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ROLE OF SMALL ADDITION OF LIQUEFIED PETROLEUM GAS (LPG) ON LAMINAR BURNING VELOCITY OF HYDROUS ETHANOL

Етанол є прийнятною заміною бензинового палива в двигунах з іскровим запалюванням. Етанол має високе октанове число, що дозволяє використовувати його при більш високому ступені стиснення двигуна. Перш ніж широко використовувати етанол в двигуні з іскровим запалюванням, необхідно краще зрозуміти характеристики його згоряння. Одним з найважливіших параметрів заміщуючого палива є швидкість горіння. Тому метою дослідження є експериментальне вивчення впливу додавання невеликої кількості зріджених вуглеводневих газів (ЗВГ) на швидкість ламинарного горіння водного етанолу. Характеристика горіння суміші етанолу і ЗВГ досліджувалася в циліндричної камері згоряння діаметром 10,8 см і довжиною 17 см. Полум'я мало сферично розширювану форму. Паливна суміш запалювалась іскрами всередині циліндра, а діаметр полум'я вимірювали по зображенню полум'я, отриманого високошвидкісною камерою. У дослідженні використовувалися два типи паливного етанолу, безводний етанол і водний етанол, що містить 0,3 % води. Частка ЗВГ в паливній суміші варіювалася від 0 % до 20 %. Результати показали, що додавання 10 % ЗВГ в етанол збільшує швидкість ламинарного горіння. Для безводного палива швидкість горіння етанолу вище, ніж для ЗВГ, а найвища швидкість горіння у етанолу, в який додано 10 % ЗВГ, найнижча – у ЗВГ. Крім того, вміст води в паливному етанолі призводить до значного зниження швидкості горіння. Однак додавання до 10 % ЗВГ робить водний етанол відносно більш стійким до підвищеного вмісту води за рахунок того, що реакції горіння сприяє більш висока концентрація радикалів в ЗВГ. Це обумовлено двома факторами: зоною часткового попереднього нагрівання, викликаного гідроксильною групою (ОН) етанолу, яка поставляє більше теплової енергії, і високою концентрацією радикалів в ЗВГ, що сприяє реакції горіння

Ключові слова: водний етанол, зріджені вуглеводневі гази, циліндрична камера, швидкість ламинарного горіння

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1. Introduction

Fossil fuels are used in large numbers and rapidly increasing while reserves continue to decline, and some day will be depleted. Bioethanol is an appropriate replacement candidate, especially in terms of availability of raw materials and environmentally friendly emissions [1–3]. The advantage of ethanol as a replacement fuel is that it can be produced from renewable energy sources such as sugarcane, cassava, waste biomass materials, and corn. The combustion of ethanol has a lower emission than fossil fuels to reduce environmental pollution and greenhouse emissions. Currently, ethanol fuel is to be the focus research on internal combustion engine research. It could be a blended fuel in gasoline and diesel engines. The greatest advantage of Ethanol as a renewable fuel of spark ignition engines compared to gasoline fuel is an excellent anti-knock property, even the octane number exceeds 100. The high-octane number of ethanol allows it to be designed in the engine with a higher compression ratio [4].

Fundamental combustion properties of ethanol should be examined before its use on the engine. One of the key parameters which is an essential characteristic of fuel on the engine is the laminar burning velocity of ethanol. The measurement of laminar burning velocity describes how fast the flame propagates into the reactant mixture ahead of the flame at a specified pressure and temperature [5]. By the

properties, it could be predicted that fuel with a higher value of laminar burning velocity has a faster combustion process in the internal combustion engine. A number of researchers have carried out studies to determine the laminar burning velocity of ethanol and blend it with gasoline in the experimental and numerical way [6–8]. In the view of application, the performance of ethanol, especially hydrous ethanol as a substitute fuel in the engine, is still less effective than that of gasoline due to the lower heating value of ethanol. However, the power of ethanol in the engine could be enhanced when we could upgrade the burning velocity of ethanol. One way to increase the combustion rate of ethanol is by adding some proper addictive. Therefore, the present work is focused on the effect of the small addition of liquefied petroleum gas (LPG) on the laminar burning velocity of hydrous ethanol.

2. Literature review and problem statement

A better understanding of ethanol combustion is needed to predict the prime mover's engine performance [1, 9]. Combustion of ethanol has been studied extensively, both to determine the burning characteristics [7, 10–13] or as a fuel in reciprocating engines [3–6]. Recent research on the SI engine shows that the percentage amount of ethanol in the fuel blend of ethanol and gasoline fuel has a substantial effect on the power and exhaust emission of SI engines [4]. The increase in the ethanol addition in the fuel blend reduced the performance of the SI engine due to the lower heating value of ethanol. Besides, the ethanol blend improves the characteristics of exhaust emission. The leaning effect of ethanol addition in the fuel blend caused the CO emissions to decrease greatly as well as the HC emissions.

Another researcher [3] investigated the engine performance and emission characteristics of the internal combustion engine with the concept of low heat rejection using ethanol blend and gasoline fuel. The result showed that the engine covered by the alumina insulation on the partially engine space improves the power and reduces the emission by more than 40 %.

Commonly, the type of ethanol fuel is divided into two types, anhydrous and hydrous ethanol. Anhydrous ethanol means that alcohol has a purity of more than 99 %. While hydrous ethanol is the grade ethanol with the water content in the fuel more than 4 %. The high cost of producing anhydrous ethanol causes the preferable use of hydrous ethanol as a fuel mixture of gasoline. However, the water content in ethanol fuel has a negative effect on the engine performance. Condensation of water inside the cylinder engine causes critical damage to the engine and significantly slower combustion rate, which results in a decrease in the engine performance.

To ensure a smooth transition to the use of ethanol, the combustion characteristics of ethanol mixed with other fuels are indispensable. Fundamental research about the burning characteristics of ethanol mixed with liquid fossil fuels has been carried out extensively [7, 12–14]. The combustion of ethanol and liquid fossil fuel mixture in internal combustion engines also has been studied [3–5, 15]. With 6.8 % water content in ethanol, the fuel consumption of the SI engine increases almost by 50 % compared to blend fuel [9]. However, in terms of HC emission, hydrous ethanol is seen to be a good choice since it could reduce the HC emission of the SI engine due to the hydrogenated properties of ethanol. In the

HCCI engine, the exhaust heat recovery technique can be used to remove the water content in the hydrous ethanol [1]. This heat exchanger was used to heat up the intake air to the engine. The result concluded that this method removes 20 % of water content in the ethanol fuel and the HCCI engine can run smoothly with hydrous ethanol fuel.

From the previous experimental studies, there was a lack of data on the combustion characteristics of hydrous ethanol. The understanding of combustion characteristics of hydrous ethanol is needed before it is used as a replacement fuel of the SI engine. Due to the water content in the ethanol, the burning velocity is much slower than that of pure ethanol. The burning velocity of the fuel could be improved by adding some substance that could increase the propagation rate of hydrous ethanol. Based on the previous experiment [16], induction of polar molecules in non-polar fuels can change the physical properties of the fuel. Since the ethanol is the group of polar molecules of fuel, we try to add Liquid Petroleum Gas as a non-polar molecule in order to improve the burning velocity of hydrous ethanol.

By adding the small portion of LPG in the hydrous ethanol, it is expected that the slow burning velocity of hydrous ethanol can be accelerated due to the change of physical properties of the fuel.

3. The aim and objectives of the study

The aim of the study is to investigate experimentally the effect of the small addition of liquefied petroleum gas (LPG) on the laminar burning velocity of hydrous ethanol.

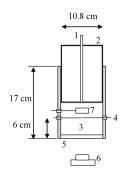To achieve this aim, the following objectives are accomplished:

1. To investigate the laminar burning velocity of:
– Hydrous and anhydrous ethanol;
– Mixture of hydrous ethanol and LPG (10 % in volume);
– Mixture of anhydrous ethanol and LPG (10 % in volume).

2. To find out the free radicals produced from the combustion process of:
– Hydrous and anhydrous ethanol;
– Blend fuel of 10 % of LPG and hydrous ethanol.

3. To make the comprising producing radical in the combustion of LPG with various percentages of ethanol and elucidate the effect of the hydroxyl group of ethanol on the production of the radical in the combustion.
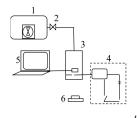
4. Experimental methods

The experiments were carried out in a cylindrical combustion chamber with a diameter of 10.8 cm and a length of 17 cm as illustrated in Fig. 1, *a*. The combustion chamber is closed by a fixed transparent wall on one side for capturing flame image inside the combustion chamber by using a high-speed camera Casio Exilim EX-FC100. While the other side was mounted with a moveable cover to keep the pressure constant.

Fuel mixture was ignited by sparks from electrodes in the middle of the cylinder. The arrangement of the test equipment was illustrated by Fig. 1, *b*. To produce a spark in a combustion chamber, a high voltage coil system with a battery power supply was used. The flame diameter was measured from the flame image captured by the high-speed

camera, which was set at a speed of 420 fps. The diameter measurement was done from the beginning of flame formation up to 50 mm to avoid the influence of the wall. Electrical resistance due to changes in the number of radicals was measured by an ion sensor. It consists of two parallel plates with a 1 mm gap which has a width and length of 8×45 mm. The ion sensor was connected to an electronic circuit to convert electrical resistance to voltage and then connected to the computer for data processing and storage.

1. Inlet
2. Moveable cover
3. Combustion chamber
4. Electrode
5. Transparent wall
6. High Speed Camera
7. Ion censor

a

1. Air-fuel mixer
2. Safety valve
3. Combustion chamber
4. Ignition system
5. Computer
6. High Speed Camera

b

Fig. 1. Schematic of experimental apparatus:
a — combustion chamber; *b* — arrangement of test equipment

The compositions of fuel mixture of various water content are listed in Table 1. Besides, the LPG composition used in this study is shown in Table 2.

Table 1

Composition of hydrous ethanol with addition of liquefied petroleum gas (LPG)

LPG/ Ethanol	99.7 % (W0)	97.5 % (W2,5)	95 % (W5)	92.5 % (W7,5)
0 % (E100)	E100	E100W2,5	E100W5	E100W7,5
5 % (E95)	E95	E95W2,5	E95W5	E95W7,5
10 % (E90)	E90	E90W2,5	E90W5	E90W7,5
15 % (E85)	E85	E85W2,5	E85W5	E85W7,5
20 %(E80)	E80	E80W2,5	E80W5	E08W7,5

Table 2

LPG composition

Items	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}
Volume fraction %	0.15	51.2	47.3	1.35

Hydrous Ethanol was varied at 99.7 %, ethanol contained 0.3 % water (W0), 97.5 % (W2,5), 95 %(W5), 92.5 %(W7,5). Hydrous ethanol with the addition of 0 % (E100), 5 % (E95), 10 % (E90), 15 % (E85), 20 % (E80), and 100 % LPG is also shown in Table 1.

5. Calculation of laminar burning velocity

Laminar burning velocity of spherically expanding flames was derived from the pictures of the high-speed camera photography. The stretched flame speed (*Sn*) was calculated from the radius increase in the flame divided by time increment [17].

$$Sn = \frac{dr_u}{dt},$$

where r_u is the flame radius and t is the time. Flame stretches rate (α) is defined as [18]:

$$\alpha = \frac{dlnA}{dt} = \frac{dA}{Adt},$$

where A is a spherical area, so the rate of flame stretch could be simplified to

$$\alpha = \frac{2}{r_u}x = \frac{2S_n}{r_u}.$$

There is a linear relationship between flame speed and stretch Markstein length L_b expressed as

$$S_L - Sn = L_b\alpha,$$

where S_L is the unstretched flame speeds which equals to *Sn* at α=0. Unstretched burning velocity U_L is derived from S_L as

$$U_{Ln} = S_L\frac{\rho_b}{\rho_u},$$

where ρ_b is the burned gas density and ρ_u is the unburned gas density.

6. Results of the combustion characteristics of the ethanol and LPG mixture

Fig. 2 is a photographic image of the premixed combustion flame of E90. Combustion started from the middle of the combustion chamber and continues to expand with time. Stretched flame speed was estimated from the increase of the radius of the spherical flame divided by the time difference
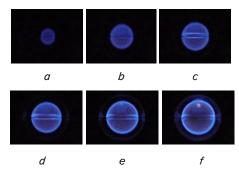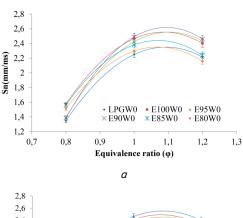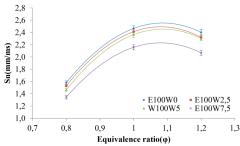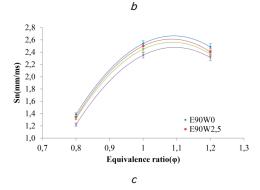

a *b* *c*

d *e* *f*

Fig. 2. Flame propagation in a stoichiometric mixture of E90, time interval 2.3 ms: *a* — 2.3 ms; *b* — 4.6 ms; *c* — 6.9 ms; *d* — 9.1 ms; *e* — 11.4 ms; *f* — 13.7 ms

Fig. 3 is the stretched flame speed for different fuel compositions versus equivalence ratio (ϕ).
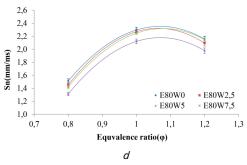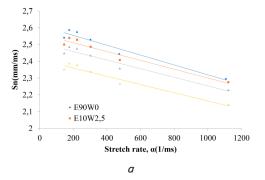

a

b

c

d

Fig. 3. Stretched flame speed (*Sn*) of various fuel compositions versus equivalence ratio: *a* — pure fuels and anhydrous composition; *b* — hydrous ethanol; *c* — hydrous E90; *d* — hydrous E80

Stretched Flame speed of pure ethanol (E100) is higher than that of the Liquefied Petroleum Gas (LPG). Anhydrous fuel with another composition has a flame speed between E100 and LPG as shown in Fig. 3, *a*. In hydrous fuel, addition of water decreases the flame speed as shown in Fig. 3, *b–d*. This is in accordance with the previous research [14]. Abrupt flame speed reduction occurs from 5 % water content (W 5) to 7.5 % (W7,5) for E100 and E80, while for E90, the flame speed decreases gradually with the increase of water content.

Fig. 4, *a* shows the relationship between Sn against α for hydrous E90 at the equivalence ratio (ϕ) of 1.0. Gradients of Sn/α are negative and the pattern is similar for all fuel compositions. This means that the flame speeds increase with increasing spherical flame radius. Markstein length on hydrous E90 is shown in Fig. 4, *b*. The length at all water contents has a positive value which means stable combustion. Stretched flame speeds (S_L) are obtained from the value of Sn at α=0 in Fig. 4, *a* (see equation (4)). Then, laminar burning velocity (U_L) is calculated from the equation 5 and is shown in Fig. 5 for pure fuel.
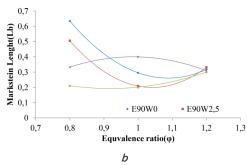

a

b

Fig. 4. Dependence of stretch and equivalence ratio on the flame speed and Markstein length of hydrous E90: *a* — Stretched flame speed; *b* — Markstein length

Fig. 5 shows the laminar burning velocity of the experimental data compared with the literature data using similar combustion methods. The LPG laminar burning velocity in Fig. 5, *b* shows the suitability of the pattern, [14, 19] shows different patterns. Fig. 5, *b* shows the ethanol laminar burning velocity of the experimental results in accordance with the previous reports [13, 20]. The ethanol laminar burning velocity is lower than in other studies due to lower initial temperatures.

Fig. 6, *a* shows that the lowest burning velocity occurs in pure LPG and the highest occurs in E90. This is in accordance with those in Fig. 3, *a*. Fuel with E90 composition has a laminar burning speed above E100 followed by E95, which is slightly below E90. While anhydrous fuel with other compositions has the laminar burning velocity between LPG and ethanol (E100). Fig. 6, *b* shows that the laminar burning velocity of E90 decreases by the addition of water, this is in accordance with the previous research [14].

The laminar burning velocity of ethanol decreases with the increase in water content as in Fig. 7. Abrupt velocity reduction occurs from the water content of 5 % (W5) to 7.5 % (W5). The small addition of LPG up to 10 % to anhydrous ethanol (E90) makes burning speed increased to the highest primarily at stoichiometry and rich mixture. In addition, the

combustion is relatively more robust to the increase in water content than other compositions, as the reduction in laminar burning speed is relatively gradual with the increase in the water content. Conversely, the small addition of LPG in the lean mixture weighed the combustion.
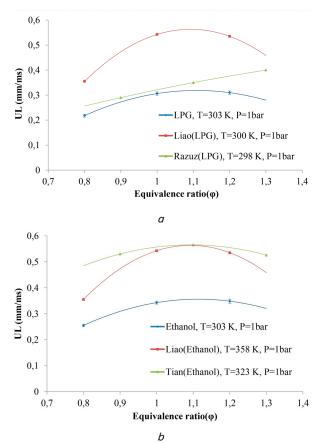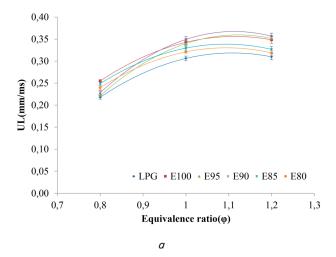

Fig. 5. Laminar burning velocity (U_L) of pure fuel:
a — LPG; b — Ethanol

Radicals are generated during the combustion process, both in the preheating zone and the flame zone (reaction). A gas that contains more radical will easier conduct electricity, which is indicated by the increase in the voltage of the ion sensor system. The pattern of the voltage measured in the combustion with φ=1 is shown in Fig. 8, 9.
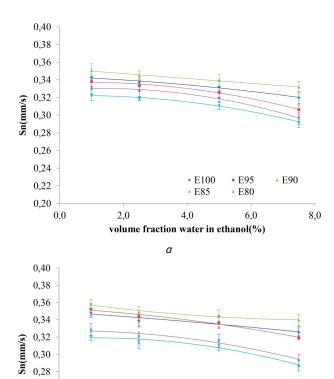

Fig. 7. Laminar burning velocity for ethanol with LPG addition as a function of volume fraction of water in ethanol:
a — φ=1.0; b — φ=1.2

Fig. 8, 9 show that the ion gets higher and the peak of voltage appears increasingly earlier as the burning velocity gets higher. This is caused by the increase in the rate of combustion reaction giving a growing number of radicals. But there are different patterns of LPG than in fuels containing ethanol. LPG has a lower burning speed or slower emergence of peak voltage, but its ion voltage is higher than the other compositions except for E90 which is slightly higher.
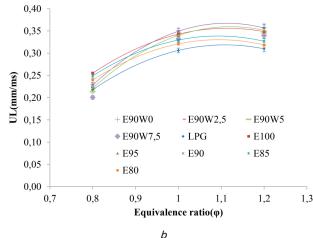

Fig. 6. Laminar burning velocity (U$_L$): a — various fuel compositions; b — Hydrous E90

This happens because there is no hydroxyl group (OH) in LPG so that no radical reduction in the preheating zone. Therefore, radical concentration remains high. Conversely, in fuels containing ethanol the radical number in the preheating zone is reduced. This is due to the partial combustion reaction to OH and H to form H_2O. Increased water content significantly decreases the number of radicals. This is due to the decrease in combustion temperature and more energy is used to heat the water which has the latent heat greater than ethanol (Fig. 8, *b*).
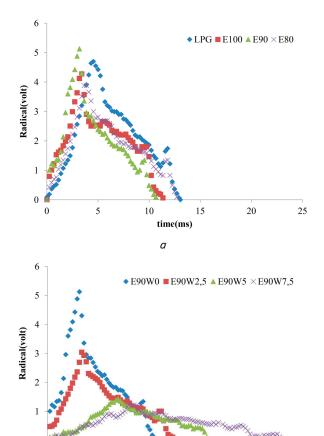

a

b

Fig. 8. Measured voltage (radical) against the combustion time at $\varphi=1$: *a* — anhydrous composition; *b* — hydrous E90
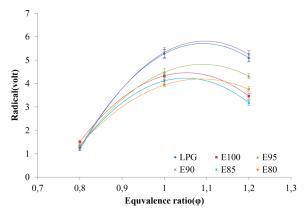

Fig. 9. Relationship between the radicals concentration against equivalence ratio

7. Discussion of experimental results

Combustion is generally divided into the preheating zone and the reaction zone. In the preheating zone, the temperature increases due to the heat energy from combustion reactions that cause the weak bond dissociation such as C–C, C–OH and C–H, respectively [18]. In the reaction zone, the stronger the bond broken is O=O which continued reaction to C and O to form CO_2, CO and H reacts with O to form H_2O.

The preheating zones of ethanol and LPG are different. For the LPG combustion, in the preheating zone only the decomposition reaction of C–C and C–H is found. While in ethanol, a hydroxyl group (OH) causes the partial combustion reaction to H and OH to form H_2O and release the heat, hereafter called partial preheating. Heat generated from the reaction causes a temperature increase to the preheating zone. This causes the higher combustion velocity of ethanol than that of LPG, although the combustion energy is lower than that of LPG.

The small addition of LPG of 5 to 10 % (E95 and E90) improves combustion, while the addition of LPG over 15 % (E85 and E80) weighed the combustion. In the E90 and E95 combustion, partial pre-heating takes place and combustion reaction is helped by high radical concentration in LPG. This causes the higher amount of fuel decomposition characterized by an increased concentration of radicals and laminar burning velocity. In contrast, the addition of LPG over 15 % (E85 and E80) weakens the partial combustion reactions by OH, so the number of radical concentrations in the combustion process becomes lower. The addition of water to ethanol causes a decrease of laminar burning velocity. This is due to the heating value of fuel getting lower, while the amount of material that does not contribute to generating energy is greater. Radical concentration also decreased significantly, which is a sign that the combustion reaction rate is also reduced. But the addition of LPG up to 10 % makes the combustion reaction assisted by a higher radical concentration of LPG so as to make the combustion reaction robust to rising water content.

Improvement of combustion performance of hydrous ethanol with the addition of the low percentage of LPG (less than 10 %) may also be explained by molecular interactions between ethanol and LPG. Ethanol is a group of polar hydrocarbons, besides the LPG gas is non-polar. Previous experiments [16] showed that the addition of some portion of polar molecules in non-polar fuels can induce polar fuel and change the physical properties of the fuel mixture. Even, in an exact proportion of the fuel mixture, the properties of fuel could be improved significantly. Based on the previous finding, it could be predicted that the addition of a small percentage of LPG in ethanol fuel has an effect on the characteristics of combustion. Addition of LPG can provide a polarizing effect on the properties of ethanol fuel so that the combustion velocity of the ethanol-LPG mixture is higher than that of pure ethanol. In this research, the optimum value of the composition of LPG which must be mixed with hydrous ethanol to obtain a high burning velocity is still not known in detail. Further research is needed to find out the optimum value of LPG concentration in ethanol through a molecular approach.

8. Conclusions

The major conclusions from the study can be summarized as follows:

1. For anhydrous fuels, ethanol burning velocity is higher than that of LPG and the highest burning velocity is in ethanol, to which 10 % LPG is added while the lowest is in LPG.

2. The addition of water to ethanol causes a decrease in combustion speed significantly. But the addition of LPG up to 10 % makes hydrous ethanol relatively more robust to rising water content due to the combustion reaction is helped by a higher radical concentration in LPG.

3. There is a correlation between the radical concentration to burning velocity, where at high radical concentration the burning velocity is also high and vice versa.

4. Fuels containing ethanol generally have a lower radical concentration than pure LPG except E90. This is due to the presence of a hydroxyl group in ethanol that causes partial preheating.

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