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Experimental Investigation and Mathematical Modelling to Study the Premixed Laminar Flame Propagation

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ABSTRACT

In the present work, experiments are conducted on a newly designed flame propagation test unit using burners of different geometries (L/D ratio) at different air-fuel ratios to calculate the flame speed. From the experimental data obtained, design plots are drawn to study the flame stability zone under different conditions. Using the above test results and standard mathematical curve fitting techniques for a function of two variables, an equation has been derived which can be utilised by the designers to design an optimum burner for premixed flames which provides stable flame with maximum flame speed for the best burner geometry.

Keywords: Flame propagation, burner, premixed flame, mathematical modelling, flame speed, fuel-air mixture, flame stability

NOMENCLATURE

a	Area of cross-section of the tube
A	Area of the flame surface
D	Diameter of the burner
d	Diameter of the tube
k	Coefficient of thermal conductivity
l	Flame front thickness near the wall
L	Length of the burner
r	Burn rate
S_s	Flame speed i.e., velocity of flame wrt the tube (cm/s)
S_u	Unburnt gas velocity (cm/s)
T_b	Burnt gas temp in flame front thickness
T_u	Unburnt gas temperature
T_i	Intermediate gas temperature in flame front
T	Temperature
t	Time
x	Position of flame from burner
α	Inclination angle of the flame front
ρ	Density (kg/m^3)
ϕ	Air-fuel ratio
ω	Mole fraction
ξ	Length of burner to diameter (L/D) ratio

Subscripts

b	Burnt gas
F	Fuel
I	Intermediate
u	Unburnt

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1. INTRODUCTION

In premixed flames propagating with subsonic speeds, flame stability plays very vital role and a lot of work has already been carried by various investigators[1,2]. It is important to understand three parameters responsible for flame instability, i.e., diffusive thermal effects, body force, and hydrodynamic effect. Diffusive thermal effect is the result of heat versus mass diffusion when the Lewis number of the reactant is < 1. The effect of hydrodynamic and body forces occur due to density difference between upper and lower fluid layers in premixed flames. Hence, these effects become predominant while dealing with premixed flame propagation and its stability.

A number of methods have been worked out to study the flame stability, flame propagation and design of a suitable burner. The method suitable for a particular application in premixed flame study depends upon type of flame. Flame can be stationery (at the tip of burner) or non-stationery (flame traveling in a tube). The former method[3] employs burner of different shapes. Some examples of this method are flat flame burner, cylindrical burner and slot burner. The latter method for non-stationery flames involves various techniques for flame propagation study. Some examples of this method are tube method, constant-pressure bomb method, constant-volume bomb method, and double-flame kernel method. In the present work on non-stationery flames, open tube method is considered for investigation.

Because of the complex nature of the equations governing the burning velocity, various investigators have proposed different forms of empirical relations and mathematically derived equations. In the experimental work done, oxidiser is usually air, and fuels are hydrocarbon or hydrogen. Liquefied petroleum gas (LPG) is one of the fuels considered for combustion studies.

Flame speed (S_u) in the linear velocity of flame front normal to itself and relative to unburnt gas. Gouy's formula[4] is very useful to calculate the S_u for flame in a tube as

$$S_u = \frac{a}{A} S_s \tag{1}$$

S_s = Velocity of flame wrt tube

In the present study, since the flame is almost parabolic, hence,

$a/A = 0.4$

Henderson and Hill have shown that the calculations using the above equation may overestimate the flame speed due to oscillations. Hence, they have derived another expression for flame speed estimate as

$$S_u = \frac{\pi}{4} \frac{(d-2l)^2 \left(S_s - S_g\right) \left| a^2 - l^2 - 2al \right| / a^2}{A - l\left(d - \frac{1}{2}\right) / \sin\alpha} \tag{2}$$

where, S_g is the unburned gas mean velocity in tube as measured from growth of speed bubble.

Le Chatellier and Mallard have given a simple model by equating the heat release in the reaction zone with the heat absorbed by the gas in preheat zone and derived the following expression:

$$S_u = \left[\frac{k}{\rho_u \, \bar{c}_p (x_b - x_I)} \frac{(T_b - T_I)}{(T_I - T_u)} \right] \tag{3}$$

On introducing the rate of reaction in the above equation, one gets,

$$S_u = \left[\frac{k(d\omega/dt)}{e_u \bar{c}_p} \frac{(T_b - T_I)}{(T_I - T_u)} \right]^{1/2} \tag{4}$$

where $\dfrac{d\omega}{dt}$ is the reaction rate in terms of fractional conversion

Mishra and Rahman[5] have carried out experimental inflammability limits studies by filling a tube of 5.1 cm dia and 180 cm length with a gas mixture, and have distinguished various fuel-oxidiser mixtures on the basis of flammability.

A number of technical papers have been published on flame speeds, stability, and flammability limits, but, not much work has been done on finding the optimum conditions for flame, its stability, and burners dimensions.

Huang[4], *et al*. have measured the laminar flame propagation of primary reference fuels using digital particle image velocimetry (DPIV) and compared the data with the results obtained using simulation techniques by considering the detailed kinetic models over a range of equivalence ratios.

Marley and Robots[6] have used high speed chemiluminescence technique to measure the laminar flame speed experimentally using unconstrained spherical propane-air flames over a range of fuel-lean and fuel-rich equivalence ratios. They have also determined the nondimensional Markstein Number, *Ma*, which indicates the response of laminar burning velocity to flame stretch.

The present work lays emphasis on deriving an equation which can be used for optimisation of some important parameters involved in the study of premixed flames.

2. EXPERIMENTAL DETAILS

2.1 Materials

To carry out studies on premixed flame propagation, a test rig was designed and necessary components fabricated. The schematic diagram of the experimental test rig is shown in Fig. 1. Figure 2 shows the section of the test set-up depicting the flame propagation during the progress of the tests.

Liquefied petroleum gas is used as a fuel in the present study. It is mixed with air (which acts as an oxidiser) in the tube. The tube is made up of heat-resistant plastic material and is transparent to observe the flame traveling in it. The main components of the test set up are a blower, two rotameters used to measure the mass flow rates of air and fuel (LPG in this case), a heat-resistant plastic tube of 5 m length, various burners of different length-to-diameter ratio (L/D), an ignition system for generating spark of desired intensity for ignition of the mixture, and fuel-air supply lines with control valves. The specifications of various components used in this test rig are as follows:

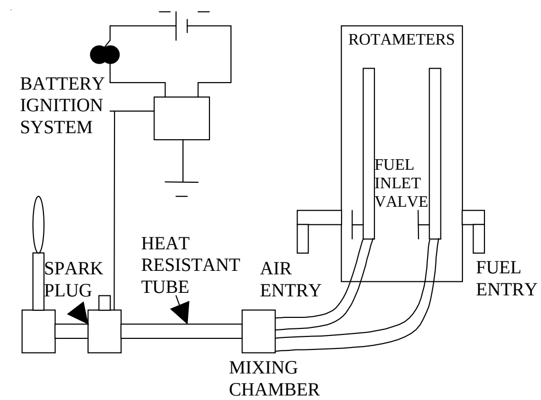

Figure 1. Schematic diagram of premixed flame test set-up.

Figure 2. Premixed flame traveling in the heat-resistant tube of the test rig.

- *Blower*: 115-230 V, 50 Hz, Speed-250 rpm, power requirement–12 W, amperage 0.62-0.31 A
- *Rotameters*: (a) air flow rotameter of dia 1.82 cm and length of tube 28 cm, SS-316 float. (b) fuel flow rotameters of length 30 cm and dia 1.51 cm, SS-316 float
- *Ignition system*: 3.0 V dc operated ignition system connected to Champion make spark plug with high tension wires
- *Burners*: Five steel burners of length–15.6 cm, 16 cm, 15 cm, 15.5 cm and 5 cm and dia–1.56 cm, 2.42 cm, 1.3 cm, 1.26 cm and 1.56 cm, respectively.

2.2 Method

The blower was switched on and air inlet valve was opened to allow a metered quantity of air to enter the tube.was established by igniter on the burner top by allowing the measured quantity of gas in the burner. Once the flame was stabilised for about 10 s at a measured air fuel ratio, both the air and gas valves were manually closed, and the ignition system button and stop watch were pressed simultaneously. A conical flame could be seen traveling in the transparent tube of known length. Time was again recorded when the flame disappeared. The same procedure was repeated at different air-fuel ratios and with burners of different L/D ratios (in the present case, five different burners were designed and used for recording the data).

The data obtained was used to calculate the flame speed (m/s) and air-fuel ratios under different flow and geometric conditions. Table 1 shows the sample calculations for one of the burners.

The rotameters fitted in the test set-up have been calibrated[6] for LPG and air and tables have been prepared to find the air and fuel flow rates in SI units.

3. EXPERIMENTAL RESULTS

This paper presents the experimental work carried out using LPG as the fuel and air as oxidiser for investigating the maximum flame speed and using five burners of different geometries.

It was observed that different burners gave different maximum speeds. Figure 3 shows the comparison of flame propagation at different air-fuel ratios using burners of different L/D ratios. The region lying within the dome of the plot shows the stable flammability regions.

4. CFD ANALYSIS AND DISCUSSION

Apart from the experimental study, a 2-D flow analysis of one of the burners (No. 5) has been carried out using computational fluid dynamics (CFD) technique. Some of the specifications/ details of the software package used for analysis are:

Software: ANSYS 8.0; Flow Analysis: CFD FLOTRAN; Flow type/option: Laminar; Element type selected: Fluid 141, 2-D Element.

It was found that the theoretical velocity of the gas obtained from this CFD analysis at the centre of the tube is 1.269 m/s. Figure 4 shows the velocity contours of gaseous flow in the tube and Fig. 5 shows a close up view of the velocity contours at the inlet section of the tube.

5. MATHEMATICAL MODELLING

Using the mathematical modelling techniques, a general equation of optimisation of the flow and geometrical condition in laminar flame propagation can be derived as given below.

Table 1. Sample observations and calculations for L/D=3.20 (Burner No. 5)

Rotameter reading (cm)		Length of flame travel (m)	Time of flame travel (m)	Fuel flow rate, x 10^{-3} (m^3/s)	Air flow rate, x 10^{-3} (m^3/s)	Volumetric air fuel ratio	Air fuel ratio (mass basis)	Flame speed (=L/t) (m/s)	Burning velocity (=0.4xF) (m/s)
Fuel	Air	L	t	V_f	V_a	$(A/F)_{vol}$	A/F	F	S_u
5.0	24	4.5	13.69	0.0300	0.46	15.333	10.12	0.329	0.131
4.5	24	4.5	11.99	0.0287	0.46	16.027	10.578	0.375	0.150
4.0	24	4.5	8.89	0.0268	0.46	17.164	11.328	0.506	0.202
3.5	24	4.5	6.58	0.0250	0.46	18.400	12.144	0.684	0.274
3.0	24	4.5	5.27	0.0233	0.46	19.742	13.030	0.854	0.342
2.5	24	4.5	4.67	0.0212	0.46	21.698	14.320	0.964	0.385
2.0	24	4.5	4.37	0.0190	0.46	24.210	15.979	1.030	0.412
1.7	24	4.5	4.82	0.0183	0.46	25.136	16.590	0.934	0.373
1.4	24	4.5	5.31	0.0173	0.46	26.589	17.549	0.847	0.339

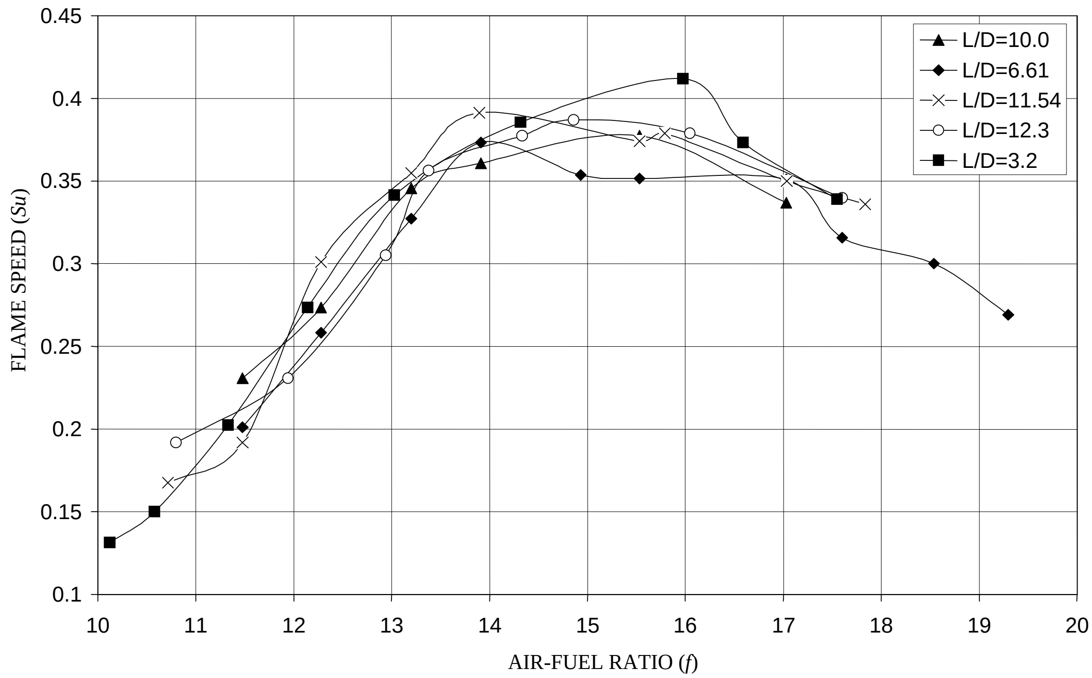

Figure 3. Variation of flame speeds with air-fuel ratio and different L/D ratios.

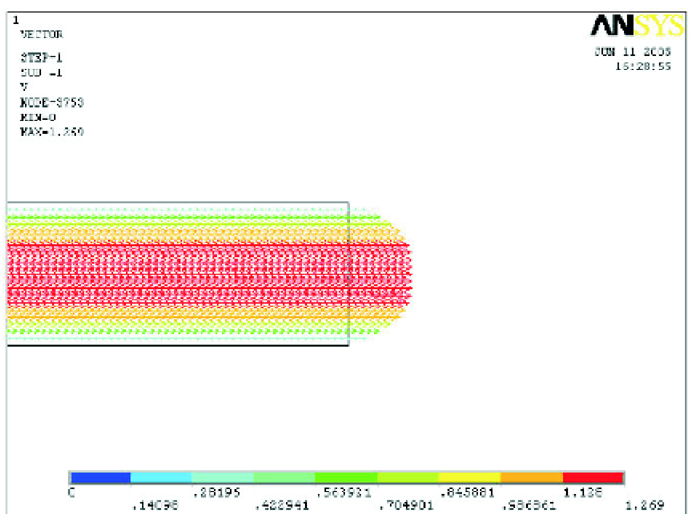

Figure 4. Velocity vectors for the mixture.

The flame speed can be expressed by an equation of the form,

$$S_u = a + b\Phi + c\Phi^2$$

This equation can be expanded for different air-fuel ratios and for different burners, for example,

$$S_u = a_1 + b_1\Phi + c_1\Phi^2 \quad \text{at } \xi = 10 \qquad (5)$$

Similarly, various equation can be given for other values of ξ, namely, ξ = 11.5, 12.3, 6.6, and 3.2.

Using the experimental results obtained above and making the use of the curve fitting techniques[7], the flame speed can be expressed as,

$$S_u = -0.0116\ \Phi^2 + 0.3496\ \Phi - 2.2648 \qquad (6)$$

Now the coefficients of these equations can be expressed in terms of second-degree equations as given below:

$$a = A_0 + A_1\xi + A_2\xi^2 \qquad \text{or,}$$

$$-2.2648 = A_0 + A_1 (10) + A_2(10)^2 \qquad (7)$$

On solving these algebraic equations for A_0, A_1, and A_2, one gets,

$$a = 19.3992 - 4.0652\xi + 0.18988\xi^2 \qquad (8)$$

Similarly, one can solve the equations for other coefficients.

Combining the above equations, one gets,

$$S_u = [(19.3992–4.0652\xi+0.18988\xi^2)$$

$$+ (–2.7297–0.57903\xi–0.02711\xi^2)\Phi$$

$$+(0.0915886–0.01948\xi+0.0009167\xi^2)\Phi^2] \qquad (9)$$

This is the desired equation which relates the flame speed (S_u) to oxidiser-fuel ratio (f) and burner geometry (ξ) in premixed flame propagation.

The present study can be used as a guideline for the designers of flame burners to come across various designs which will give various flame speeds at various air-fuel ratios. Figure 6 shows the various

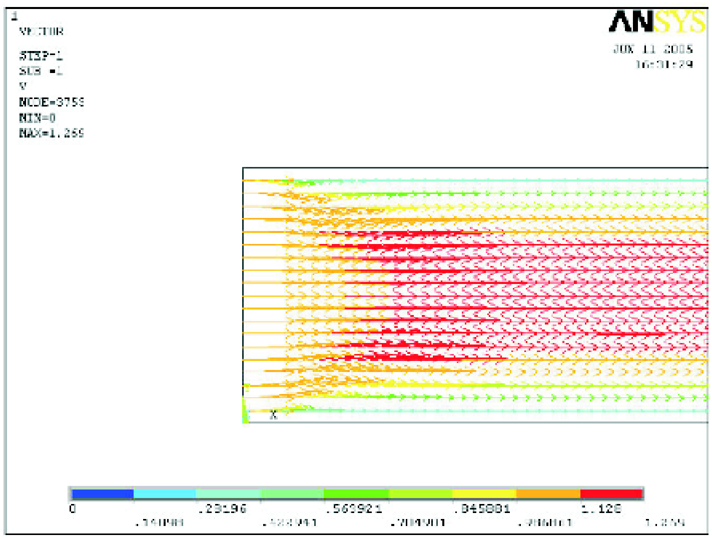

Figure 5. Velocity vectors at inlet of the duct.

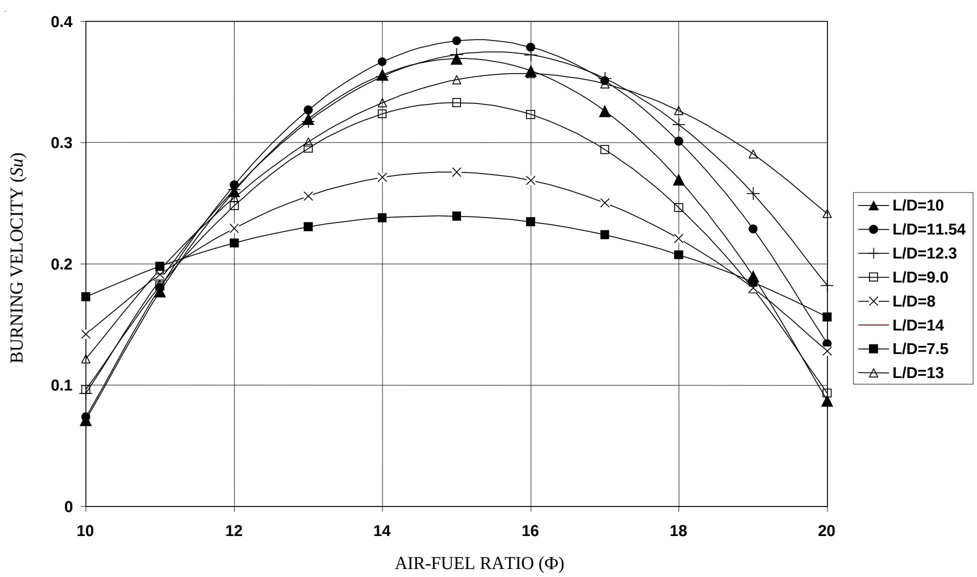

Figure 6. Design plot for various burner geometries.

plots obtained using Eqn (7) which can be used directly for optimised design of the burner. As the solution of the mathematical equations become complex, hence, only limited data has been taken in the present case.Using more data points, the results can be further refined and the equation can be derived with better accuracy.

6. CONCLUSIONS

The following conclusions have been drawn:

- An experimental investigation has been carried out here under different flow and burner geometrical conditions using LPG as fuel and air as oxidiser and the data has been plotted to find flame speeds for premixed flame propagation.
- Using the experimental results obtained, a generalised equation has been derived to find the flame speeds under different burner geometries and oxidiser-fuel ratios. Mathematical techniques can be used to find the maximum flame speed for a burner geometry and oxidiser-fuel ratio.
- Studies carried out using the CFD solver gives the flow field in the flame tube. It can be further refined under different conditions of air-fuel ratios for different fuels.
- The experimental set-up can be stretched to conduct tests on different gaseous fuels and plots can be prepared to compare different burners on different fuels. In this way, the optimisation of flame propagation can be further refined.
- This experimental set-up can also be used for flash backback and blow out conditions of flame for different fuels and burners.

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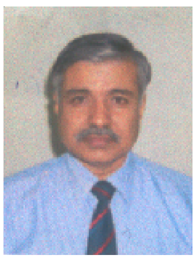

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