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Research Article

Experimental Investigation of Flame Speed of Gasoline Fuel-Air Mixture

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Abstract

Flame speed is an important aspect of fuel combustion characteristics. It affects combustion system design and performance. In this study, a laboratory experimental rig has been built to investigate the effect of equivalence ratio of gasoline-air mixture in a centrally ignited constant volume combustion chamber on flame speed at an initial pressure of 1bar and an initial temperature of 483 K using high speed flame photography technique. The results of the outwardly expanding spherical flame showed that the flame speed depends on both equivalence ratio and flame radius. It decreases slightly with the increase of flame radius and increases with the equivalence ratio until slightly larger than stiochiometric and then decreases. The flame speed reached 1.45 m/s at Φ= 0.8, (1.6) m/s at Φ= 1 and 1.27 m/s at Φ= 1.5

Keywords: *Flame speed, gasoline fuel, spherical Flame, high speed photography*

Nomenclature

Sn-Stretched Laminar Flame Speed (m/s)
R-Specific Gas Constant (J/kg.K)
T-Temperature (K)
ρ -Density (kg/m3)
(c.c)f Volume of fuel in cubic centimeter
P-Pressure (bar)
V-Volume (m3)
m_a, m_f-Mass of air and mass of fuel
ϕ-Equivalence Ratio

1. Introduction

The main purpose from the combustion studies is the acquisition of a thorough knowledge of the all mechanisms of processes of ignition, distribution of the species, propagation of the flame and release of energy of the combustion mixtures. All practical importance of such knowledge is evidently the control of the combustion operation from the point of view of safety and its utilization as a source of energy.

The most relevant definition of flame is visible chemical component undergoing highly exothermic chemical reaction takes place in a small zone with the evolution of heat. The flame speed is the measured rate of expansion of the flame front in a combustion reaction [Taylor *et al* ,1991]. Flame may also be defined as luminous zone of the rapid exothermic reaction in the combustion process beside the formation of heat energy and light. A non-luminous region can be observed just after the flame where the temperature is slightly reduced. One caught add that the reaction is localized, that light is usually produced and that the reactants need not be gases (although they are in most cases).

The measuring of flame speed needs a special technique for detection of flame front arrival along a certain space, therefore many investigators worked hard to find out the different techniques of measuring flame speed.

[Dugger,1952] used optical techniques. The photograph of this method needs that the screen should be close to the flame front. Any increase in distance between the screen and the flame front will increase the separation between the light and dark areas and will be difficult to interpret the image. Reference [Botha and Spalding ,1954] extended the flat flame method to measure higher flame speed by using a water-cooled porous disk. The cooling effect induces heat loss from the flame and stabilizes the flame closer to the disk. The tests are repeated at different cooling rates so that the values of flame speed S_L can be plotted against the cooling rates. To obtain the adiabatic flame speed S_L, extrapolation of the curve of S_L versus cooling rate back to zero cooling rate is performed. Some uncertainty is associated with this method including the unknown loss of radical species such as H to the porous plate. Reference [Gulder (1983); Gulder,1984] used ionized probe technique since combustion operation is a fast chemical reaction. This

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phenomenon happens because of the ionization of reaction atoms. Therefore the level of ionization is very high at the flame front. This technique cannot give the real position of the flame front because the ionization levels stay high behind the flame front.

[Odger, Kretschmer and Halpin ,1985] used thermocouple technique. The main feature of this technique is that it allows the flame for propagating inside the combustion chamber and for passing over many thermocouple junctions located inside the chamber. The flame temperature is greater than that of the burned and unburned gas, so that, the thermocouple can be used as a sensor probe for this phenomenon. Reference [Zhao *et al* ,2003] measured flame speed for gaseous fuels, propane/air and dimethyl ether/air mixtures . A preheating method was used to vaporize liquid fuels of n-heptane/air and n-decane/air mixture to elevated temperatures prior to measurements. Measurements were also performed on the gasoline surrogate fuel consisting of n-heptane and iso- octane mixture at 500 C. The laminar flame speed of the surrogate fuel was compared to actual gasoline and primary reference fuel (PRF) model. The adiabatic flat flame method was further extended to measure the laminar flame speed of ethane, propane, n-butane and isobutene by [Bosschaart and De Goey ,2004]. Reference [Jerzembeck, *et al* ,2009] carried out a research on spherical flames of *n*-heptane, iso-octane and gasoline/air mixtures to determine flame speed under engine-relevant conditions by using the constant volume bomb method. Data were obtained for an initial temperature of 373 K, equivalence ratios varying from 0.7 to 1.2, and initial pressures from 10 to 25 bars. To track the flame front in the vessel a dark field He–Ne laser Schlieren measurement technique and digital image processing were used. The laminar burning velocities were obtained through a linear extrapolation to zero stretch. Reference [Van Maaren, *et al* ,1994] utilized the flat flame method to measure the adiabatic flame speed of methane/air mixtures and good agreement was achieved when compared to the literature. The adiabatic flame speed is determined and based on the measurement of the burner plate temperature profile. The uniform plate temperature profile indicates zero net heat loss of flame and hence the adiabatic flame speed is obtained.

[Vagelopoulos *et al* , 1998] measured the unstretched laminar flame speed of methane/air, ethane, propane/air for a wide range of equivalence ratio. The laminar flame speed values were found to be systematically lower than the values that have been determined by using the traditional stagnation flow technique and linear extrapolations to zero strain rate. The flame speed was directly determined when the planar flame undergoes transition from positive to negative stretch region, during which the flame undergoes a near-zero strain rate condition. The minimum velocity at this near-zero stretch state was regarded as true laminar flame speed.

In this work an experimental rig, as shown in figure (1 a,b), is built and flame propagation is analyzed.

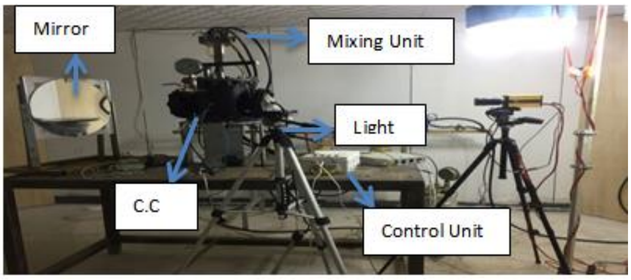

Fig.1 a- Photograph of Experimental Rig

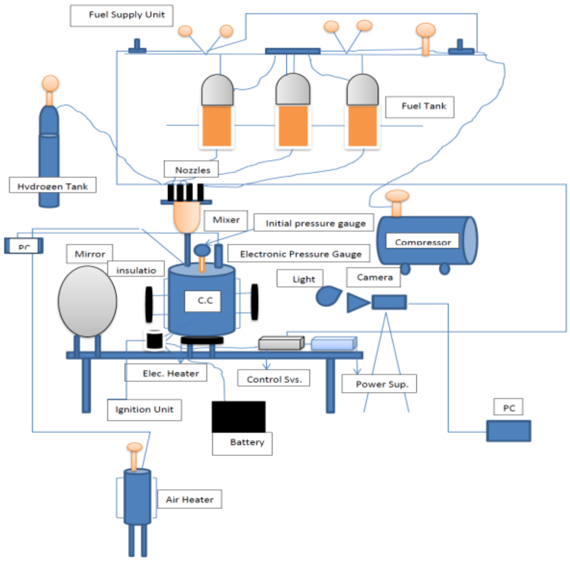

Fig.1 b- Schematic Diagram of Experimental Rig

2. Experimental Rig Setup

Constant volume combustion chamber method and Shelerian technique is used to measure a flame speed. A new experimental facility is designed .It consists of many units includes fuel supply unit, injection unit, mixture preparing unit, constant volume combustion chamber unit, heating unit, ignition circuit and control unit, Capturing unit.

A. Fuel Supply Unit

Fuel can be supplied by air pressure about 2 bars .This unit illustrated as shown in Fig. (2).

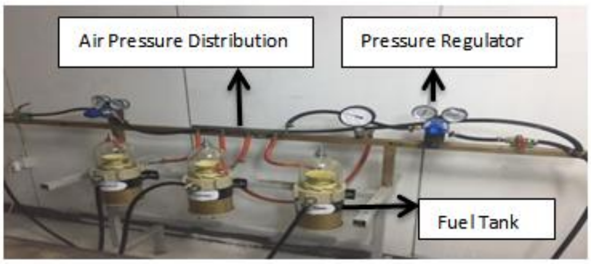

Fig.2 Fuel Supply Unit

It consists of compressor, pressure regulator, Borden gauge, air pressure distribution and fuel storage tank.

B. Injection Unit

This unit consists of electrical injector depend on pulse width (PW). This injector work to inject liquid fuel according to the calculated value in computer program after procedure calibration for the injector and for fuel used.

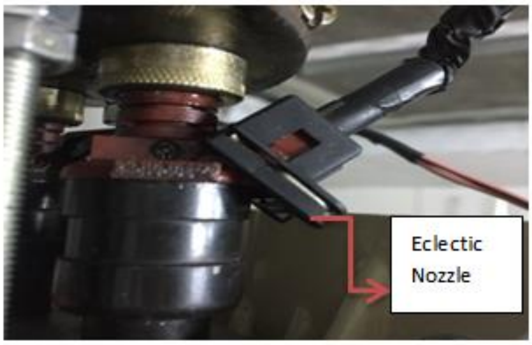

Fig.3 Injection Unit

C. Mixture Preparing Unit

To prepare the liquid fuel-air mixture, a mixing tank (mixer) has been designed and constructed for fuel. The purpose of using the mixer is to obtain a homogeneous mixture. This unit includes mixer with capacity of 700 milliliters and this equivalent to (1/10) from the volume of combustion chamber. Outer diameter of the mixer is 85 mm, thickness (2.5 mm), length (110 mm) as shown in figure (4).

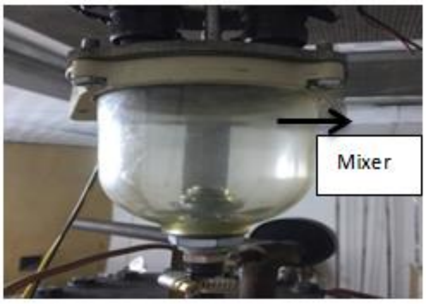

Fig.4 Mixer

D. Constant Volume Combustion Chamber

A cylindrical chamber with (190mm) inner diameter, (250mm) height, (10 mm) wall thickness and a volume of (7.2 L) .It also has two (20 mm) thick upper and lower flanges with a diameter of (300 mm), made of iron to resist the high pressure and temperature that result from the combustion. The cylinder is provided with centrally electrodes connected to the ignition system.

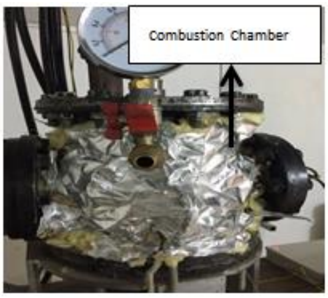

Fig. 5 Combustion Chamber

This unit consists of pressure gauge to measure pressure of combustion, safety valve, gasket and vacuum pump.

E. Heating Unit

This unit includes combustion chamber heating that include electrical heater ART.NO.ES.1520 with 220 V-240 V, 50-60 HZ, 1500 W subjected at the bottom of combustion chamber to heat all surrounding of chamber that it is insulated to maintain the chamber heated. Inlet air heating (COOPERHEAT), type VTP 230 -240 V, power of 30 W /m, 15 m that it coil around the cylindrical tube of air (outer diameter = 45cm , length =37 cm , and thickness =6mm) made from stainless steel another source of heating used to heat air that it is input to the mixer as shown in figure 6.

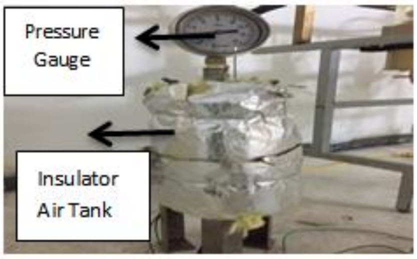

Fig.6 Air heating

F. Ignition System and Control Unit

Two opposed, co-linear electrodes that form a spark gap in the center of the CC. ignite the mixture. Control system is used to control the injected amount of fuel that calculated depend on equivalence ratio.

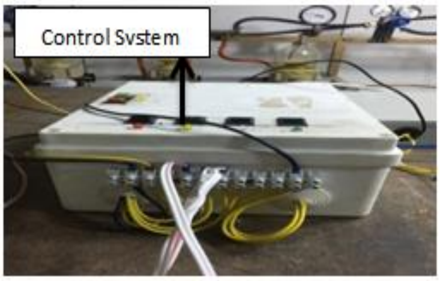

Fig. 7 Control Unit

G. Capturing Unit

An optical system is used to visualize the flame and flame propagation process with AOS - Q-PRI portable high-speed camera, the ultra-high image resolution of (3 Mega Pixel), (1.3 GB) internal memory and (16,000 FPS) is used to measure the flame propagation. The setting used in the experiment is (576*500 pixels) for (4000 FPS), the total time of recording is (1.2 sec).A 10% of the time is set as pre-triggering to ensure that all the process is recorded when the triggers, the ignition unit, and the camera, are switched on. A light source and concave mirror are used as shown in figure 8.

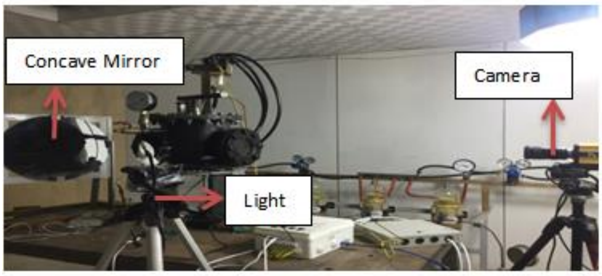

Fig.8 Capturing Unit

3. Experimental Procedure

Flame speed is measured after calculating the amount of fuel that injected by injector to the mixture preparing unit according to equivalence ratios. Heated air is prepared from air heater with temperature reached to 230C. This temperature is greater than saturation temperature and boiling temperature of fuel to vapor fuel and prevent condensation and maintain all fuel vapored. Also, combustion chamber is heated to maintain same fuel conditions. Both combustion chamber and air heater is insulated to prevent heat transfer. Combustion chamber is vacuumed after any testing to remove any previous products from combustion process. Mixture is then ignited by ignition system and then capturing the flame propagation by using capturing unit.

$$C_8 H_{18} + a(O_2 + 3.76\, N_2) \rightarrow 8CO_2 + 9H_2O + 3.76\, a\, N_2$$

$$a = \frac{8+(^{18}/_{4})}{\emptyset} \quad (1)$$

$\emptyset = 1$ $(Stoichoimetric\ \ Combustion)$
a = 12.5 ,$P_i = 1\ bar$

$$\left(\frac{m_a}{m_f}\right)_s = \frac{N_a * mw_a}{N_f * mw_f} = \frac{4.76*12.5*28.8}{1*114} = 15.0316 \quad (2)$$

$$m_a = \frac{PV}{RT} = \frac{101.325*0.00707}{0.287*493} = \frac{0.717381}{141.491} = 0.00507\ Kg \quad (3)$$

$$m_f = \frac{0.00507}{15.0316} = 0.00033729\ kg$$

$$c.c_f = \frac{m_f}{\rho_f} = \frac{0.00033729}{719.7} * \ 10^6 = 0.4686\ c.c \quad (4)$$

$\emptyset = 0.8$ $(Lean\ mixture)$

$$\left(\frac{m_a}{m_f}\right)_{act.} = \frac{\left(\frac{m_a}{m_f}\right)_s}{\emptyset} = \frac{15.0316}{0.8} = 18.7895 \quad (5)$$

$$m_f = \frac{0.00507}{18.7895} = 0.00026983\ kg$$

$$c.c_f = \frac{m_f}{\rho_f} = \frac{0.00026983}{719.7} * \ 10^6 = 0.374922\ c.c$$

$\emptyset = 1.5$ $(Rich\ mixture)$

$$\left(\frac{m_a}{m_f}\right)_{act.} = \frac{\left(\frac{m_a}{m_f}\right)_s}{\emptyset} = \frac{15.0316}{1.5} = 10.0210667$$

$$m_f = \frac{0.00507}{10.0210667} = 0.00050593\ kg$$

$$c.c_f = \frac{m_f}{\rho_f} = \frac{0.00050593}{719.7} * \ 10^6 = 0.7030\ c.c$$

4. Results and Discussion

Flame propagation can be capturing for initial pressure 1 bar and three different equivalence ratios 0.8, 1, 1.5. We can see from three figures for different radius and time and note that the flame speed is reduced for high radius of the spherical flame. Also, when equivalence ratio increases, amount of fuel increase. Time for all photo (4.125 ms, 12.375ms, 22 s, 30.464 m, 38.5ms and 48.5 ms respectively).

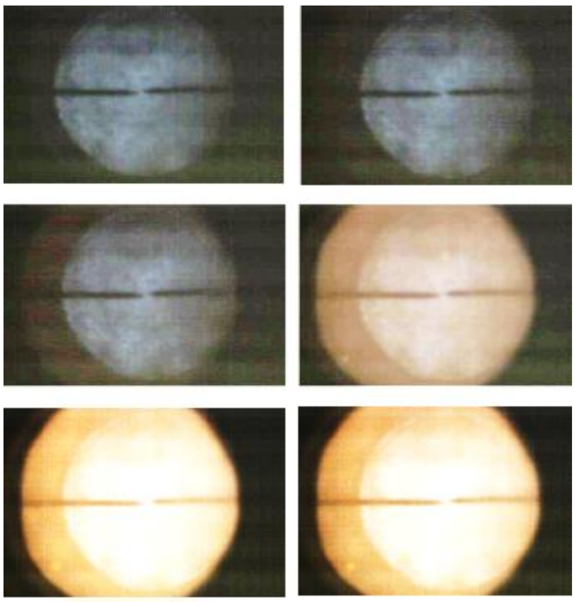

Fig.9 Flame Propagation at P=1 bar , $\emptyset = 0.8$

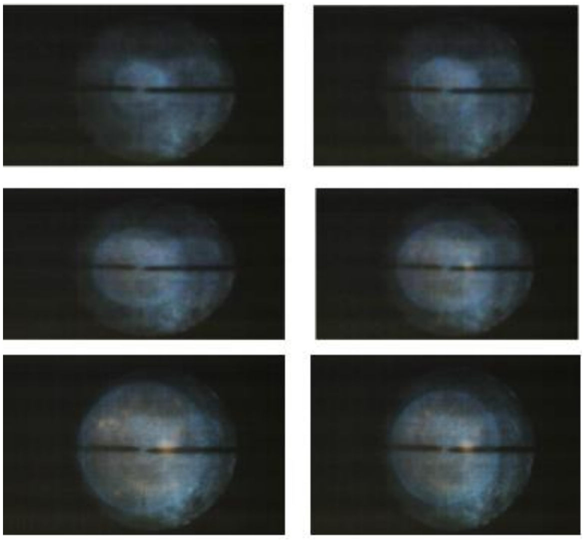

Fig.10 Flame Propagation at P=1 bar, $\emptyset = 1$

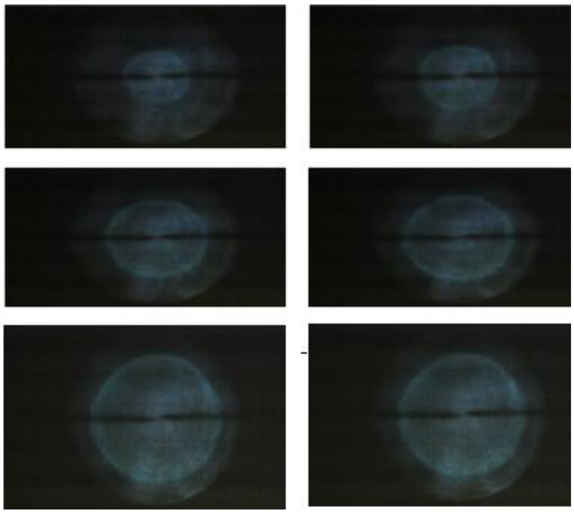

Fig.11 Flame Propagation at P=1 bar, $\emptyset = 1.5$

Number of flame 4000 flame per second. Total time for regarding this number 1100 milli second. Time for one flame equal 0.275 milli sec. Figure (12) represented that flame radius is increased with time and equivalence ratio. At large radii, the effect becomes obvious due to the consequence of the electrode thickness and increasing the combustion radius.

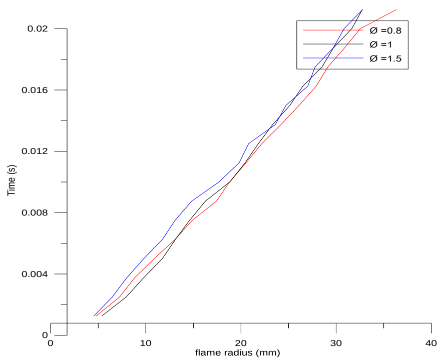

Fig. 12 Relation between flame radius and time for different equivalence ratios

Figure (13) showed decreasing in flame speed S_n with increasing in flame radius from (5-10 mm) according to equivalence ratio. The high initial value of S_n is due to the elevating effect of ignition, and the subsequent gradual decrease of S_n indicates that the flame is not fully developed until the radius reaches (15 mm). According to this, flame speed for a fully developed flame is relatively high and approximately stable, together with the consideration of isobaric combustion.

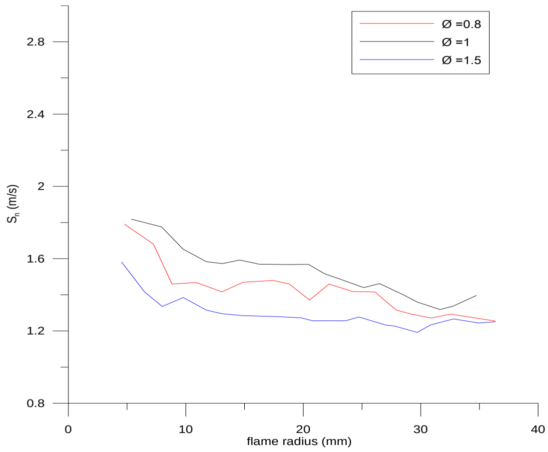

Fig. 13 Relation between flame speed and radius for different equivalence ratios

Figure (14) showed that the flame speed increases as the mixtures go from the lean limits towards the stoichiometric mixture, and then it decreases as approaches for rich mixtures at the same time. This behavior of the flame speed comes from the relation between the flame speed and flame temperature. Where in the lean side, the quantity of fuel is increased with the increment of the equivalence ratio together with the availability of oxygen quantity enough to burn a fuel as a complete combustion, so heat release of combustion will increase, which it means increase flame temperature and then increases flame speed as a result of increment of burning velocity and unburned gas velocity [Kanury,1975]. On the rich side, increment of equivalence ratio means increment of fuel quantity in the mixture and also the available quantity of oxygen becomes insufficient to burn the fuel completely, which causes an incomplete combustion of fuel, so (CO) results instead of (CO2) and unburned hydrocarbons. This matter leads to decrease heat release from combustion and then decrease of flame temperature and flame speed. In addition, thermal properties of the combustion products (such as specific heat and thermal conductivity) are decreasing and this also will reduce the flame speed as a result of decreasing the flame temperature.

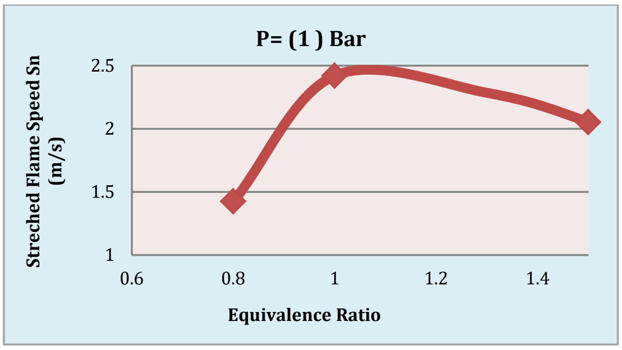

Fig.14 Relation between flame speed and equivalence ratio at time (10) ms

Figure (15) showed the good comparison between present work and two investigators for three equivalence ratios.

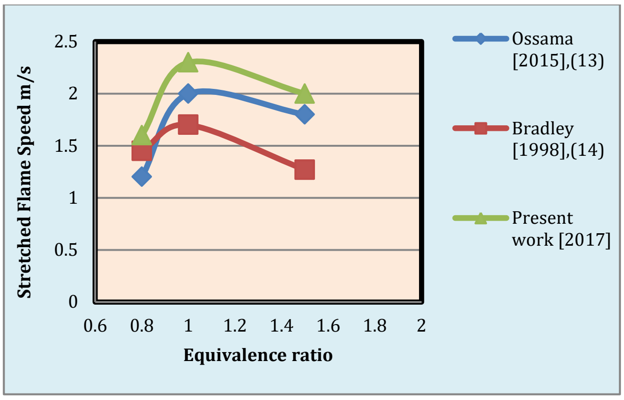

Fig.15 Comparison between present work and two investigators for three equivalence ratios

Conclusion

1) Flame speed will be increased at reach to the equivalence ratio equal 1.1 and then decreased to constant values at rich mixture at the same time.
2) Flame speed will be decreased with increasing flame radius.
3) Time of combustion will be increase with increasing flame radius and equivalence ratio.

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