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The Flame Speeds, Temperature and Limits of Flame Propagation for Producer Gas-air Mixtures – Experimental Results

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Abstract

This paper reports the experimental results on the flame temperature, flame speed and limits of propagation of wood gas-air mixture at ambient conditions (0.95 atm, 300 K). The peak temperature measured at an A/F close to 1.32 is 1546 ± 25 K. The peak flame speed is 0.50 ± 0.05 m/s. The lean and rich limits were obtained at 26 % fuel (corresponding to an equivalence ratio, $\phi = 0.47$) and (56 % fuel $\phi = 1.65$) on weight basis. The variation of the flame temperature and flame speed with the mixture ratio is presented. The difference between the theoretical adiabatic flame temperature and observed peak temperature of nearly 400 K is sought to be explained partly due to heat loss in measurement by thermocouple and importantly by the kinetic effects, implying incomplete reaction.

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Introduction

The last decade has seen significant work on the development of biomass based gasifiers for energy generation in India. Though considerable work on wood gas has been done all over the world[1], basic studies on the flame propagational features of wood gas are very few[2]. One among the various applications of producer gas is in the running of internal combustion engines which in turn can be used as power source. The combustion process in I.C. reciprocating engines is governed by turbulent flame propagation. The turbulent flame speed can be correlated to the laminar flame speed, turbulent scale and intensity. Thus, for understanding the operation of the engine with gas it is essential to determine the laminar propagation characteristics of the flame, namely the flame speed and the limits of propagation of the premixed gas-air mixture. In addition, on a fundamental level, laminar flame propagation in a premixed mixture forms the basis for assessing the reactivity of the mixture. Thus several basic phenomena like ignition, quenching, lifting and blow-off of high speed premixed mixtures are all related to the chemical reactivity of the gaseous mixture and therefore can be directly related to the flame speed of the mixture. Hence, in places where chemical reactivity is to be treated one can use flame speed as a representative quantity. Also the knowledge of flammability limits is useful in ignition and fire prevention.

Flame speed of a specific mixture of producer gas from charcoal reactor with air and oxygen is available in literature[1]. Though computational work has been reported[2] on the flame speed of wood gas considering full chemistry and realistic diffusion, the flammability limit for such a gas mixture is still not investigated. Also no experimental determination of these seem to have been made. Moreover, the gas composition from a typical wood gasifier changes slightly with time while in operation, which in turn may affect the flame speed and the flammability limits of the mixture. These facts demand a systematic investigation to determine these parameters. Present experimental work is an effort in this direction.

Apparatus

The apparatus for the experiment essentially consists of a wood gasifier system developed at the laboratory and flame tube with its accessories.

The wood gasifier as shown in *Figure 1* is a 3.7 kW gasifier. A detailed description of this system can be found in an earlier publication[3]; briefly, it consists of the main reactor approximately 250 mm diameter and 1.5 m tall, a cooler and a sand bed filter. The system operates under suction mode. The generated combustible gas passes through a cooler where it exchanges heat with circulating water and cools from approximately 450 K to ambient. The gas then passes through a sand bed filter wherein dust and other impurities are removed. Since the gas flow rates normally expected to be drawn from the gasifier are of the order of 2–4 g/s and one would expect good quality gas at such flow rates, the total gas flow from the gasifier is maintained at around 2 g/s. For the experiment typical gas flow rates were of the order of 1 g/s with the rest burning off at the burner.

Since the composition of the gas was an important parameter, periodically samples were drawn from the gasifier and analysed in a gas chromatograph for its major constituents, namely, H_2, CO, CO_2, CH_4 and N_2, based on thermal conductivity technique. The analysis was run thrice, once for the determination of CH_4 and CO (with H_2 as the carrier gas), the second time for CO_2 (with H_2 as carrier gas) and again for H_2 (with N_2 as carrier gas). N_2 was obtained by difference from 100 %.

Different methods have been employed by the early experimenters[4] for a detailed review) to study the flammability limits of a given combustible mixture. The most important of these are flame tube, large spherical vessel, flat flame burner and stagnation point flow burner. The most common geometry is the cylindrical tube[4]. For the present experiments a glass flame tube as shown in *Figure 2* having 54 mm ID and about 1220 mm long with one end open was chosen. The top end was kept open so that flame propagation could take place under constant pressure. It was fitted with a set of stainless steel electrodes 2 mm dia close to one of its ends and a gap of approximately 4 mm was maintained between them. A high voltage source connected across these electrodes was used to generate a high energy spark to ignite the combustible mixture. An interesting procedure was adopted to fill the tube with gas-air mixture and ensure it was filled before sparking. This was done by igniting the mixture at the top where a burner arrangement is made. In order to ensure no flash-back, this end of the tube was provided with a single G.I. mesh placed on it, on which were arranged a number of 5 mm I.D. aluminium tubes 60 mm long and enclosed in a mild steel tray filled with cold water to cool them and the glass tube. This arrangement ensured that the flame would not flash back, but the tube was filled with the right composition uniformly.

The bottom end of the glass tube was fitted with a set of stainless steel meshes enclosed in a mild steel cover. This arrangement served as a flame arrestor and quenched the flame as it reached this end of the glass tube, thereby preventing it from entering the feed lines of the gas and air.

The tube with its fittings was mounted on a wooden platform and clamped. A scale graduated in centimeters and big enough to be read from a distance was fixed on the platform beside the tube and parallel to it. The platform itself was secured to a vertical stand with the burner end having aluminium tubes at the top.

A mixing chamber was fabricated in which the gas from the gasifier and air mix and homogenise before entering the flame tube. Air was admitted at one end of the chamber and gas was introduced through a converging nozzle into the chamber. This was done in order to draw the gas from the gas line against the back pressure of the air line.

In order to ensure accurate measurement of flow rates, the venturimeters were to be calibrated against a primary standard. A coated mild steel tank 250 mm dia and 98 l capacity was fabricated for this purpose. The venturimeter to be calibrated was connected in line with the tank and a combination of valves was used, initially to set the static pressure drop across the venturimeter to a desired value and then to direct the flow of air from an air compressor into the tank. The mass rate of flow was computed from the time taken to displace a known volume of water from the tank. A number of runs was made at each setting of the pressure drop to ensure repeatability of the results. The data was plotted and a relationship of the form $Q = k \sqrt{H}$ between the mass flow rate Q and the pressure drop H established (k = venturi constant).

The gas and air feed lines were of 25 mm ID and sensitive control valves for the gas line, air line and the mixture (past the mixing chamber) were introduced. Gas drawn from the gasifier and air drawn from a high speed blower through separate control valves were passed through pre-calibrated venturimeters and the flow rates set against the static pressure drops shown by the water manometers. Thus, known flows of the gas and air enter the mixing chamber where they mix uniformly and proceed to enter the flame tube. All care is taken to ensure that the whole system is leak-proof. A Pt - Pt 13 % Rh thermocouple (type R, wire dia = 0.20 mm, bead dia = 0.50 mm) was initially used to measure the flame temperature. The peak temperature measured (at stoichiometry) was of the order of 1650 ± 25*K*. Since this was within the melting temperature of a Chromel-Alumel thermocouple, it was decided to deploy a Chromel-Alumel thermocouple (type K, wire dia = 0.25 mm, bead dia = 0.50 mm) additionally to confirm the measured temperatures. The Chromel-Alumel thermocouple recorded lower flame temperatures than those shown by the Pt - Pt 13 % Rh thermocouple. The difference was of the order of 150–250 K. This gave rise to the suspicion that Platinum was having a catalytic effect on the reaction in the presence of H_2 and O_2, resulting in higher flame temperatures. Such occurences have been reported earlier[5]. To determine the correct value, the Pt – Pt 13 % Rh thermocouple was given a 2 μ coating of Silicon dioxide and used again. Now the temperatures recorded were similar to those shown by the Chromel-Alumel thermocouple within 50 K.

The runs were video-recorded and a stop watch having a least count of 0.01 s was used to measure the flame speeds from the film. *Plate 1* shows the Flame Tube Apparatus, with a flame at the top burner, prior to ignition.

Experiments

Experiments were aimed at getting the flame speed vs equivalence ratio and the flame temperature vs equivalence- ratio, as also to determine the limits of flame propagation.

The runs were started after the delivery from the gasifier stabilized. Known rates of gas and air were allowed into the flame tube with the control valve for the mixture fully open. At the top burner end the mixture was ignited and it continued to burn there.

The thermocouple was manouvered in the flame to get the peak flame temperature and was fixed in position there. This temperature was noted down.

The control valve for the mixture was then fully closed to stop the flow of mixture into the flame tube. Some time delay was given to allow the gases in the tube to homogenize. At this time, the flame over the flame tube quenched.

The quiescent mixture in the tube was then ignited and a flame (for a mixture within the flammability limits) propagated downward in the tube. It was observed that at and around the stoichiometric composition, the flame profile was curved (roughly parabolic), whereas the flame front flattened as the composition became lean or rich. Near the limits (both lean as well as rich), the flame was essentially flat and cellular (wavy), and it retained this profile through out propagation. As the flame reached the bottom end of the tube, it quenched at the arrestor.

The run was video-recorded and the flame speed computed (from the film) from the time taken by the flame to travel through a known distance and was noted down.

The runs were begun with an equivalence ratio (defined as the ratio of fuel and air to fuel and air at stoichiometry, on weight basis) of one and repeated for increasing and decreasing values of ϕ until the rich and the lean limits were obtained. The limits were identified as the mixture ratios at which the flame did not just propagate or quenched just a little distance away from the point of ignition. This definition for the limit is standard[6] and used by most experimenters.

Results and Discussion

Table 1 gives the results of measured compositions at different conditions, the nominal composition assumed in an earlier work[2] and the compositions measured on this gasifier by Parikh[7] under similar experimental conditions. It can be noticed that the compositions measured in our laboratory appear less energetic compared to those measured by Parikh (because the nitrogen content is distinctly smaller by 3 to 4 %). This may be because of the flow rates being at the lower end of the working range in the present case. There is also a variation in the composition between the three cases dealt with here. Perhaps this must be understood to be the differences which occur in the gasifier rather than specifically related to the three distinct cases. *Figure 3* shows the variation of the flame temperature (as measured by a Chromel-Alumel thermocouple) as a function of equivalence ratio. Also plotted are the adiabatic flame temperatures obtained from thermochemistry calculations using NASA SP 273. The three curves correspond to the nominal composition (dotted line), and the two energetic compositions of Parikh[7]. The differences in the theoretical flame temperatures between the various compositions is about 100 K with the nominal composition leading to lower value. The air-to-fuel ratio leading to peak flame temperature is about 1.2 – 1.3 and depends weakly on the variation in the composition. The difference in the results between the experimental and theoretical flame temperatures is very large except at limit compositions. This was a worrisome point. As discussed earlier, Pt – Pt 13 % Rh thermocouple was tried initially. This gave substantially large temperatures, typically 130 – 350 K more than the temperatures measured by Chromel-Alumel thermocouple as seen from *Table 2*. The results from the Pt – Pt 13% Rh thermocouple coated with silica by using sputtering technique up to about 2 microns thick led to results which are substantially lower than the uncoated one and close to the values obtained from Chromel-Alumel thermocouple to within 50 K. Even allowing for the catalytic effects, the temperature difference which needs to be accounted for is 200 to 250 K. Part of this is argued to be the finite bead size effect. Finite bead size causes heat loss by radiation to the ambient. The measurements of temperature were made using thermocouples of different bead size (Refer *Table 3*) and these are plotted in *Figure 4*. It is seen that the curve is virtually linear and the result extrapolated to zero bead size is 1630 K. One can attempt to rationalise these results based on a simple model of the balance between the convective heat transfer and radiant heat transfer. This gives

$$h_g A_s (T_g - T_s) = \varepsilon_s \sigma A_s T_s^4$$

where h_g is the gas phase heat transfer coefficient, A_s is the surface area of the sphere for heat transfer, T_g is the gas phase temperature, T_s is the surface temperature, ε is the surface emissivity, and σ is the Stefan–Boltzmann constant. The left hand side is the convective heat transfer from the gas to the bead and the right hand side is the heat lost by radiation to the ambient. The gas itself has a very low emmissivity and hence absorbs little of the radiation.

The heat transfer coefficient h_g is given by forced convection correlation for flow past a sphere as[10]

$$h_g d / k_g = 2 + 0.35 \, Re^{0.5}$$

Combining these two equations one can write

$$h_g = T_s + [\ \varepsilon_s\ d\ \sigma\ T_s^{\ 4}\ /\ k_g\ \{\ 2 + 0.35\ \mathrm{Re}^{0.5}\ \}\ ]$$

For given values of the geometric parameter (d), flow property (gas density and velocity), and surface temperature one can get the corrected gas temperature or given the gas temperature one can obtain the surface temperature. For the case of stoichiometric composition considered here, the properties are:

$\rho = 0.225$ kg/m^3, velocity = 2.0 m/s, gas viscosity = 5×10^{-5} kg/m.s, gas conductivity (k_g) = 0.092 W / m K, $\varepsilon_s = 0.17$, $\sigma = 5.67 \times 10^{-8}$. These values can be used in the above equation to estimate the effect of bead size.

Calculations made by taking T_g = 1630 K, the extrapolated value gives the prediction for the temperature as a function of the bead size as shown in *Figure 4*. There are differences between the two curves at large bead size. The measured temperature is lower than the predicted because the peak temperature occurs in thin reaction sheets and it is averaged out due to large size of the bead.

Thus the heat loss effect can explain about 90 K of the difference. This still leaves about 100 – 150 K unexplained. The explanation for this is as follows. Due to catalytic effect which is due to kinetic effects, the increase in temperature indicated by the thermocouple due to catalytic effects at the surface was about 200 K. At this condition the highest temperature experienced is only at the bead and unlike the case discussed earlier the heat loss is from the bead to the gas and the ambient both by convection and radiation. Consequently, the net difference in temperature due to the combined effects can be expected to be higher. The precise estimation of this is crippled by the inability to evaluate the catalytic effects around the thermocouple material. It is suggested that the observed difference is because of these effects.

Summarising, the peak temperature of the premixed flame is about 1630 K and the difference between this and the theoretical flame temperature of about 1900 ± 50 K (the variation due to compositional changes) is due to non-release of energy in intermediate products of combustion.

The results of the flame speed with A/F are plotted in *Figure 5*. It is seen that there is some scatter in the flame speed data. This is essentially due to variations in the composition of the gas from the gasifier. The peak flame speed is about 0.55 ± 0.05 m/s and occurs in a range of A/F ratios between 1.2 to 1.4 .

The lean limits were obtained as around an A/F of 2.8 ± 0.05 and the rich limits as between 0.83 ± 0.03. These correspond to equivalence ratios of 0.47 ± 0.01 and 1.6 ± 0.05. The limit flame speeds are 10.3 cm/s for the lean case and 13 cm/s for the rich case. These results can be compared with those of hydrogen, methane, and carbon monoxide (Refer *Table 4*). It can be seen that the results of producer gas match more closely with those of methane than the other gases. However, it is more reactive than methane (because the stoichiometric flame speed is 0.38 m/s for methane and about 0.50 m/s for producer gas). This has implications on dual-fuel operation in reciprocating engines. These results can be used for validating the kinetic processes which occur in models on flame propagation.

Summary

This paper reports the measurement of flame temperature, propagation speeds and limits of propagation of producer gas (wood gas) – air mixtures at ambient conditions. The differences between the measured peak temperatures and adiabatic flame temperature are explained as due to kinetic effects. The peak flame speed is more than of methane and carbon monoxide, but much less than of hydrogen. This implies that the reactivity of producer gas is more than of methane, but not significantly so. These first set of data can be used for verifying model predictions of flame propagation behaviour the which aspect is a subject of another paper.

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Table 1 Producer gas composition (percentage)

Component	Experimental			Nominal [2]	Earlier reported [7]	
H_2	18	18	23	20	22.6	22
CO	19	20	17	19.5	23.3	21.7
CO_2	14	13	14	12.5	11.9	12
CH_4	4	3	3	2	1.7	1.8
N_2	45	46	43	46	40.5	42.5

Table 2 Temperature measurement with different Thermocouples

A/F Ratio	Equivalence ratio	Temperature ± 25K		
		Chromel-Alumel	Pt-13% Rh	PT -13%Rh (coated)
2.81	0.47	1160	1505	1210
2.64	0.50	1255	1577	1300
2.20	0.60	1286	1627	1340
1.32	1.00	1546	1698	1530
0.88	1.50	1300	1433	1320
0.83	1.60	1290	1433	1280

Table 3 Bead size effect on temperature

Wire diameter (mm)	Bead diameter (mm)	Measured Temperature (K)	Theory Bead Size Effect (K)
0.25	0.50	1546	1546
0.55	0.90	1490	1497
0.90	1.75	1345	1415

Table 4 Flammability limites and Flame speeds of different Gas - Air mixtures

Gas	Equivalence ratio at the limits (wt. basis)		Peak Flame speed (cm/s)	Limit Flame speed (cm/s)	
	Lean	Rich		Lean	Rich
H2	0.01	7.17	270	65	75
CO	0.34	6.80	45	12	23
CH4	0.535	1.69	35	2.5	14
Producer gas	0.47 ± 0.01	1.6 ± 0.05	50 ± 5	10.3	13

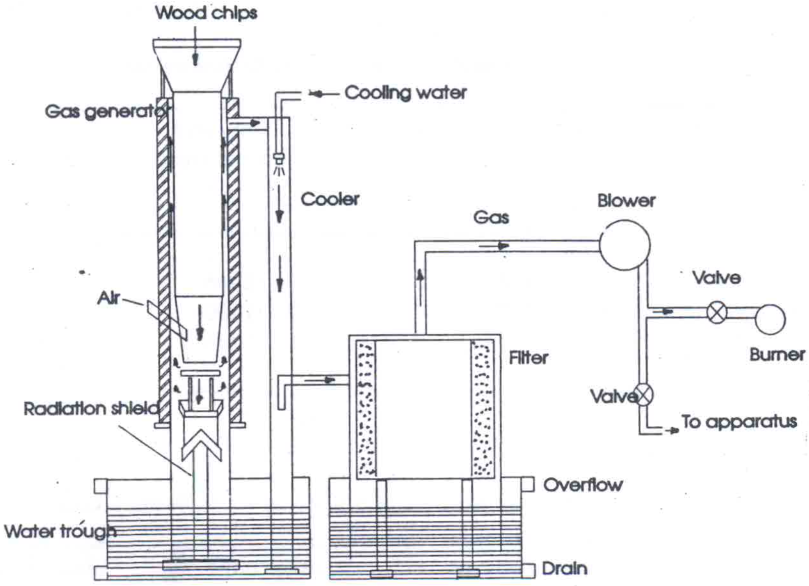

Figure 1 Wood Gasifier System

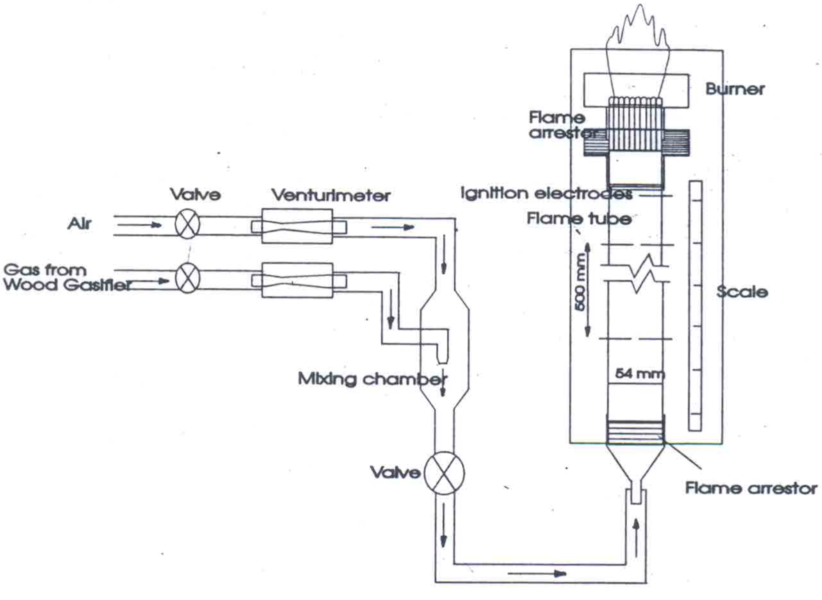

Figure 2 Flame Tube Apparatus

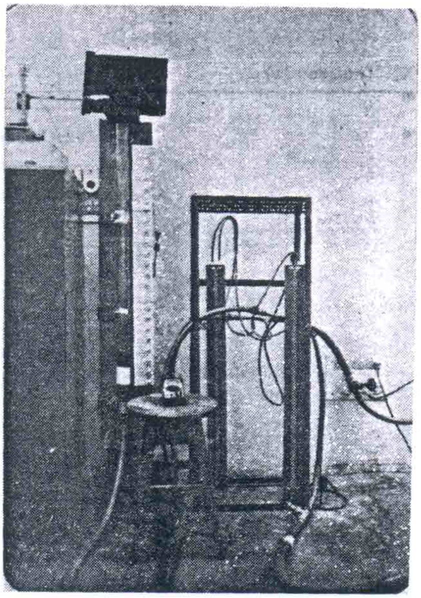

Plate 1 Flame Tube Apparatus with a flame at the Top Burner, prior to Ignition in the tube

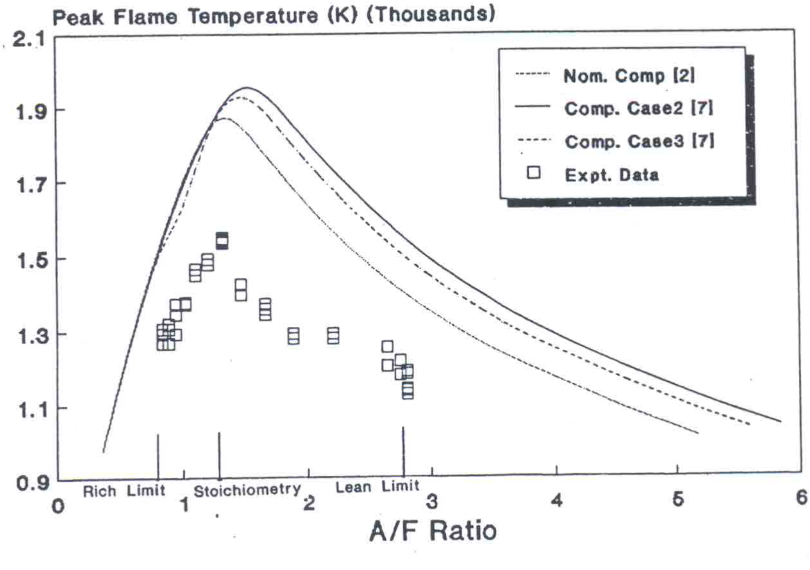

Figure 3 Flame Temperature *vs.* A/F Ratio

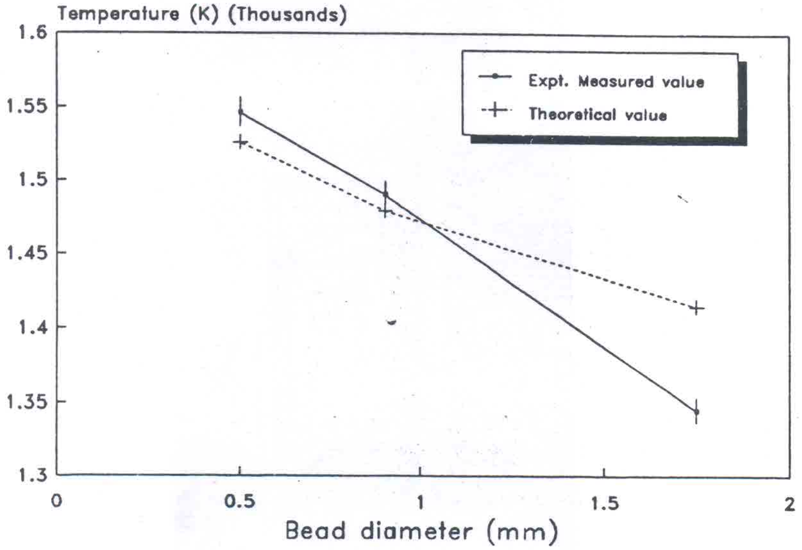

Figure 4 Bead size effect on Flame Temperature

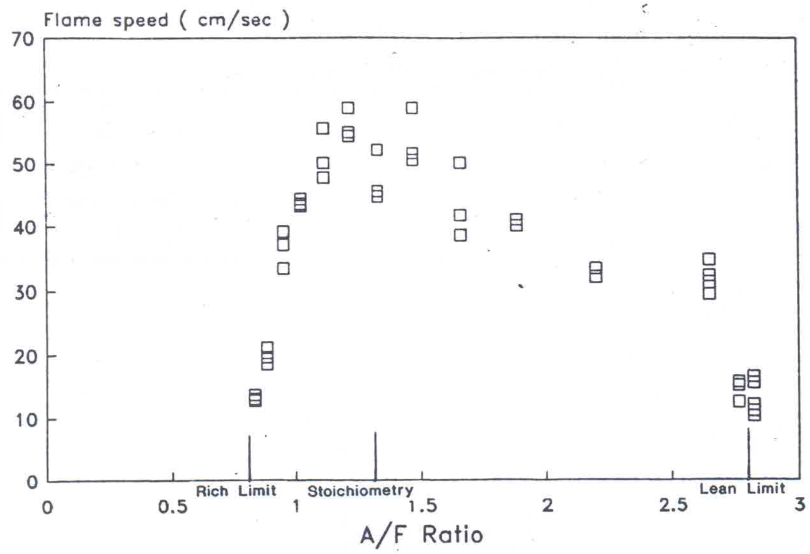

Figure 5 Flame speed *vs.* A/F Ratio