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EFFECT OF MIXTURE CONSTITUENTS ON THE LAMINAR BURNING VELOCITY OF LPG-CO_2-AIR MIXTURES

Ajay Tripathi[1], H. Chandra[2] and M. Agrawal[3]
[1]Indian Institute of Technology Kanpur, Kanpur, U. P., India
[2]Bhilai Institute of Technology Raipur, C. G., India
[3]Institute of Professional Studies, Gwalior, India
E-Mail: trip2ajay@indiatimes.com

ABSTRACT

One of the most attractive applications of liquefied petroleum gas (LPG) is its use in IC engines, particularly for automotive applications, as it is known to be a clean source of energy. Even though it is already being used in IC engines, the fundamental combustion properties such as laminar burning velocities, which is a physicochemical property of a fuel, is still not very well established, which can act as a basic input for engine modeling. The present work utilizes a few standard methods of flame speed measurement known from the literature to obtain the flame speed of LPG-air and LPG-air-diluent mixtures as a function of air-fuel ratio and diluent concentration. Variation of burning velocity obtained by two different experimental techniques, that is, orifice burner and cylindrical tube method for a mixture of LPG-air and diluent mixtures at different air fuel ratios is quantified. CO_2 is selected as a diluent to account for the presence of exhaust gases in the fresh charge as a consequence of exhaust gas recirculation. It was found that there is effect on burning velocity with the variation of effects of diluents on the burning velocities have been found to cause performance problems for combustion appliances using these types of fuel gases.

Keywords: engine, LPG, burning velocity, LPG-air mixture, diluent, burner, flame tube.

1. INTRODUCTION

LPG is widely used in IC engines yet its fundamental combustion properties such as laminar burning velocity is still not very well established, which can act as a basic input for engine modeling. One of the most important intrinsic properties of any combustible mixture is its laminar burning velocity. It depends on the mixture composition, temperature and pressure. It is measurable characteristic of the mixture. It is important in all kinds of combustion-based systems. For instant, in the design of burners and combustion chamber of gas turbine, the flame speed must equal to the mixture flow velocity for a stable flame to be obtained.

Three combustion velocities, that is, laminar burning velocity, spatial velocity of flame front and unburnt gas velocity are generally defined in any combustion system. Laminar burning velocity is defined as the velocity of the combustion wave normal to itself and relative to the unburnt gas. It is defined as volume of unburnt gas consumed per unit time divided by the area of the flame front in which that volume is consumed in a laminar premixed combustion process. In an engine, the burning velocity is usually higher than the corresponding laminar burning velocity due to presence of turbulence, which can be considered with the scale and intensity of turbulence. Lewis and Elbe [1] suggested that the laminar burning velocity, ignition delay and engine knock are correlated.

A fairly large number of workers have been engaged in this field for the last decades. Fells and Rutherford [2] used Schlieren method to determine the laminar burning velocity of methane-air mixture, with and without diluents. He used both sharp edged orifice and bell shaped nozzle and compared the result of two types of burners. Gorden and Heimel [3] determined the flame speed of methane-air, propane-air, and ethylene-air mixtures at low initial temperatures. They used shadowgraph method for nozzle type burner. Fine [4] determined stability limit and burning velocities of hydrogen air flames at reduced pressure. From the above survey, it was found that various kinds of burners have been tried like circular tube, shaped nozzle, orifice and rectangular slot type. It was found that in circular tube and rectangular slot type, the unburnt gas velocity profile is parabolic, while orifice burners yield essentially uniform velocity profiles and straight-sided flame cones. Kanitkar *et al.*, [5] determined experimentally the flame speed, temperature and limits of flame propagation for producer gas-air mixture. They used flame tube method with its one end opened for exhaust gas removal and other end closed after filling the tube with required air fuel mixture. The method used by Coward and Hartwell [6] consists of law of cylindrical tube closed at one end and filled with the gas mixture under test.

The present paper analyses the laminar burning velocity of LPG-air and LPG-air and diluent mixture using the burner method. Flame arrestor, orifice burner and its assembly were designed for analyzing the laminar burning velocity. Various results for laminar burning velocity of LPG-air and LPG, air and CO_2 mixtures were obtained at atmospheric pressure using burner method and results were compared with the standard available data for methane, ethane and propane.

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2. EXPERIMENTAL SET UP AND PROCEDURE

2.1 Orifice burner

A schematic diagram of the experimental set up is shown in Figure-1. The constituent parts of the experimental setup used to measure the laminar burning velocity of fuel air mixture at atmospheric pressure and temperature are flame arrestor, burner assembly, gas metering system, Schlieren photography system and mixing chamber.

2.2 Flame arrestor

Flame arrestor was designed to trap the flame to avoid the explosion of premixed air-LPG mixture. It was essential that the trap should not introduce an excessive resistance to the flow. It consists of an arrangement of circular fine meshes of different sizes, that is, of 60, 80 and 40 mesh, placed at two positions at 100 mm distance enclosed in a stainless steel apparatus as shown in Figure-2. The diameter of enclosure is 25.4 mm. The flame got trapped due to achieving its quenching distance. The critical distance of a circular tube, where a flame extinguishes rather than propagates is referred to as the quenching distance. Before fixing the flame arrestor to the setup, it was thoroughly tested in the flame arrestor testing unit.

2.3 Burner assembly

The burner assembly contains orifice plates with three different orifice diameters of 12.5 mm, 15 mm and 17.5 mm. These different plates were used according to the flow rate of the mixture. It constitutes stainless steel tube of 67.5 mm diameter through which fuel and air mixture was passing. For cooling the burner close to orifice where, flame cone was forming, outer brass covering of 115 mm diameter and 76 mm length was provided.

2.4 Gas metering system

In order to measure the flow rate of air, fuel and diluents, rotameters were used of different flow rates. Air rotameter was of 0-20 liters per minute (lpm), with 0.2 lpm least count, while fuel rotameter was of size ranging from 0-1 lpm with 0.05 lpm least count. All rotameters were calibrated before using by water displacement method. The calibration curves for air, CO_2, LPG and methane were drawn after rechecking the readings.

2.5 Schlieren photography system

The Schlieren apparatus is an optical device, which enables to observe the intensity of illumination. This system consists of light source assembly with condenser lens, two concave mirrors, one plane mirror and screen for obtaining the images.

The image of the filament of the electric bulb is collimated by a slit located at the focus of the first mirror, thus producing a parallel beam of light, which passes through the working section and falls on the second mirror. The light after falling on the second mirror passed through a knife-edge. The knife-edge was used to reduce the intensity of light falling on the second mirror.

2.6 Mixing tube

It was made up of long copper pipe of 55 mm diameter. It has one inlet for the supply of fuel along the length and four inlets for the air along tangential direction. This tube is used for proper mixing of air and fuel in the chamber. The mixing tube had the arrangement for vortex breaking resulting in breaking of air jets, which are passing in tangential direction, which leads to proper mixing of air and fuel.

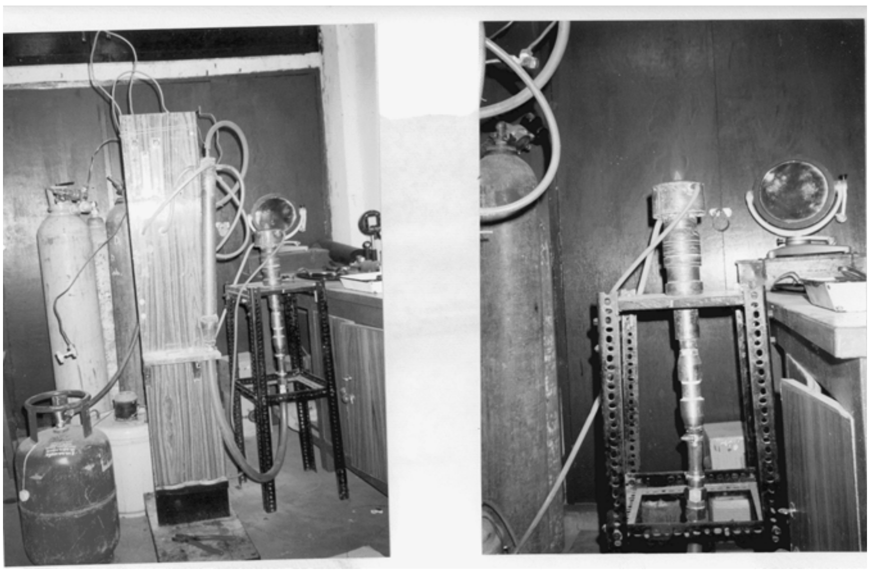

Figure-1. Experimental set up.

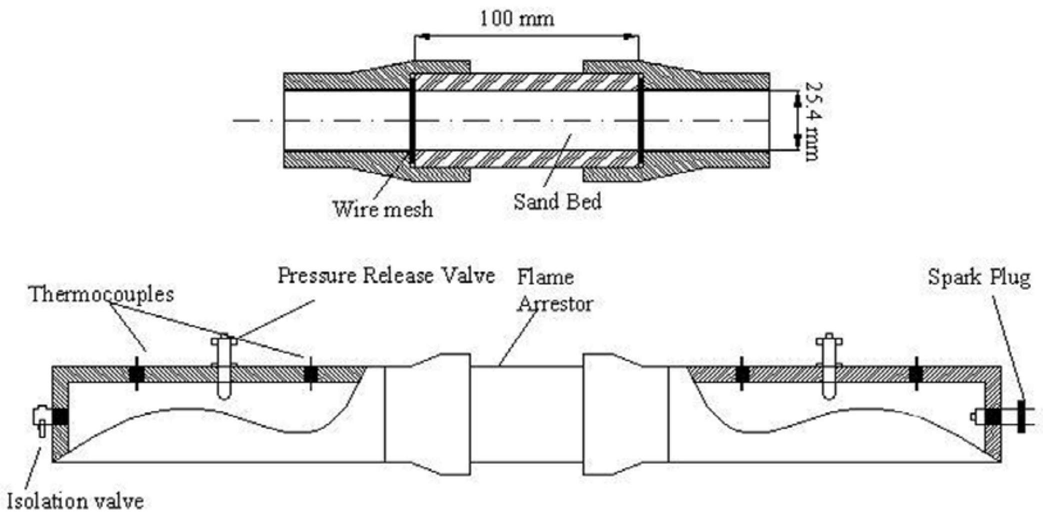

Figure-2. Flame arrestor.

3. EXPERIMENTAL METHODOLOGY

3.1 Calibration of rotameters

The flow rates of fuel, air and diluents were measured with the help of different ranges of rotameters. It was necessary to calibrate rotameter properly because the rotameters, which are available in the market, are calibrated only for air. For using the same rotameter for fuel and diluents, it was necessary to calibrate for the same, which was done with the help of water displacement method.

3.2 Measurements of burning velocity

3.2.1 Orifice burner method

For burning velocity measurements of pure fuel-air mixture, fuel and air were made to flow through the system at pre-determined rates, which were adjusted, with the help of flow regulating valves attached with rotameters. From the mixing chamber the fuel air mixture was passing through the orifice burner, where the flame stabilizes. In the burning velocity measurement in presence of diluents, the procedure was similar however in addition to fuels, the diluents too was made to flow at the desired rate in to the mixing chamber through a separate rotameter. The Schlieren system, with its entire component positioned and adjusted properly, was then used to take the photograph of the flame. A large number of readings with different mixture composition within the stability limits as well as with different flow rates of the mixtures within the laminar range are taken. Before conducting the experiments with LPG-air mixture, it was necessary to check the authenticity of the results, which was done by determining the burning velocity of methane-air mixture with the setup, whose data is already available in the literature.

3.2.2 Flame tube method

This setup was used as explained by Coward and Hartnell [6]. This method comes under the category of constant pressure methods. It consists of a long cylindrical tube containing fuel-air mixture. It is provided with two stainless steel electrodes at one end and a gap of approximately 3 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. Provision for unburnt gas velocity is made at the other end, by providing two small openings for flexible tube to measure velocity. These two small openings were at one-meter distance and two photo sensors were provided to sense the flame passing through these two openings. These sensors are connected to electronic circuit, designed for the purpose, which times the interval between them. This circuit was such that as the flame reached the first photo sensor, its time counter started, counting the time in seconds and as the flame reached the second sensor, its time counter stopped, thus counting the time. Thus, the burning velocity is obtained, as the distance is already known between two sensors. The least count of the electronic equipment was 0.001 seconds. Measurement of this uniform velocity, S_l together with the area air of a flame front yields an average burning velocity by the following equation,

$$S_l = S_S \pi R^2/A_f \quad (1)$$

After the provision of small hole at the end of the tube towards which flame travels, and a larger one on the other end, the equation becomes

$$S_l = (S_S - S_{ug}) \pi R^2/A_f \quad (2)$$

The equivalence ratio used here is defined as

$$\phi = (\text{fuel/air})_{actual} / (\text{fuel/air})_{stoic} \quad (3)$$

4. RESULTS AND DISCUSSIONS

4.1 Laminar burning velocity of methane

From methane air-mixture it was found maximum burning velocity obtained was 42 cm/s, while theoretically (Fells and Rutherford A.G, 1969) it was 40 cm/s. Hence, it can be shown that the results obtained for LPG-air mixtures with and without diluent are reliable. Burning velocity curve for methane is shown in Figure-3.

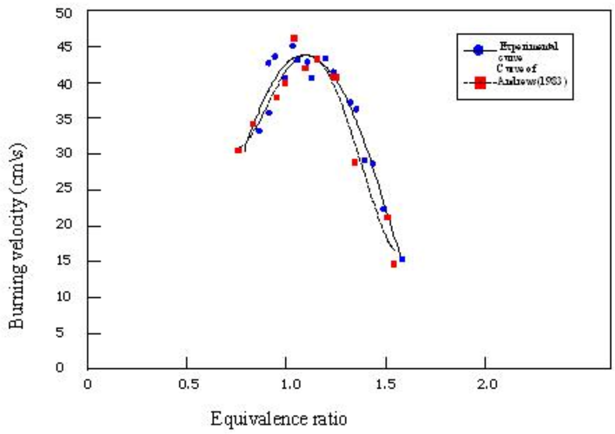

Figure-3. Laminar burning velocity of methane.

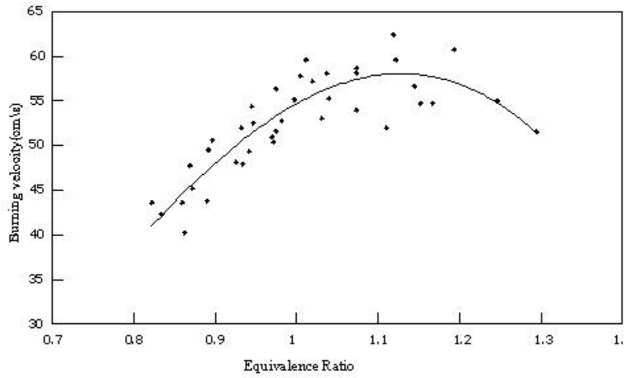

Figure-4. Burning velocity of LPG-air-methane.

4.2 Laminar burning velocities of LPG-air mixtures

All the data for LPG-air mixtures have been obtained for measurement taken on flame stabilization on orifice burner. The maximum burning velocity of LPG-air mixture is found to be 57.5 cm/s, which occurs at ϕ =1.2. Burning velocity curve is shown in Figure-4.

4.3 Effect of diluent on burning velocity

Figure-5 represents burning velocity against equivalence ratio of LPG-air mixture with different levels of dilution by CO_2, whose effect is to reduce the burning velocity at every mixture composition. The reduction is obviously greater at higher level of dilution. From the Figure, it was found that for 20 % CO_2 in fuel, the maximum burning velocity reduces to 50 cm/s, which occurred at ϕ = 1.25. For 30 % CO_2 in fuel, the maximum burning velocity reduce to 47 cm/s, which occurred at ϕ = 1.29. Similar trends are visible from the Figure.

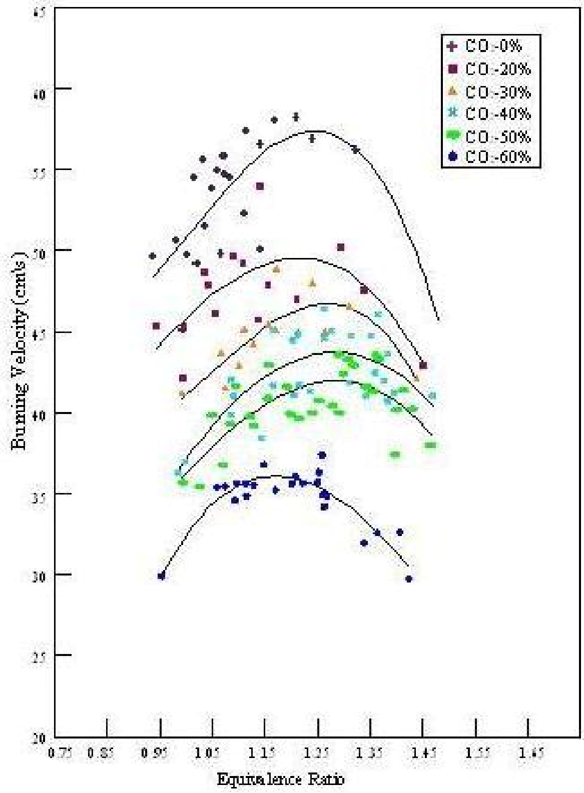

Figure-5. Burning velocities of LPG-CO2-air mixtures.

4.4 Influence of mixture composition

Figure-4 shows plot of burning velocities of LPG-air mixture against per cent fuel in the fuel-air mixture, which gives direct information about the influence of mixture composition on burning velocities. The leanest mixture for which suitable flame could be obtained on the orifice plate burner was 2.75 per cent fuel in the mixture. As the percentage of LPG is increased the burning velocity is increased reaches to the maximum value of 57.5 cm/s at 4.8 per cent LPG. The stoichiometric percent for LPG was 4.2 per cent.

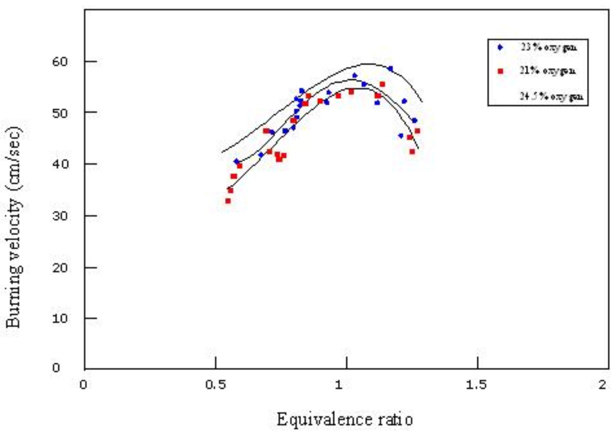

Figure-6. Variation of burning velocity with air.

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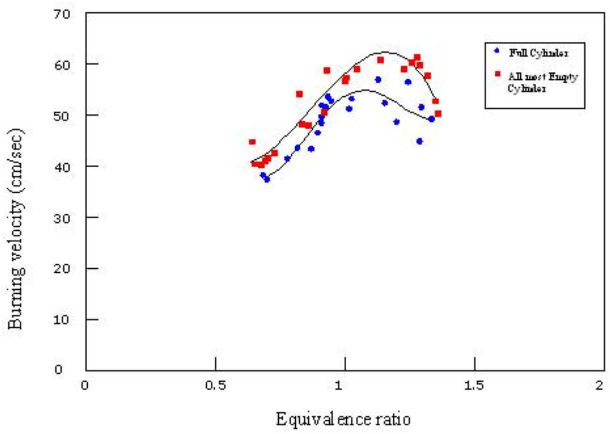

Figure-7. Variation of burning velocity with volume of LPG inside cylinder.

4.5 Experimental uncertainty

Uncertainty analysis of burning velocity measurement was done using following equation

$$U_{sl} = [(\partial S_l/\partial \alpha)^2 + (\partial S_l/\partial d)^2 + (\partial S_l/\partial V_f)^2 + (\partial S_l/\partial V_a)^2]^{1/2} \quad (4)$$

Where,

$$\partial S_l = S_{ug} \, \text{Sin}\alpha \quad (5)$$

$$= [\frac{V_f + V_a}{A}] \, \text{Sin}\alpha \quad (6)$$

Where A= Area of the burner i.e. $\pi d^2/4$

$$\partial S_l/\partial \alpha = [\frac{V_f + V_a}{A}] \, \text{Cos}\alpha \quad (7)$$

$$\partial S_l/\partial d = [\frac{V_f + V_a}{A}] \, \text{Sin}\alpha \quad (8)$$

$$\partial S_l/\partial V_f = \partial S_l/\partial V_a = \text{Sin}\alpha/A \quad (9)$$

$$U_{sl}\,\% = U_{sl} \times 100/ S_l \quad (10)$$

For maximum burning velocity i.e. 62.44 cm/sec

$U_{sl}\,\% = 2.213 \times 100/62.44 = 3.54\%$

For minimum burning velocity i.e. 40.154 cm/sec

$U_{sl}\,\% = 1.0722 \times 100/40.154 = 2.67\%$

Mean Uncertainty measurement

(3.54+2.67)/2 = 3.105%

Uncertainty in equivalent ratio (ø)

$$\text{Equivalent ratio } (\text{ø}) = \frac{(air/fuel)_{stoic}}{(air/fuel)_{act}} \quad (11)$$

$$U_{ø} = ((\partial ø/\partial air_{act})^2 + (\partial ø/\partial fuel_{act})^2))^{1/2} \quad (12)$$

For burning velocity of 62.44 cm/sec and LPG composition of

C_2H_6 = 4.1%, C_3H_8 = 39.9, CH_4= 1.9%, C_4H_{10} = 44.98%, C_5H_{12} = 9.12%

Percentage Uncertainty = 0.078x100/1.11= 7.02%

5. CONCLUSIONS

The main conclusions of the present research study are as follows:

a) The measurement of burning velocity by the use of flame tube method is suitable, especially when the mixture is either too lean or too rich to form the cone over the burner;
b) LPG is slow burning fuel giving maximum burning velocity of 57.5 cm/s;
c) Mixture composition of LPG was not same before and after the experiment because when the cylinder was full, the gases having lighter molecular weight will come out, like methane and ethane, but after doing the experiment per cent of methane and ethane reduces and the concentration of other higher gases like propane and butane increases;
d) Laminar burning velocity obtained by full LPG cylinder and almost empty cylinder was not same because of change in the composition of LPG and also it changes with the oxygen per cent in the air. As the oxygen percent in the air increases burning velocity also increases; and
e) As the percentage of CO2 in the mixture goes on increasing from 0 to 60%, there is continuous decrease in maximum burning velocity, which is nearly 57.5 cm/s at 0% and 35.5 cm/s at 60%. The point of maximum velocity was shifting towards stoichiometric ratio as the percentage of CO2 goes on increasing.

Notations

S_l: laminar burning velocity (cm/s)
S_S: spatial burning velocity (cm/s)
R: radius of orifice burner (cm)
A_f: area of the flame front (cm^2)
S_{ug}: velocity of unburned gases (cm/s)
φ : Correspondence ratio
U_{sl}: Uncertainty in burning velocity
Uø: Uncertainty in equivalence ratio

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