.5	—	—
	4.0	—	—	520	340	—	—	—	—

<sup>a</sup> Pressure *p* (atm).  
<sup>b</sup> Temperature *T*(K).  
<sup>c</sup> Velocity *S<sub>u</sub>* (cm/s).

In previous work [3, 4] an expression of the form

$$\log S_u = \log S_{u0} + \alpha \log(T/T_0) + \beta \log p \quad (12)$$

was used to obtain an overall fit of the burning velocity as a function of *T* and *p*. This is

TABLE 3A  
Parameters for Eq. (10)

Fuel	p <sub>i</sub> <sup>a</sup>	S <sub>u</sub> <sup>b</sup>	ε <sub>i</sub>	σ <sub>i</sub> <sup>c</sup>
H <sub>2</sub>	0.5	286	0.594	4.0
	1.0	229	0.576	0.7
C <sub>2</sub> H <sub>2</sub>	0.5	173	0.481	1.6
	1.0	134	0.437	3.0
C <sub>3</sub> H <sub>8</sub>	0.5	49.1	0.292	0.5
	1.0	36.7	0.274	2.3
CH <sub>4</sub>	0.5	49.2	0.380	2.0
	1.0	35.2	0.149	0.7

<sup>a</sup> Pressure *p* (atm).  
<sup>b</sup> Velocity *S<sub>u</sub>* (cm/s).  
<sup>c</sup> Standard deviation σ (%).

possible in cases where the isobaric temperature exponent

$$\alpha = (\partial \log S_u / \partial \log T)_p \quad (13)$$

and the isothermal pressure exponent

$$\beta = (\partial \log S_u / \partial \log p)_T \quad (14)$$

are approximately constant. Note that α and β are related to ε by the equation

$$\epsilon = \beta + \alpha(\gamma - 1)/\gamma, \quad (15)$$

where

$$\gamma = (\partial \log T / \partial \log p)_s = C_p/C_v \quad (16)$$

is the specific heat ratio for the unburned gas.

The local values of β are given by the slopes of the dashed lines in Fig. 2. Values of α can be obtained from the separation of points at the same pressure on two isentropes. As can be seen in Fig. 3 there are significant differences in the magnitudes of α and β for the various pure fuels. Moreover the variations of α and β with

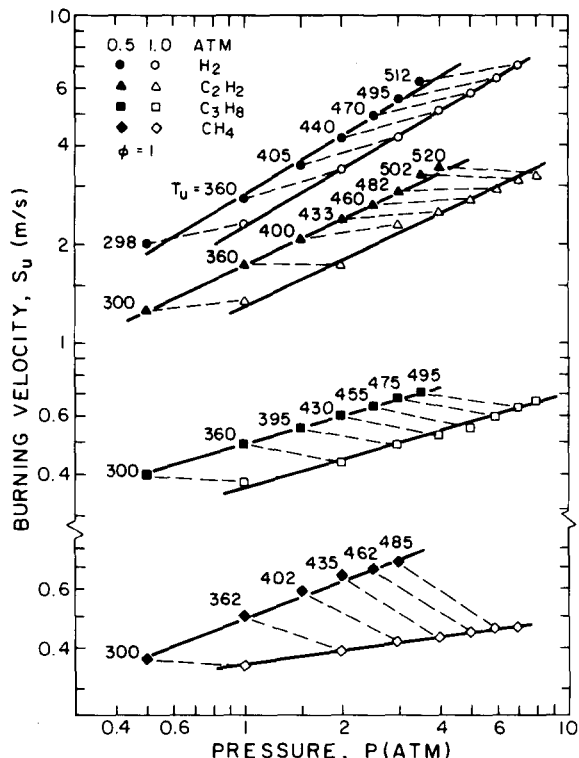


Fig. 2. Burning velocities of stoichiometric hydrocarbon-air mixtures as a function of pressure along two isentropes. Note scale for  $\text{CH}_4$  has been displaced to avoid overlap of points: dashed line, unburned gas isotherms at temperatures (K) shown; solid line, least-squares fit of Eq. (10) to data for "best-fit" parameters in Table 3A.

pressure are correlated. This is consistent with Eq. (15) and is most noticeable in the case of methane, where a decrease in the value of  $\beta$  is accompanied by an increase in the value of  $\alpha$ . For hydrogen, acetylene, and propane the variations in  $\alpha$  and  $\beta$  are sufficiently small to permit a good fit of the data using Eq. (10), and the

TABLE 3B

Parameters for Eq. (12)

Fuel	$S_{u0}^a$	$\bar{\alpha}$	$\bar{\beta}$	$\sigma^b$
$\text{H}_2$	217	1.26	0.26	4.0
$\text{C}_2\text{H}_2$	128	2.00	-0.06	3.0
$\text{C}_3\text{H}_8$	34.5	1.93	-0.19	2.5

<sup>a</sup> Velocity  $S_u$  (cm/s).

<sup>b</sup> Standard deviation  $\sigma$  (%).

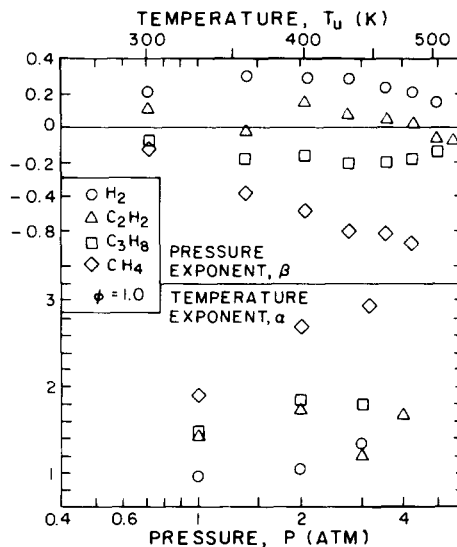


Fig. 3. Values of pressure and temperature exponents  $\beta$  and  $\alpha$  as a function of pressure computed from the appropriate first differences in Table 2. Upper scale shows the isentropic unburned gas temperatures.

values of the best fit parameters  $S_{u0}$ ,  $\bar{\alpha}$ , and  $\bar{\beta}$  along with the standard deviation  $\sigma$  of the points from the fitted curves are given in Table 3B. It can be seen from the values of  $\sigma$  for these three fuels that the overall fit of the data obtained with Eq. (12), which involves 3 parameters, is almost as good as that obtained with Eq. (10), which involves 4 parameters (two for each isentrop).

Both the magnitudes and variations of  $\alpha$  and  $\beta$  for propane, acetylene, and methane are in reasonable agreement with previous experimental results [3-7, 14, 15], although the pressure dependence of  $\beta$  for methane shown in Fig. 3 is slightly steeper than that previously reported. No previous experimental observation of the pressure and temperature dependence of the burning velocity for hydrogen-air mixtures has been found, but a comparison of the present results with the theoretical calculations of Warnatz is shown in Fig. 4. It can be seen that there is good agreement between the measured and calculated values of the burning velocity  $S_u$  and pressure exponent  $\beta$  at  $p = 1$  atm and  $T = 298\text{K}$  but that the calculated temperature exponent  $\alpha$  is somewhat higher than the measured value. It can also be seen that the present value

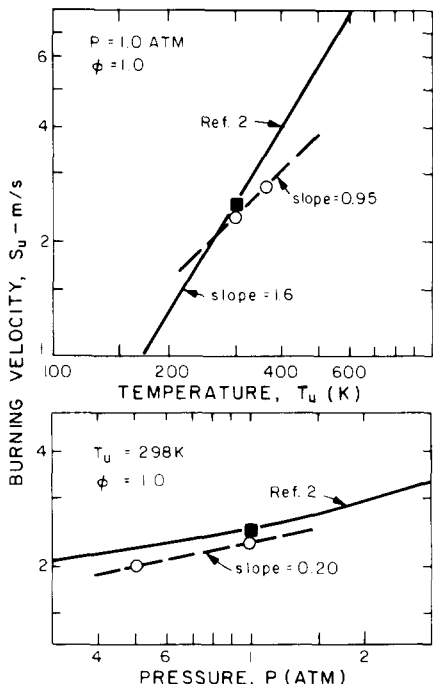


Fig. 4. Comparison of present burning velocities for stoichiometric hydrogen-air mixture  $\circ$  with theoretical curves calculated by Warnatz [2] — and previous measurements summarized by Warnatz  $\blacksquare$ .

of  $S_u$  is in reasonable agreement with previously measured values at  $p = 1 \text{ atm}$  and  $T = 298 \text{ K}$ .

It has been suggested [16] that the value of the pressure exponent  $\beta$  is a function only of the flame speed  $S_u$ . This conjecture is not supported by the results in Fig. 3, although there is a general tendency for fuels with higher flame speeds to have larger values of  $\beta$ . An alternative suggestion for which there is some physical basis is that the value of  $\beta$  will tend to be positive for fuels such as hydrogen and acetylene where Eq. (4) shows that combustion leads to a decrease in the total moles of gas and hence a significant fraction of the energy is released in three-body recombination reactions. In other cases where three-body reactions are primarily important in chain termination, the value of  $\beta$  is expected to be negative. Competition between these two effects may well lead to situations such as that for acetylene where the value of  $\beta$  goes through zero as pressure increases. This has also been observed by Rallis et al. [6].

### Hydrogen with Simulated Residual Gases

Results for these mixtures show that simulated residual combustion gas slowed the flame noticeably, and the percentage reductions plotted as functions of unburned gas temperature are given in Fig. 5. As expected, increasing the residual gas proportion produced larger decreases in burning velocity. Although the differencing calculation for the percentage reduction in  $S_u$  magnifies any errors and probably explains some of the variation in the individual curves of Fig. 5, a fairly consistent trend is evident. In all cases, the percentage reduction in burning velocity became less as combustion proceeded and the unburned gas temperature rose. At about  $T_u = 500 \text{ K}$ , all curves appear to be leveling off. A point of interest is that, when comparing 10% residual curves for the upper and lower pressure isentropes, the former exhibited larger burning velocity decreases particularly at the higher unburned gas temperatures.

### Hydrocarbon-Hydrogen Gas Mixtures

The locally averaged laminar burning velocities for several hydrocarbon-hydrogen mixtures are given in Table 4 as a function of pressure for a single isentrope starting at  $T_i = 300 \text{ K}$  and  $P_i = 1.0 \text{ atm}$ . As can be seen from the log-log plots of this data in Figs. 6 and 7, the burning velocities of these mixtures exhibited some

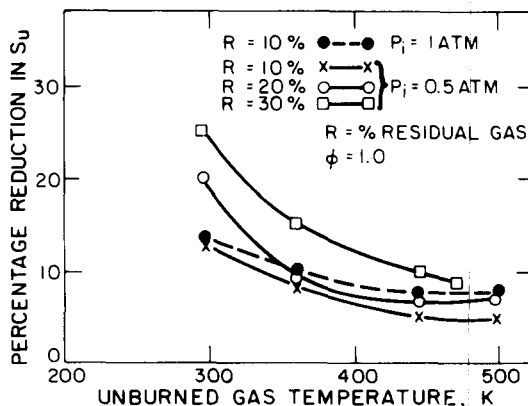


Fig. 5. Effect of simulated combustion products on the burning velocity of stoichiometric  $\text{H}_2$ -air mixtures.

TABLE 4

Burning Velocities of Stoichiometric Hydrocarbon-Air Mixtures as a Function of Pressure along an Unburned Gas Isentrope

Fuel	$C_2H_2 + 3H_2$		$C_3H_8 + 2H_2$		$C_3H_8 + 8H_2$		$CH_4 + 2H_2$	
H/C = $X$	4		4		8		8	
$p^a$	$T_u^b$	$S_u^c$	$T_u$	$S_u$	$T_u$	$S_u$	$T_u$	$S_u$
1.0	300	180	300	59	300	120	300	110
1.5	332	230	335	67	335	135	335	105
2.0	360	275	362	71	363	117	362	96
2.5	383	312	383	69	385	114	385	93
3.0	402	350	402	66	404	124	405	97
3.5	419	375	418	66	420	134	423	103
4.0	435	400	433	70	436	140	439	108
4.5	449	420	446	76	450	142	453	110
5.0	463	438	460	81	464	141	467	111
5.5	475	455	469	83	475	139	479	109
6.0	485	470	482	84	486	137	489	108
6.5	495	485	491	83	496	134	499	104

<sup>a</sup> Pressure  $p$  (atm).<sup>b</sup> Temperature  $T$  (K).<sup>c</sup> Velocity  $S_u$  (cm/s).

interesting trends. The most straightforward result is that obtained by mixing hydrogen and acetylene. The runs at  $H/C = X = 4$  show a burning velocity increasing from less than 200 cm/s at 1, 300K to 470 cm/s at 6 atm, 485K. That is, the results fall between those of pure hydrogen and pure acetylene. To give  $X = 4$ , the proportion of hydrogen was 0.75 and the values for the mixture can be compared to those that would be obtained by averaging the flame speeds of the constituent gases in molar proportions. Agreement varies throughout the range, but the measured results are generally about 10–15% lower than the weighted average.

With both propane–hydrogen and methane–hydrogen mixtures, local decreases in the burning velocity cause peaks in the curves of  $S_u$  against  $p$  or  $T$ . This is most noticeable in the  $X = 4$  propane–hydrogen data given in Fig. 7. The burning velocity initially accelerates from a value about 50% higher than that of the equivalent pure propane but then falls and rises again as burning continues. The burning velocity levels out after this second peak, then falls rapidly for unburned gas pressures above 7 atm.

This is probably due to some minor asymmetry in the flame causing early contact with the wall. The final peak velocity of 85 cm/s at 5.5 atm is again about 50% higher than pure propane, but, obviously, intermediate values are quite differently related. As the proportion of hydrogen in the fuel mixture is 0.667, the burning velocities are not even approximately related to those of the pure gases averaged in molar proportions. The  $X = 8$  propane–hydrogen results show similar trends. As would be expected, the values of  $S_u$  are higher (almost double) the  $X = 4$  values, but the second peak now occurs at a lower pressure.

Methane–hydrogen results at  $X = 8$  exhibit very similar behavior, the peaks occurring at about the same positions as  $X = 8$  propane–hydrogen results. The only marked difference is that the methane–hydrogen mixture has a burning velocity about 80% that of the equivalent propane–hydrogen mixture. The proportion of hydrogen in the former is 0.667, while in the latter it is 0.889, and so this might be expected. The  $X = 4$  propane–hydrogen mixtures have a hydrogen proportion of 0.667 but give a burning



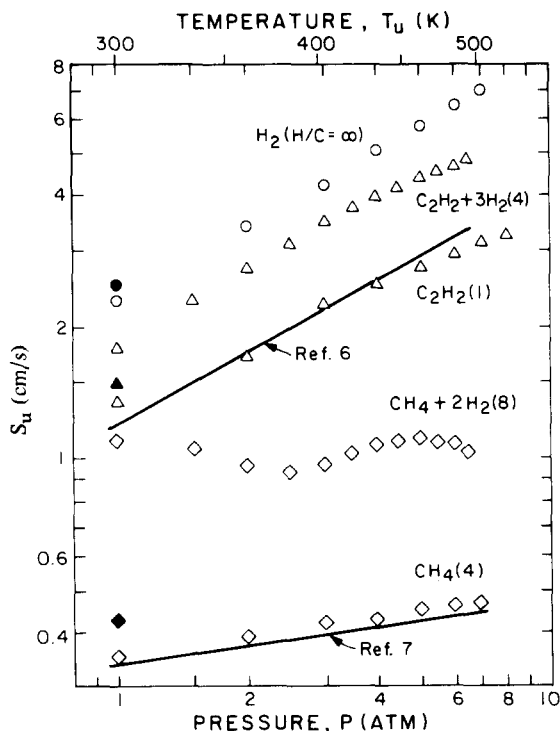


Fig. 6. Burning velocities of stoichiometric  $C_2H_2$ - $H_2$ -air and  $CH_4$ - $H_2$ -air mixtures as a function of pressure along an unburned gas isentrope. Values in parentheses give the hydrogen/carbon atom ratio. Curves show results of previous measurements for pure fuels. Solid points are values calculated by Warnatz [2] for pure fuels.

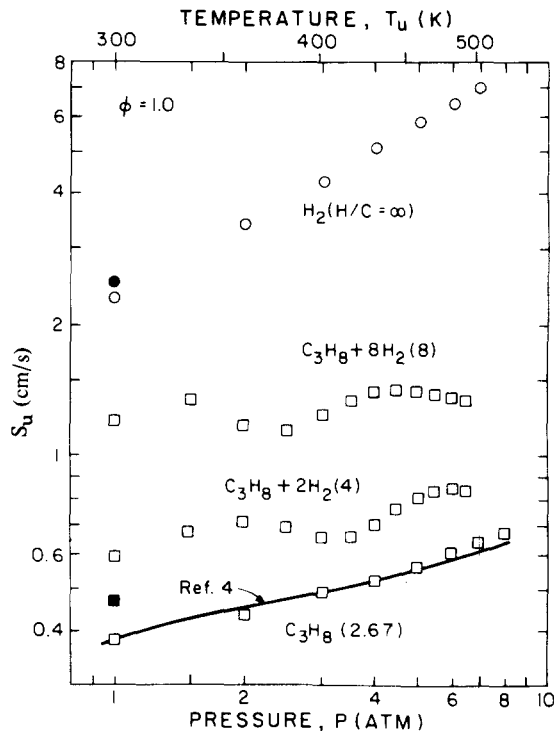


Fig. 7. Burning velocities of stoichiometric  $C_3H_8$ - $H_2$ -air mixtures as a function of pressure along an unburned gas isentrope. Values in parentheses give the hydrogen/carbon atom ratio. Curve shows the results of previous measurements for pure fuel. Solid points are values calculated by Warnatz [2] for pure fuels.

velocity about 80% that of  $X = 8$  methane-hydrogen mixtures which have the same hydrogen proportion.

No clear explanation of this double peak behavior is attempted here. The interaction of the burning of the two gases may cause complex changes in the temperature and pressure dependence as unburned gas conditions vary. Several different mixing techniques were tried in case gas stratification was involved. However, results were very similar in all cases, thereby eliminating this as a cause.

It should also be noted that the burning velocities of both propane-hydrogen and methane-hydrogen are much lower than a simple averaging technique would predict. For example,  $X = 4$  hydrogen-propane mixtures have an  $S_u$  of about 85 cm/s at 5.5 atm, compared with a value predicted by gas proportions of about 430

cm/s. On the other hand, hydrogen-acetylene tests give  $S_u = 475$  cm/s at 6 atm, whereas the proportional method gives 560 cm/s. While this latter agreement is not perfect, it is significantly better than the former. In both cases, the slower burning gas seems to dominate as the measured velocities are less than the average.

#### 4. CONCLUSIONS

For methane, propane, and acetylene, the burning velocities measured in the present experiments confirm the values and trends measured in previous combustion bomb experiments. For all the pure fuels studied the burning velocities at atmospheric temperature and pressure are 10-20% less than the values calculated by Warnatz. Considering the uncertainty of many of the rate constants used in the calculations, such agreement is considered remarkably good.

Some unusual results were obtained when hydrogen was mixed with the other gases. Both methane-hydrogen and propane-hydrogen gave a peak in the burning velocity curves shortly after flame initiation, followed by a reduction and then a second increase in the burning velocity. Throughout the range the burning velocity was substantially less than proportional averaging of values for the constituents would indicate. Acetylene-hydrogen burning velocities were moderately close to the values calculated on this basis but were still slower, indicating a dominance of the more slowly combusting molecules. No simple relationship between burning velocities and any of the physical parameters (e.g. H-atom fraction or H/C ratio) was evident in any of the results.

The experiments indicate that the laminar burning velocity of combustible gaseous fuel mixtures is a complex phenomenon requiring further fundamental experimental and theoretical investigation.

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## REFERENCES

1. Chigier, N. (Ed.), *Energy and Combustion Science*, Pergamon Press, New York, 1979.
2. Warantz, J., *Combust. Sci. Tech.* 26:203-213 (1981).
3. Metghalchi, M., and Keck, J. C., *Combust. Flame* 38:143-154 (1980).
4. Metghalchi, M., and Keck, J. C., *Combust. Flame* 48:191-210 (1982).
5. Agnew, J. T., and Graiff, L. B., *Combust. Flame* 5:209-219 (1961).
6. Rallis, C. J., Garforth, A. M., and Steinz, J. A., *Combust. Flame* 9:345-356 (1965).
7. Garforth, A. M., and Rallis, C. J., *Combust. Flame* 31:53-68 (1978).
8. Martin, M. K., and Heywood, J. B., *Combust. Sci. Tech.* 15:1-10 (1977).
9. Gordon, S., and McBride, B., NASA SP-273, 1971.
10. Svehla, R., NASA TR R-132, 1962.
11. Ryan, T. W., and Lestz, S. S., Automotive Engineering Congress, SAE Paper 800103, Detroit, 1980.
12. Vilches, F. R., M.S. Thesis, Mech. Eng., M.I.T., February 1982.
13. Keck, J. C., *Nineteenth Symposium (International) on Combustion*, The Combustion Institute, 1982, pp. 1451-1466.
14. Andrews, G. E., and Bradley, D., *Combust. Flame* 19:275-288 (1972).
15. Babkin, V. S., and Kozachenko, L. S., *Combustion Explosion and Shock Waves* 2:46-52 (1966).
16. Gunther, G., *Verbrennung und Feurunger*, Springer, Berlin, 1974.

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