Studying the Effect of H_2, O_2 and CO_2/N_2 Addition on the Laminar Flame Speed of CH_4/LPG-Air Mixtures

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1   Introduction

Pollution has been a concerning issue for most developed countries. As the world's population increases, the demand for transportation means also increases. Consequently, the emissions produced by the transportation means contribute to a large percentage of the pollution in cities. Therefore, there is a global interest to implement a number of alternative fuels with good combustion characteristics and low emissions produced in order to be used with combustion engines.

The term "alternative fuel" refers to any fuel that can be used with the current combustion engines without altering the main design of the engine. Currently, it becomes attractive for engine manufacturers to explore different alternative fuels that could substitute conventional fuels in all combustion engines. Many gaseous fuels can be classified as alternative fuels for engines such as methane (CH_4), which is the main component of the natural gas, liquefied petroleum gas (LPG), hydrogen (H_2), and propane (C_3H_8). Gaseous alternative fuels have attracted the attention of many researchers due to their rich reserve volume and fairly abundant worldwide. However, a number of challenges need to be tackled when considering these potential alternatives as fuels for combustion engines. Low rate of heat release, poor lean-burn capability and combustion instability are the main difficulties associated with these alternative fuels [1]. However, many of these challenges can be overcome by mixing another fuel with a high burning rate into the chosen fuel mixture [2].

 The flame speed is one of the important parameters that affect the combustion efficiency. Both laminar and turbulent flame speeds play a great role in examining the feasibility of using any alternative fuel with combustion engines. It is very significant to recognize the effect of modifying fuel compositions on their quantitative combustion characteristics. One of these essential characteristics in the combustion process is the laminar flame speed (S_L). Many vital combustion characteristics are related to the flame speed such as flashback and blow off, flame stability, flame stabilization and quenching distance [2-4]. Therefore, it is expected that the laminar flame speed values are different when two or more fuels mix together from the S_L values of each one of these fuels when tested separately. Recently, S_L has been measured using counter flow flame [6], spherical flame in a closed vessel [6], Bunsen burner [7] and the tube method [4]. The latter is the simplest method with reasonable accuracy comparing with the other methods, and it has been used in the present study. Laminar flame speeds have been extensively studied for a large number of liquid and gaseous fuels [8-10]. In addition, considerable attention has been given to measure S_L of some alternative gaseous fuel mixtures such as biogas [11]. However, using biogas as a fuel in combustion engines has many disadvantages such as low rate of heat release, inadequate lean-burn capability and poor combustion

stability. On the other hand, these problems can be improved by adding hydrogen, for example, which has high a burning velocity [1]. Other fuel mixtures, such as syngas, has also been tested [2].

Laminar flame speeds of methane and LPG fuel mixtures have not received much attention in previous investigations. Both of these fuels are also among the most promising alternatives. The laminar flame speed of each fuel has been extensively studied when used separately [2,5,9]. However, mixtures of these two important fuels have not been considered in laminar flame speed measurements before. Therefore, the main aim of this work is to measure the laminar flame speeds of a number of alternative gaseous fuel mixtures, in particular CH$_4$ and LPG. Mixtures of these two fuels with other fuels and gases such as hydrogen, oxygen, carbon dioxide and nitrogen have also been investigated.

2   Experimental Methods

Laminar flame speeds of a number of alternative fuel mixtures have been measured using the tube method. The test rig consists of a 480 cm long quartz tube that can withstand high temperatures with a 1.5-in inner diameter as shown in Fig. 1. In addition, the tube has smooth walls to avoid any turbulence generation that can affect S_L measurements. The inlet of the tube is attached to a mixing chamber to supply the fuel-air mixture at ambient pressure and temperature with a low velocity to ensure laminar flow with Reynolds number $Re = 1000$. The outlet of the tube is partially closed with wire mesh to avoid air entrainment to the end part of the tube. The fuels are supplied to the mixing chamber from pressurized cylinders by using two-step pressure regulators. The fuels used in the present work are methane (CH$_4$) with 99.96% purity, liquefied petroleum gas (LPG) (60% butane, 20% iso-butane and 20% propane), hydrogen (H$_2$) with 99.95%. In addition, three gases have been used also in some of the fuel mixtures; oxygen (O$_2$) with 99.5% purity, nitrogen (N$_2$) with 99.99% purity and carbon dioxide (CO$_2$) with 99.96% purity. The fuel, gas and air flow rates were measured by using calibrated rotameters with maximum uncertainty of 5%.

A piezoelectric gas igniter is used to generate a spark that is attached to the inlet of the tube to initiate the flame as shown in Fig. 1. Two type-K thermocouples with response time is about 50 ms are used to detect the temperature rise when the flame front passes the thermocouple location. The thermocouple signals are detected by using a Instek GDS-3152 two-channel Digital Storage Oscilloscope with 150 MHz sampling rate. Simultaneously, the flame propagation speed is mentored independently by using high-sensitivity high-resolution Canon digital camera with videography resolution 1920 x 1080 pixel and 30 fps shutter speed. The leading edge of the flame is detected as the flame front is expected to evolve after ignition into a hemispherical shape.

Mixtures of gaseous fuels, which are Liquefied petroleum gas (LPG), methane, and hydrogen, have been tested at different composition ratios within the laminar regime to measure the flame propagation speed. In addition, many mixture strength values, equivalence ratios ø, ranging from 0.1 to 3 have been considered for each fuel under investigation. The laminar flame speed has been also measured with the addition of different percentages of oxygen, carbon dioxide and nitrogen with the selected air-fuel mixtures. The accuracy of the measurement has been verified by first measuring the laminar flame speeds of some standard fuels like methane (CH$_4$) and compare the results with those available in the literature. The experiment for each fuel mixture has been repeated many times for the same flow condition until a good repeatability of the measured S_L is obtained. After the flame is ignited and starts propagating along the tube, it passes by two thermocouples placed at two predefined positions. The first one is placed about 30 cm from the beginning of the tube and the second one is placed 30 cm before the end of the tube. The reason behind that is to avoid the effect of the spark discharge at the beginning of the flame development due to the plasma expansion of the spark [13], and to ensure a fully developed laminar flow.

Thus, the increase in temperature due to flame front is detected by the two thermocouples showing a voltage rise on the oscilloscope as two peaks. Then, the noise of the signal is reduced by a wiener2 filter using Matlab software. Thus, the time between the two peaks can be obtained with more accuracy. Knowing the distance between the two thermocouples and the time taken by the flame, its velocity can be calculated simply as the distance divided by the time. In order to verify the results

obtained using the oscilloscope, the camera was used to record movies of the flame front propagation and then the videos were analysed, Fig. 2. The results obtained by the camera have been compared with those of the oscilloscope.

3   Results and Discussion

Laminar flame speeds of CH₄/LPG-air mixture

To ensure the accuracy of the measurements taken by the current test rig, the laminar flame speed has been measured for the methane-air mixture over a wide range of equivalence ratios. Then, the results have been compared with those of Ref. [12]. Figure 3 shows that a good agreement has been obtained between S_L, measured by the oscilloscope and those of Ref. [12], while there is some deviation for those taken by the camera. One possible reason is that the camera might not be exactly normal to the tube due to space limitations. Therefore, the new results are obtained mainly by analyzing the thermocouple signals, while the camera movies are used for qualitative comparison and for visualization purposes..

Laminar flame speeds have been measured with different mixing ratios of LPG and CH₄ fuels with air ranging from 20 – 60% LPG as a fuel content in the mixture. The measured S_L of the mixtures has also been compared with those of the pure fuels with air; i.e. LPG-air and CH₄-air flames. Figure 5 shows the results for S_L of these mixtures. The results show that S_L of all mixtures follow the well-established trend of peak at slightly rich mixture, because more fuel is required to compensate for the effect of dissociation at higher temperature, and decrease as the mixture strength becomes richer or leaner, Fig. 4. However, it can be observed that the peak value of the S_L of LPG-air flames is about 44 cm/s at about ø=1.1, while that of CH₄-air mixtures is about 40 cm/s and it peaks at ø=1.05. These results are in full agreement with Ref. [14] and can be related to differences in the chain-branching and the recombination reaction mechanisms in the two flames [14].

It can also be noted from Fig. 4 that S_L of a mixture of LPG and CH₄ with air at any percentage is higher than S_L of both pure fuels when used separately with air. It is also interesting to find that increasing the percentage of LPG in the fuel mixture from 20% to 60%, increases S_L considerably from 45 cm/s to 52 cm/s, respectively. The highest increase in S_L is around stoichiometric condition as shown in Fig. 4. The reason can be related to the expected increase in flame temperature with the increase of LPG percentage in the fuel mixture. This may lead to change the production and consumption rate of the molar fraction of H, O, OH and CH₃ radicals in the reaction zone. The differences in S_L between all CH₄/LPG mixtures decrease as the mixture goes leaner or richer, Fig. 4.

Effect of H₂ addition

The effect of H₂ addition on S_L of the CH₄/LPG-air mixtures has been examined. H₂ has been added with a percentage of 5 – 30% of the fuel composition (i.e., CH₄/LPG/H₂) at ø=1. It can be observed from Fig. 5 that the addition of hydrogen to the CH₄/LPG-air mixture has a noticeable effect on the S_L since H₂ has a strong reactivity that enhance the flame propagation speeds [15]. Therefore, S_L increases almost linearly with the increase of the H₂ ratio from 52 cm/s at 0% of H₂ to about 80 cm/s at 30% H₂, Fig. 5. The high S_L at 30% H₂ can be understood from the great thermal and mass diffusivity of H₂. It should be mentioned that the obtained trend of S_L with the H₂ addition is in a full agreement with the previous studies of S_L of the H₂-air mixtures [6,7]. Moreover, The S_L of CH₄/LPG/H₂-air mixtures are higher than those of CH₄/H₂-air mixtures reported in the literature due to the presence of LPG. In the present work, S_L of CH₄/LPG/H₂-air mixture is about 80 cm/s at 30% H₂, while it has been reported to be about 50 cm/s for the same H₂ ratio with CH₄/H₂-air mixture [16]. This is a clear evidence that changing the fuel compositions, even with small ratios, has a strong effect on the combustion characteristics of this fuel, which includes S_L. In addition, this comparison between S_L of CH₄/LPG/H₂-air and CH₄/H₂-air mixtures supports the conclusion mentioned in the previous section that the presence of LPG in the fuel mixture increases the flame temperature and, as a result, increases S_L.

Effect of O_2 addition

Small O_2 ratios have been added to the fuel composition in order to investigate the effect of O_2 addition on S_L of CH_4/LPG-air mixtures. Oxygen has been added to the fuel mixture with percentages ranging from 0-3%. As expected, The results show that S_L increases significantly with a slight increase in the excess O_2 percentage. Figure 6 shows that S_L of CH_4/LPG/O_2-air mixtures increase from 52 cm/s at 0% O_2 to about 88 cm/s at 3% O_2 with a mixture strength ø = 1.
This substantial increase can be attributed to the fact that during the combustion of any fuel with air, the nitrogen in the air, which is an inert gas, dilutes the reactive oxygen and remove some of the energy in the hot combustion gas. However, an increase in oxygen ratio in air can decrease the energy loss in combustion gases and raise the flame temperature to enhance more radicals in chain reaction. As a result, this brings more chance for particle collisions such as the O, OH, H to cause more new chain reactions, which speed up the combustion reaction. Both of these two reasons increase S_L with added O_2 percentage [7,16].

Effect of CO_2/N_2 addition

Currently, Exhaust Gas Recirculation (EGR) is an effective method that is employed in the majority of internal combustion engines to reduce NOx emissions by reducing the flame temperature. Therefore, it is important to study the influence of EGR on S_L of CH_4/LPG-air mixtures as potential alternative fuels for combustion engines. In this work, EGR has been replaced with CO_2/N_2 mixtures, as main components of EGR, to simulate the effect of EGR. That is because obtaining actual EGR from a combustion engine was not possible in the present investigation. CO_2/N_2 ratios have been chosen to be about 15% CO_2 and 85% N_2, which are very close to those of actual EGR produced from a modern spark ignition engine at cursing conditions [17].
The concentration of CO_2/N_2 mixture in the fuel stream has been increased from 0% to 40%. Figure 7 clearly shows that as CO_2/N_2 percentage in the CH4/LPG-air mixture increases, the S_L decreases. Moreover, it can be noted that a linear relation between the reduction in S_L and the increase in CO_2/N_2 percentage is established, Fig. 7, which agrees with previous work [5]. S_L is about 52 cm/s at 0% of CO_2/N_2, while it decreases to only 4 cm/s at 40% of CO_2/N_2, as shown in Fig. 8. This severe reduction of S_L with the addition of CO_2/N_2 happens mainly through the thermal mechanism. However, kinetics involving CO_2 are nearly as important as the thermal mechanism at low dilution fractions [5,7]. These effects cause the flame speed to slow down with the increase of CO_2 in the fuel mixture.

4 Conclusions

Laminar flame speeds of alternative fuel mixtures, mainly CH_4 and LPG fuels, have been studied at different mixture strength values. Moreover, the effect of H_2, O_2 and CO_2/N_2 addition on S_L of CH_4/LPG-air mixtures have also been considered. The study has been carried out using the tube method in which an optical-quality quartz tube has been employed. The flame is ignited at the inlet of the tube and S_L is measured by two methods simultaneously; two type-k thermocouples fixed at the inlet and exit of the tube, and a high-speed camera. Results of both methods show excellent agreement with the literature. Furthermore, the results of CH_4/LPG-air mixtures show that S_L of a mixture of these two fuels with any percentage is higher than S_L of both pure fuels when mix with air, i.e. CH_4-air and LPG-air mixtures. In addition, increasing the percentage of LPG in the mixture increases S_L considerably, especially around stoichiometric condition.
It has been found that S_L increases almost linearly with the increase of H_2 ratio and S_L of CH_4/LPG/H_2-air mixtures are higher than those of CH_4/H_2-air mixtures reported in the literature due to the presence of LPG. The results show also that S_L of CH_4/LPG-air mixtures increases significantly by a slight increase in the excess of O_2 percentage in the fuel mixture. Finally, the influence of EGR, simulated by a mixture of CO_2/N_2, on S_L of CH_4/LPG-air mixtures has been investigated. The results show a clear reduction in S_L with the addition of CO_2/N_2 due to the increase in CO_2 ratio, which decrease the reaction temperature and slowdown the flame speed.

Acknowledgement

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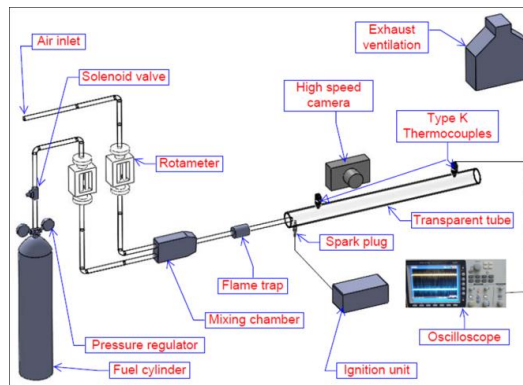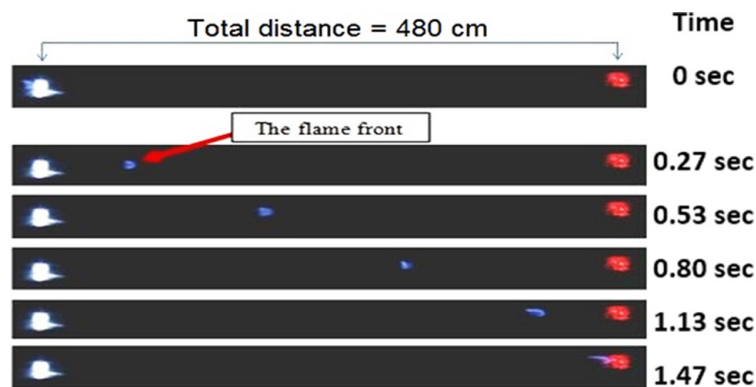

Figure 1. Schematic diagram of the test rig.

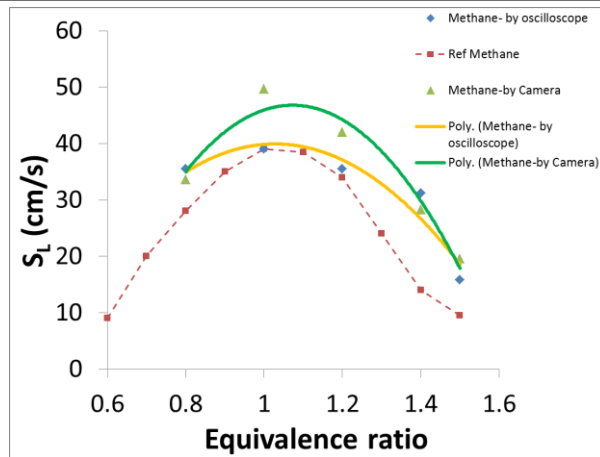
Figure 2. Snapshots of flame following ignition at *Re* = 1000.

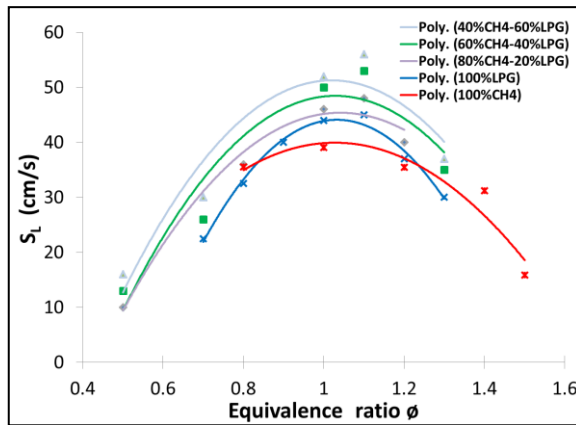**Figure 3.** S_L of methane-air flames at different equivalence ratios in comparison with Ref. [12].

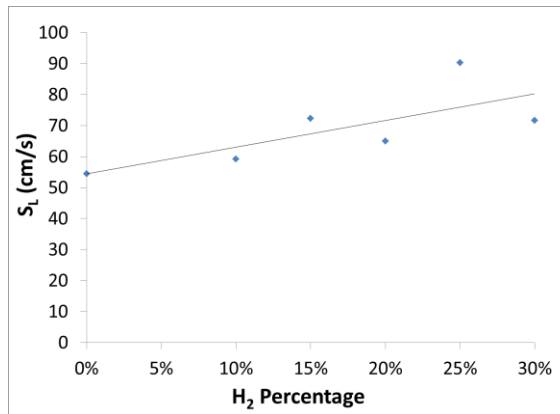**Figure 4.** S_L of CH$_4$/LPG-air mixtures at different mixture strength values.

Figure 5. Effect of H$_2$ addition on S_L of CH$_4$/LPG-air mixtures at stoichiometric condition.
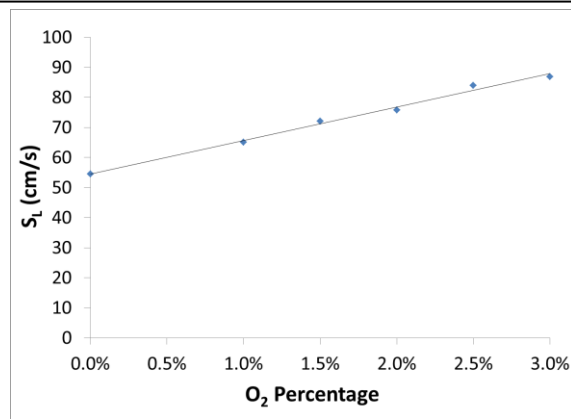
Figure 6. S_L of CH₄/LPG-air mixtures with O₂ addition at stoichiometric condition.
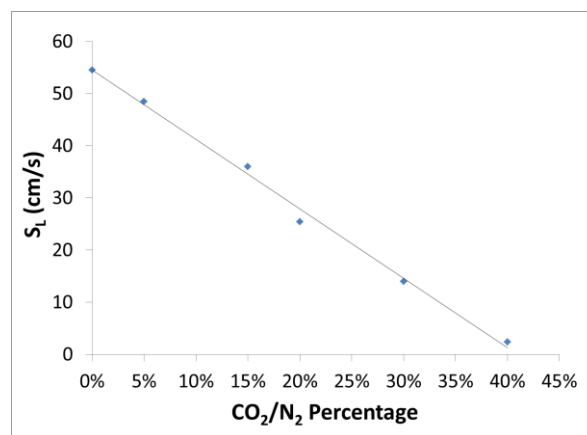

Figure 7. S_L of CH₄/LPG-air mixtures with the addition of CO₂/N₂ mixture at stoichiometric condition.