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Research Article

# Experimental Study of Lean-burning Limits of Hydrogen-enriched LPG Intended for Domestic Use

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**Abstract**

The lean-burning limits of hydrogen-enriched Liquefied Petroleum Gas (LPG) have been studied using a Bunsen burner. The lean-burning limits under different conditions are important design considerations in developing gas-fired domestic appliances. In this study, the lean-burning limits of hydrogen-enriched LPG have been obtained across a wide range of Reynolds numbers (600 to 1800) and $H_2$ volumetric fractions (0% to 25%). The results show that the lean-burning limit is increased, on average, by 4.0% to 7.2% for every 5% increment of $H_2$ volumetric fraction under different Reynolds numbers. A numerical simulation carried out in CHEMKIN using the USC Mech II reaction mechanism, and the observation of flame characteristics show that the increase in lean-burning limit with increasing $H_2$ content is due to the higher burning velocity of LPG-$H_2$ mixtures compared with pure LPG. More fuel is required to offset the effect of increased burning velocity under the same Reynolds number, leading to an increase in the lean-burning limit. To facilitate the visualization of the variation of the lean-burning limit with increasing $H_2$ volume fraction in the mixed fuel at different Reynolds numbers, a lean-burning limit map is developed based on correlations obtained. The results of this study provide reference values for the lean-burning performance of hydrogen-enriched LPG fuel for practical domestic use.

**Keywords**

LPG; hydrogen enrichment; lean-burning limit; Reynolds numbers

## 1. Introduction

Gaseous hydrocarbon fuels, including natural gas, town gas, and liquefied petroleum gas (LPG), dominate both domestic and commercial use in China as they are conveniently available, safe to use, and reliable [1]. LPG is also one of the main domestic fuels in other Asian countries such as India, Indonesia, and Thailand. Commercial LPG consists mainly of propane ($C_3H_8$) and butane ($C_4H_{10}$) and may also contain small concentrations of some unsaturated components such as propene ($C_3H_6$) and butene ($C_4H_8$) [2]. LPG is regarded as a clean domestic fuel; however, the emission of toxic gases such as carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides ($NO_x$) are still of concern when it comes to indoor combustion of LPG [3, 4]. The emission of carbon dioxide ($CO_2$), a major combustion product of LPG, is also of great concern as it is one of the principal greenhouse gases contributing to global warming [5].

In this study, the focus is to investigate Hydrogen ($H_2$) enriched LPG as an alternative domestic fuel designed to address some of the concerns related to the direct burning of LPG. $H_2$ is a zero-carbon energy source and is the subject of increasing research due to its favorable properties [6]. It is lightweight (2 g/mol) and has a high calorific value of 120 - 142 MJ/kg - roughly three times that of propane and butane. The fact that its only combustion product is harmless water vapor ($H_2O$) is the most important characteristic that makes hydrogen a superior fuel compared to hydrocarbon fuels. However, $H_2$ is not yet a feasible option for domestic use because of the high risk of leaks, low-energy ignition, high flammability, and the consequential risk of explosion. These risks can be minimized by blending $H_2$ with LPG, a process that also results in a blended fuel with enhanced combustion characteristics. Several research studies have been carried out into the combustion, thermal and emission characteristics of $H_2$ enriched LPG [7-10].

The physical and chemical properties of $H_2$ and LPG, shown in Table 1, have a major impact on the combustion process and emission formation of the blended fuel. It should be noted that, since LPG is a mixture of gases, the composition of LPG used in different regions of the world is generally different. For example, the United States requires the volumetric percentage of propane in LPG to be at least 85%, while in Hong Kong, the requirement is that LPG contains about 30% propane and about 70% butane by volume. Therefore, the properties of major constituents of LPG (propane and butane) are given separately in Table 1.

**Table 1** Physical and Chemical Properties of $H_2$ and the Major Constituents of LPG.

| Physical/Chemical Properties | Hydrogen ($H_2$) | Propane ($C_3H_8$) | Butane ($C_4H_{10}$) |
|---|---|---|---|
| Calorific Value (MJ/kg) | 142 | 50 | 49.5 |
| Specific Gravity (Air = 1) | 0.0696 | 1.5503 | 2.09 |
| Auto-ignition Temperature (°C) | 500 | 455 | 405 |
| Adiabatic Flame Temperature (°C) | 2127 | 1980 | 1970 |
| Stoichiometric Air/Fuel Ratio (by volume) | 2.4:1 | 23.8:1 | 31:1 |
| Flammability Limit (% by volume) | 4%-75% | 2.1%-9.5% | 1.8%-8.4% |
| Minimum Ignition Energy (mJ) | 0.017 | 0.26 | 0.26 |

Hydrogen enrichment has been used to modify gaseous hydrocarbon fuels to enhance combustion and reduce harmful emissions. Aravind et al. [7] carried out a numerical study of the effect of hydrogen addition in the range 0 - 50% on the combustion characteristics of LPG-air mixtures under different propane and butane fractions, temperature (300 K to 450 K) and pressure (1 bar to 10 bar). Their results showed that hydrogen addition improves the burning ability of the LPG-air mixture by linearly increasing the laminar flame speed independent of the mixture components' fraction, pressure, and temperature. The experimental and numerical studies reported by Wei et al. [11] also demonstrated that the laminar burning velocities of biogas increased almost linearly with an increase in hydrogen volume fraction. Tutak et al. [12] reported an experimental study of hydrogen-enriched diesel fuel and a natural gas mixture for a dual fuel diesel engine. They found that the addition of hydrogen increased maximum combustion pressure and combustion temperature and accelerated the natural gas combustion process. All the studies described point to the positive effect of $H_2$ enrichment on the combustion process of various fuels.

An important indicator of domestic gaseous fuel performance is the lean-burning limit, which is used to assess both combustion performance and safety. The lean-burning limit is the boundary composition of the fuel-air mixture at which a gas [mixture] can be ignited and maintain stable combustion [13]. There are two burning limits, the upper or rich-, burning limit and the lower, or lean-, burning limit, referring to the highest (fuel-rich) and lowest (fuel-lean) fuel concentration in the mixture, respectively. If a fuel-oxidizer mixture is to ignite, its composition must lie within the burning limits described by the volumetric fraction of the fuel. A second parameter known as the flammability limit is more widely used to quantitatively describe the boundary composition of a flammable fuel-air mixture [14, 15]. The flammability limit is normally measured using one of the two standard methods, the first of which uses a glass tube that allows visual observation of the flame propagation, while the second uses a closed spherical explosion vessel with a rise in pressure used to determine whether flame propagation has occurred [16]. Fundamental flammability data for pure hydrogen ($H_2$), methane ($CH_4$), and propane ($C_3H_8$) are widely obtained by the second pressure rise method [17, 18], and the flammability limits of some mixtures of $H_2$ and other gaseous fuels are also reported in the literature. The flammability of hydrogen-enriched methane has been studied intensively [16, 19]. Miao et al. [15] measured both the upper (UFL) and lower (LFL) flammability limits of hydrogen-enriched natural gas (rather than pure methane) using a constant volume combustion chamber and a high-speed schlieren photographic system. The experiments were conducted for $H_2$ fractions ranging from 20% to 80%, and the results showed that with increasing $H_2$ fractions, the flammable range of hydrogen-enriched natural gas extends as the UFL increases even though there is no obvious change in the LFL. Wang et al. [20] conducted a numerical study of the adiabatic burning velocity of $H_2$ enhanced LPG + air flames under different $H_2$ fractions (0% to 45%) and dilution factors (21% to 16%). The results of their simulation showed that the lean-burning flammability limits are extended by $H_2$ addition. However, no experimental validation has been reported. The recently published experimental work by Jithin et al. [21] shows that $H_2$ addition causes an increase in laminar burning velocity for all methane-oxygen mixtures because of the combined effect of $N_2/CO_2$ dilution and $H_2$ addition.

The use of Hydrogen-enriched hydrocarbon fuels in internal combustion engines has also been studied. Ho Choi et al. [22] investigated the effects of hydrogen enrichment of LPG on exhaust emission, thermal efficiency, and performance of an LPG-fueled engine. Their results showed reduced emission of unburned hydrocarbons but a rise in $NO_x$ emission compared with pure LPG. In another study, researchers investigated the effect on engine performance of hydrogen enrichment of LPG together with changing the location of fuel injection [23]. They reported improved brake thermal efficiency and a considerable reduction in $CO_2$ and hydrocarbon emissions. Wang et al. [24] investigated the combustion characteristics and extension of ignition limits of a micro free-piston engine in a study that showed that the hydrogen enrichment of methane advances the ignition time of the mixture and expands the ignition limit as the heat released by the combustion of hydrogen can accelerate ignition and combustion of the unburned methane. There have been several other research studies that have demonstrated the positive effects of $H_2$ enrichments of gaseous fuels on engine performance and emission reduction [25-27]. The study of the lean-burn limits of various mixed fuels used in internal combustion engines has also been the subject of extensive research, as lean combustion is an effective method for enhancing thermal efficiency and reducing emissions. Akram et al. [28] investigated the lean-burn limits and burning characteristics of n-heptane blended with $H_2$ in a study that showed that the lean-burn limits of n-heptane increased with the addition of $H_2$. They determined through a theoretical investigation that the formation of the H radical and $CH_2O$ played a substantial role in improving the lean-burn limits. Gong et al. [29] conducted an experimental investigation of the lean-burn limits of hydrogen-enriched methanol used to fuel a dual-injection spark-ignition engine with methanol late injection. Their study also found an increase in the lean-burn limit with increasing hydrogen content.

In addition to the studies on the characteristics of hydrogen-enriched LPG described above, there have been further studies focusing on laminar burning velocity [8, 30], pollutant emissions [9, 31], and flame stability [10]. Experimental studies of the flammability limits of blended fuel mixtures have been done using standard closed chambers or combustion tubes methods. However, for practical domestic use, it is important to use instead a Bunsen burner to establish the lean-burning limits of the hydrogen-enriched LPG as this closely mimics the actual combustion process in domestic gas appliances (the Bunsen burner was the forerunner of the modern gas-stove burner and the gas furnace). There is very little work reported in the literature focusing on investigating the lean-burn limits of hydrogen-enriched LPG using a Bunsen burner. This study aims to correct this. In addition, as the effect of the Reynolds number on the combustion performance is another important factor to consider when developing domestic gaseous fuels, this study investigates and determine the lean-burning limits of hydrogen-enriched LPG under a wide range of both $H_2$ volumetric fractions (0% to 25%) and Reynolds numbers (600 to 1800). The range of the Reynolds numbers has been selected based on the laminar flame speeds normally used in domestic appliances, with the lower limit (600) being based on the practical limit for sustaining a stable flame (which a preliminary study revealed proved difficult for Reynolds numbers below 600), and the upper limit (1800) being set to include the full range of laminar flow. The volume fraction of $H_2$ enrichment was capped at 25% based on the findings of prior research [9] that showed that there was a significant change in the flame temperature and emissions for fuel mixtures with an $H_2$ volume fraction greater than 30%. The findings of the present study should provide useful reference data for improving the safety and efficient use of hydrogen-enriched LPG for domestic applications.

## 2. Experimental Setup and Method

The experimental test rig was based on that described by Wei et al. [32] and Zhen et al. [9, 33, 34] in their research studies on the characteristics of biogas-hydrogen premixed flames. Lee et al. [35] used a similar setup for their investigation of the flame stability of Landfill Gas (LFG) and LFG-mixed fuels. As the focus of this study is the lean-burning limits of hydrogen-enriched LPG, the stability of the flame with lean mixtures of fuel is an important consideration. The stability of the flame with lean mixtures is characterized by the process of 'flashback' [36], which -is the upstream propagation of flame back into the burner. This is a behavior associated with the laminar burning velocity of the fuel and the flow velocity of the fuel exiting the burner port. When the velocity of the fuel exiting the burner port falls below the laminar burning velocity, flashback occurs, which can lead to flame pulsation and explosion. In this study, the onset of flashback triggered by decreasing the fuel flow rate of the various components of the LPG-$H_2$ blends was used to establish lean-burning limits at various Reynolds numbers.

The experimental test rig (shown in Figure 1) consisted of two high-pressure gas cylinders (LPG and $H_2$), an air compressor, a Bunsen burner, and a data acquisition system. The LPG used in this study was a commercial gas (Shell Hong Kong Limited, 16 kg LPG) containing at least 29.7% $C_3H_8$, 69.3% $C_4H_{10}$, and less than 1% $C_3H_6$ and $C_4H_8$. Filters were used to remove impurities and moisture from the LPG and air streams. After passing through the pressure gauge (range from 0 to 2 bar) and flow meter, the LPG and $H_2$ were mixed before then being mixed with the air before being fed into the Bunsen burner. The burner was of the standard type, consisting of a mixing chamber and a nozzle with a long cylindrical tube. The tube had an outer diameter of 10 mm, an inner diameter of 7.86 mm, and a length of 275 mm. The burner length was selected to be long enough to ensure a fully developed flow at the nozzle outlet. Steel wool and steel mesh were placed inside the mixing chamber to ensure good mixing of the fuel and air. They also acted as a safety precaution by preventing potential upstream propagation of flame during flashback. A gasket ring was installed between the mixing chamber and the bottom of the burning nozzle to prevent gas leakage.

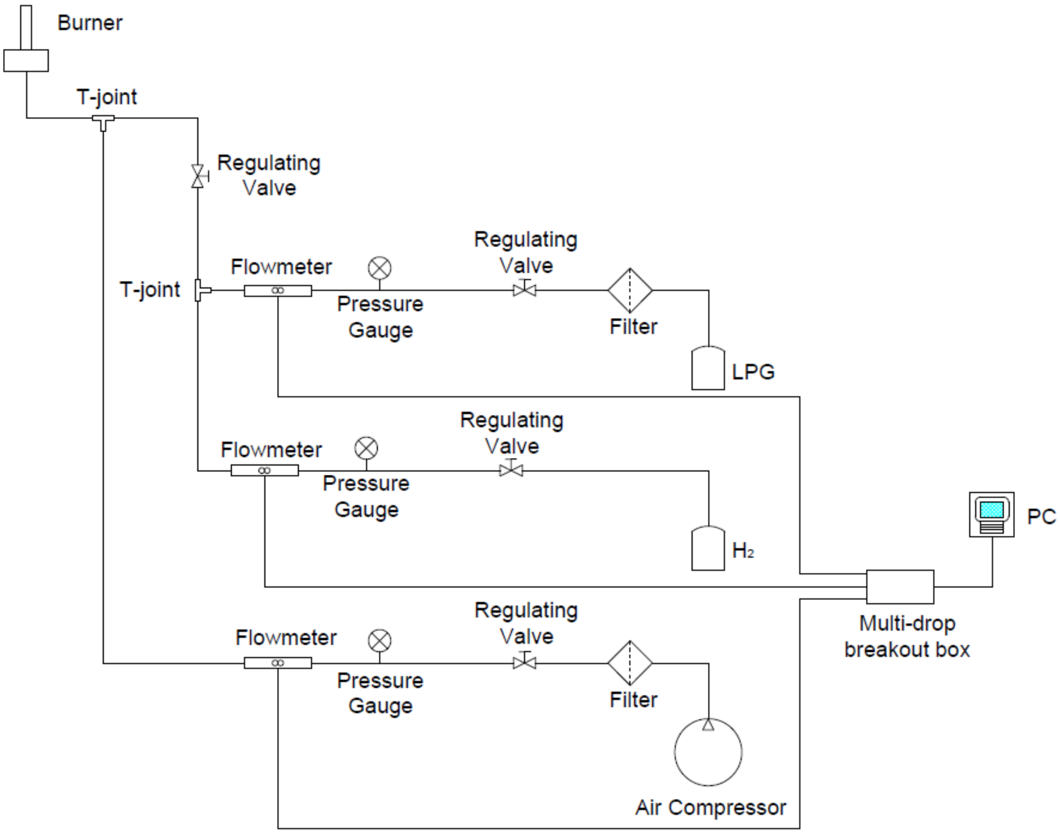


**Figure 1** Schematic diagram of the experimental setup.

The flow rates of the air and fuel were regulated and recorded by an integrated data acquisition system. Three PID-based electronic flow controllers were used, one each to control the volumetric flow rate of air, $H_2$, and LPG, respectively. The specifications of the flow controllers are given in Table 2. The input signal and output signal are both RS-232 serially encoded. HyperTerminal software was used to control the flowmeter settings directly via the RS-232 port of the computer connected to the flowmeters. During the experiment, all gases were maintained at 1 bar.

**Table 2** Specifications of the flow controllers used in the experiments.

| Gas | Brand | Catalog number | Flow range | Accuracy |
|---|---|---|---|---|
| Air | Cole-Parmer | GY-32907-71 | 0.1 to 10 lpm | ±0.8% of reading,<br>±0.2% full scale |
| H2 |  | GY-32907-67 | 0.01 to 1 lpm |  |
| LPG |  | GY-32907-69 | 0.05 to 5 lpm |  |

The experimental procedure to determine the lower burning limit (lean-burning) of $H_2$ enriched LPG was as follows: first, the air and fuel supply was set to a stoichiometric ratio, Φ, of 1, and then, set the air/fuel jet to the given Reynolds number while keeping the same air/fuel ratio. Next, the mixed fuel was ignited at the burner outlet to see if a stable open flame could be maintained. If the mixture could be ignited and a stable flame was maintained, the fuel flow was reduced (Reynolds number remaining unchanged) until flashback occurred, and the flowrates of the fuels and air at that time were recorded. This process was repeated three times and averaged to estimate the lean-burning limit of the LPG-$H_2$ mixture under any given Reynolds number.

## 3. Parameters Setting and Definition

Reynolds number was varied from 600 to 1800 in increments of 200 and is calculated based on the fuel-air mixture at room temperature as follows (Equation 1):

$$Re = \frac{\rho_{mix} v_{exit} d}{\mu_{mix}} \tag{1}$$

where $\rho_{mix}$ is the density of the fuel-air mixture (kg/m$^3$); $v_{exit}$ is the exit flow velocity from the burner (m/s); $d$ is the inner diameter of the nozzle, (m); and $\mu_{mix}$ is the dynamic viscosity of gaseous mixture (N.s/m$^2$).

$H_2$ fraction was set at 0% (pure LPG), 5%, 10%, 15%, 20% and 25%. The hydrogen volumetric percentage in the LPG-$H_2$ mixture was calculated using Equation 2:

$$H_2\% = \frac{V_{H_2}}{V_{H_2} + V_{LPG}} \times 100\% \tag{2}$$

where $V_{LPG}$ and $V_{H2}$ are the volumetric flowrates of LPG and $H_2$, respectively (m$^3$/s).

The lean-burning limit (LBL) was calculated from volumetric flowrates according to Equation 3. It was experimentally determined for each set of conditions.

$$LBL = \frac{V_{LPG} + V_{H_2}}{V_{LPG} + V_{H_2} + V_{air}} \times 100\% \tag{3}$$

where $V_{LPG}$, $V_{H2,}$ and $V_{air}$ are the volumetric flowrates of LPG, $H_{2,}$ and air, respectively (m$^3$/s).

Finally, the equivalence ratio is defined as in Equation 4.

$$\emptyset = \frac{\left(\frac{F}{A}\right)_{actual}}{\left(\frac{F}{A}\right)_{stoichiometric}} \tag{4}$$

where $\left(\frac{F}{A}\right)_{actual}$ is fuel-to-air ratio under actual conditions and $\left(\frac{F}{A}\right)_{stoichiometric}$ is the fuel-to-air ratio under stoichiometric conditions.

## 4. Validation

To validate the results in this study, we have compared the measured lean-burning limit of the LPG-air mixture with other published data. As there is little published data on the lean-burning limit of LPG-air mixture used with a Bunsen burner, reported flammability limits are instead used for comparison and validation. The results of the comparison are presented in Table 3. They show that the results of the present study match those reported by Hamidi and Ilminnafik [37] but are higher than those reported by Mishra and Rahman [14] by 33.9%, which is outside the usual acceptable error range in the comparative verification process (±10%). The difference can be attributed to two reasons: 1) the fractions of butane and propane in the LPG used by Mishra and Rahman are very different from those used in the present study and by Hamidi and Ilminnafik, and 2) the test methods used for each research study are different. The results of the comparison show that in practical applications, the expected lean-burning limit of gaseous fuel is different from its flammability limit obtained from standard tests, and, in general, the lean-burn limit is higher than the lower flammability limit.

**Table 3** Comparison of flammability/lean-burning limit of LPG-air mixture reported in the present study and the literature.

| LPG components | Flammability /Lean-burning limit (by volume) | Method | Ref | Absolute error | Relative error |
|---|---|---|---|---|---|
| 29% butane and 70% propane | 1.81% | Flammability tube +Visual observation | [14] | 0.93% | 33.9% |
| 50% butane and 50% propane | 2.7% | Combustion bomb +Visual observation | [37] | 0.04% | 1.5% |
| 69.3% butane and 29.7% propane | 2.74% | Bunsen burner +Visual observation | Present study | NA | NA |

## 5. Results and Discussion

Using the results of the experimental studies detailed above, the influence of $H_2$ addition (0% to 25%) and Reynolds number (600 to 1800) on the lean-burning limit of LPG-$H_2$ mixed fuel were analyzed, and regression analysis was used to obtain the correlations of the lean-burning limit, which were then used to plot a lean-burning map of hydrogen-enriched LPG.

### *5.1 Influence of $H_2$ Addition on the Lean-burning Limit of LPG-$H_2$ Mixed Fuel*

Figure 2 is a plot of lean-burning limits versus $H_2$ fraction at various Reynolds numbers. It can be seen from Figure 2 that the lean-burning limit generally increases with the increasing $H_2$ fraction at all Reynolds numbers. Thus, the lowest lean-burning limit (2.74%) occurs when no $H_2$ is added at Re = 600. With the increase in $H_2$ fraction from 0% to 25%, the lean-burning limit increases almost linearly from 2.74% to 3.72% at that same Reynolds number. This trend is reproduced across all the other Reynolds numbers. The lean-burning limit increases by, on average, 4.0% to 7.2% for every 5% increment of $H_2$ volumetric fraction under different Reynolds numbers ranging from 600 to 1800.

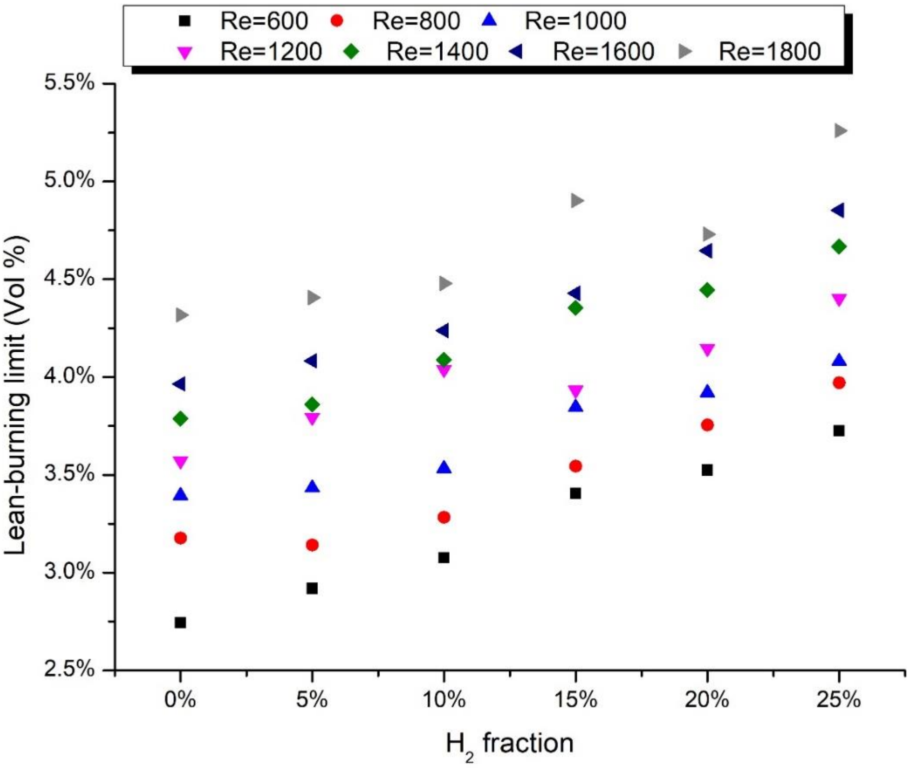


**Figure 2** Influence of $H_2$ fraction on the lean-burning limit of LPG-$H_2$ blends at a range of Reynolds numbers.

The increase in the lean-burning limit by adding more $H_2$ into LPG can be attributed to the increase in the laminar burning velocity of the mixed fuel. A numerical simulation was performed to quantitatively investigate the effect of $H_2$ addition on the burning velocity of the LPG-$H_2$ mixture. CHEMKIN software (ANYSYS) was used with a USC Mech II reaction mechanism model, which incorporates 111 species and 784 reactions [7]. For verification, the simulation results were compared with the data published by Jithin & Velamati [38] under the same inlet temperature and atmospheric condition. The simulation results agreed well with the published data, with a maximum discrepancy of 6.6% in predicting laminar burning velocity.

Figure 3 shows the simulation results. As can be seen, the highest fuel burning velocity occurs at the stoichiometric condition ($\Phi = 1$), increasing linearly from 40.75 cm/s to 42.34 cm/s as the $H_2$ fraction is increased from 0% to 25%. The flame could maintain sustained burning only when the burning velocity matched the fuel flow velocity. When the burning velocity is higher than the fuel flow velocity, flashback occurs, while flame lift takes place when the burning velocity is less than the fuel flow velocity. Adding $H_2$ into LPG increases the burning velocity of the mixed fuel. Thus, more fuel is required to offset the effect of increased burning velocity under the same Reynolds number, increasing the lean-burning limit.

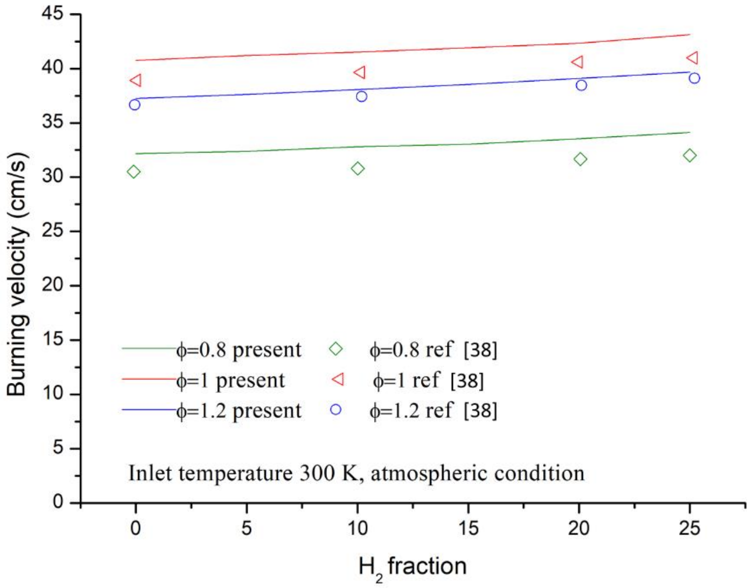
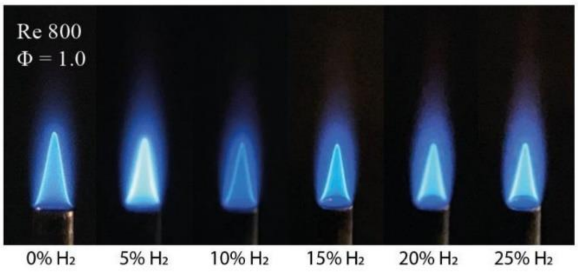


**Figure 3** Influence of the $H_2$ fraction on the burning velocity of LPG-$H_2$ blends at a range of equivalence ratios (Φ).

A study of the flame height also provides evidence for increased burning velocity resulting from the addition of $H_2$. Figure 4 shows images of the flames and measured heights of the reaction cone for different $H_2$ fractions at Re = 800 and Φ = 1.0. As can be seen, the height of the reaction cone falls as the $H_2$ fraction is increased. For a stable premixed flame, the perpendicular component of the fuel jet velocity should be equal to the burning velocity at all points along the flame front [39]. When hydrogen is added to LPG, the kinematic viscosity of the air/fuel mixture increases. Therefore, the air/fuel mixture volume flow rate and the mean exit flow velocity must increase proportionally to maintain a constant Reynolds number. It would be expected, then, that the conical flame front would increase in height to match the increased flow velocity if the laminar burning velocity remains unchanged. However, the measurement shows that the reaction cone height has, instead, reduced, which provides clear evidence that the hydrogen addition has, rather, increased the burning velocity of the blended fuel. The same behavior was observed at all the other Reynolds numbers for the same equivalence ratio. This observation is consistent with that reported by Zhen et al. [40] in their study of LPG-$H_2$ mixed fuel conducted at Re = 1500 and Φ = 1.0.



| $H_2$ fraction in fuel blends | 0% $H_2$ | 5% $H_2$ | 10% $H_2$ | 15% $H_2$ | 20% $H_2$ | 25% $H_2$ |
|---|---|---|---|---|---|---|
| Flame reaction cone height (mm) | 20.36 | 20.34 | 19.74 | 19.72 | 19.70 | 19.09 |

**Figure 4** Images of flames and measured heights of the reaction cone for the given $H_2$ fractions at Re = 800 and Φ = 1.0.

Figure 5 shows the variation in flame shape for a range of equivalence ratios at Re = 800. A visual comparison of flame images for 0% $H_2$ and 25% $H_2$ shows that the overall flame shapes and the characteristics remain almost the same. This supports the contention that there is a good blending of the LPG and $H_2$ in the fuel jet, even though the physical properties of LPG and $H_2$ are quite different. The yellow tips visible in the flames of $H_2$-rich mixtures are characteristic of incomplete burning.

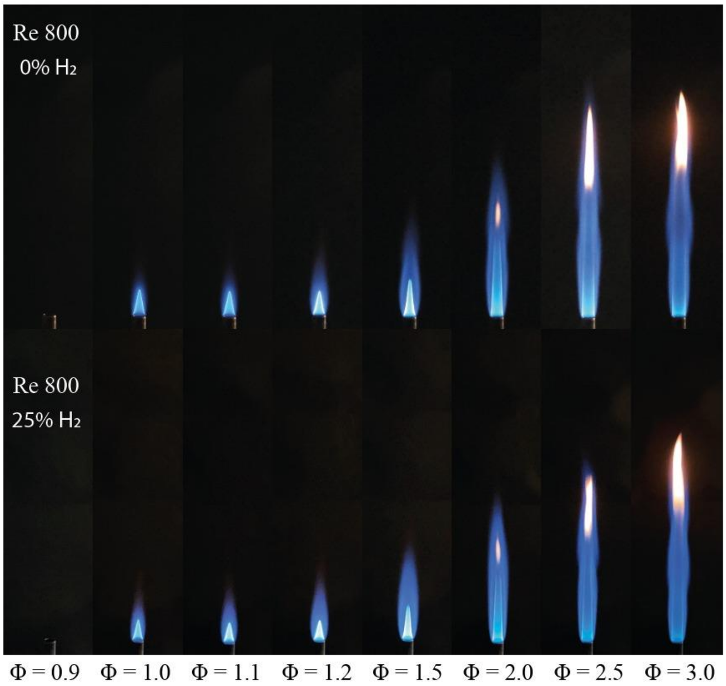


**Figure 5** Flame shapes with 0% and 25% $H_2$ addition for a range of equivalence ratios and Re = 800.

### *5.2 Influence of Reynolds Number on the Lean-burning Limit of LPG-$H_2$ Mixed Fuel*

Figure 6 shows a plot of lean-burning limit versus Reynolds number for a range of $H_2$ fractions. As can be seen, the lean-burning limit increases with increasing Reynolds number for all $H_2$ fractions. Without $H_2$ addition (for pure LPG), the lean-burning limit increased from 2.74% to 4.32% when the Reynolds number increased from 600 to 1800. The mixed fuels showed a similar trend. This increase in the lean-burning limit with the increasing Reynolds number can be attributed to the increased burning velocity. Fu et al. [41] reported that an increase in Reynolds number enhances the laminar burning velocity due to the flame stretch effect caused by the high flow velocity associated with high Reynolds numbers. A richer mixture of fuel is therefore needed to maintain a stable flame.

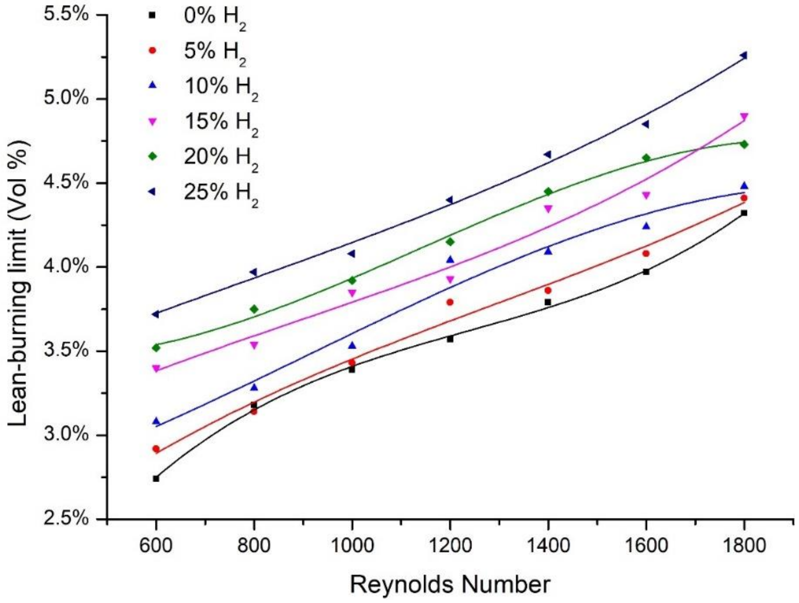


**Figure 6** Influence of Reynolds number on the lean-burning limit of LPG-$H_2$ blends for a range of $H_2$ fractions.

Overall, it can be concluded that the lean-burning limit of hydrogen-enriched LPG is greater than that of pure LPG due to the combined effect of increasing hydrogen fraction and Reynolds number of the air/fuel jet.

A cubic polynomial regression analysis was used to obtain correlations of the lean-burning limit of LPG-$H_2$ mixture under different $H_2$ fractions, and the results are summarized in Table 4. All the correlations apply within the Reynolds number range of 600 ≤ Re ≤ 1800 and return coefficients of determination ($R^2$) values of between 0.94949 and 0.99715, indicating the high credibility of the correlations. These correlations can be used as empirical formulae to predict the lean-burning limit of hydrogen-enriched LPG for a range of $H_2$ fractions.

**Table 4** Correlations of the lean-burning limits of LPG-$H_2$ mixtures obtained by regression analysis.

| $H_2$ fraction | Correlation | $R^2$ | Applicability |
|---|---|---|---|
| 0% | $\Phi = 1.36174 \times 10^{-11}Re^3 - 5.05794 \times 10^{-8}Re^2 + 7.06931 \times 10^{-5}Re + 3.72846 \times 10^{-4}$ | 0.99715 | $600 \leqslant Re \leqslant 1800$ |
| 5% | $\Phi = 4.14659 \times 10^{-12}Re^3 - 1.62264 \times 10^{-8}Re^2 + 3.19612 \times 10^{-5}Re + 0.01468$ | 0.97489 | |
| 10% | $\Phi = -3.76561 \times 10^{-12}Re^3 + 9.86051 \times 10^{-9}Re^2 + 5.5728 \times 10^{-6}Re + 0.0244$ | 0.94949 | |
| 15% | $\Phi = 3.65455 \times 10^{-12}Re^3 - 9.58601 \times 10^{-9}Re^2 + 1.82871 \times 10^{-5}Re + 0.02556$ | 0.96004 | |
| 20% | $\Phi = -7.31313 \times 10^{-12}Re^3 + 2.51148 \times 10^{-8}Re^2 - 1.60591 \times 10^{-5}Re + 0.0376$ | 0.99199 | |
| 25% | $\Phi = 2.34531 \times 10^{-12}Re^3 - 5.26248 \times 10^{-9}Re^2 + 1.42604 \times 10^{-5}Re + 0.03013$ | 0.98637 | |

### *5.3 A Lean-burning Limit Map for Hydrogen-enriched LPG*

Based on the correlations given in Table 4, a lean-burning map for hydrogen-enriched LPG can be plotted (Figure 7). The lean-burning map with its series of lean-burning limit isolines can serve as a useful visualization tool for researchers, engineers, and technicians who need to check the lean-burning limit of LPG-$H_2$ blended fuel under certain Reynolds numbers and $H_2$ fractions. Considering the applicability of the applied correlations, 600 ≤ Re ≤ 1800, the isolines with Reynolds numbers lower than 600 are expressed by dash lines to indicate the lack of real data.

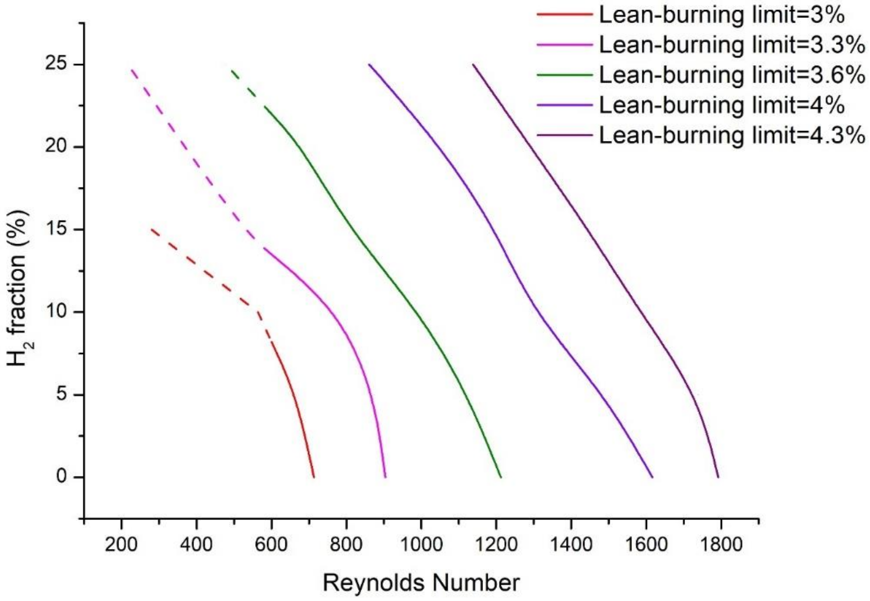


**Figure 7** A lean-burning limit map for hydrogen-enriched LPG.

## 6. Conclusions

This paper presents the results from an experimental study to investigate the lean-burning limit of hydrogen-enriched liquefied petroleum gas (LPG) with a Bunsen burner under a wide range of Reynold numbers (600 to 1800) and hydrogen ($H_2$) volumetric fractions (0% to 25%). Also presented are correlations of the lean-burning limit of LPG-$H_2$ mixtures obtained by regression analysis. The main findings can be summarized as follows:

1. The lowest lean-burning limit of LPG-air mixtures measured in this study using a Bunsen burner is 2.74%. This value is higher than the lower flammability limits obtained from standard test methods for LPG with a similar composition.
2. The lean-burning limit of hydrogen-enriched LPG measured by a Bunsen burner generally increases with increasing hydrogen fraction at all Reynolds numbers ranging from 600 to 1800. The lean-burning limit is increased by, on average, 4.0% to 7.2% for every 5% increment in the $H_2$ volumetric fraction.
3. The lean-burning limit of hydrogen-enriched LPG measured by a Bunsen burner increases with increasing Reynolds number for all $H_2$ fractions (0% to 25%). Correlations of the lean-burning limit of hydrogen-enriched LPG versus Reynolds number obtained by cubic polynomial regression analysis return $R^2$ values ranging from 0.94949 to 0.99715.

4. A lean-burning limit map of hydrogen-enriched LPG has been developed. The lean-burning map with a series of lean-burning limit isolines can serve as a useful visualization tool to check the lean-burning limit of LPG-$H_2$ fuel mixtures at a given Reynolds number and $H_2$ fraction.

This study has used the Bunsen burner, the forerunner of the modern gas-stove burner and the gas furnace, to obtain the lean-burning limits of LPG-$H_2$ mixtures. The results of this study provide reference values of the lean-burning performance of hydrogen-enriched LPG fuel for practical domestic use, such as for cooking or heating. Further investigation is necessary for the safe and reliable utilization of hydrogen-enriched LPG as a domestic fuel. Some of the areas for future investigation include the effect of intermediate species on the combustion process, a gas interchangeability analysis of various domestic LPG gas appliances in the market to assess their readiness to use hydrogen-enriched LPG, the thermal characteristics of the impinging flame, the optimal hydrogen-blending ratio for practical use, and the development of proper guidelines for fuel blending, delivery, usage and safe handling for domestic use.

## Author Contributions

Udaya Kahangamage: Conceptualization, Writing-Reviewing and Editing, Supervision. Yi Chen: Methodology, Writing-Reviewing and Editing, Supervision. Chun Wah Leung: Funding acquisition, Supervision. Tung Yan Ngai: Investigation.

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## Competing Interests

The authors have declared that no competing interests exist.

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