Experimental Investigation of Iraqi Liquefied Petroleum Gas (ILPG)/H_2/Air Premixed Flame Stability Zone

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Highlights:

- The combustion system in this study was designed to work with Iraqi liquefied petroleum gas (ILPG) blended with hydrogen gas, consisted of non-swirling burners with different diameters, a mixture preparation unit operating on the principle of partial pressure of components according to the Dalton law and a high-speed camera, and was aimed to investigate the flame stability zone (flame flashback and blow-off).
- The laminar boundary layer mechanism described by Lewis and von Elbe for flame flashback and blow-off limits was adopted with high-speed recordings and observations of flow rate at flame flashback and blow-off.
- Fuel mixtures of ILPG and hydrogen gas with different equivalence ratios from (0.6-1.4) with an increment of 0.2 were used.
- The combustion system was operated at atmospheric conditions (298K and 1 bar) for the unburned mixture.
- The effect of burner diameter, equivalence ratio and hydrogen blending ratio on the flame stability zone was investigated.

Abstract. Flame stability, environmental changes and fossil fuel shortage represent major challenges to any successful combustion device utilization. In this study, the stability zone of laminar premixed ILPG/H_2-air flames was investigated experimentally. Non-swirling burners with different diameters (10, 12.5, and 17 mm) were employed to characterize the flashback and blow-off limits. Different hydrogen blends (0%-50%) at equivalence ratios (ER) (0.6-1.4) were used. The results show that maximum flashback limits occurred at ER slightly richer than stoichiometric, with the mixture flow rate at a flashback of (3.75, 7.25 and 14) LPM for the 50% hydrogen blending ratio and a burner diameter of (10, 12.5 and 17 mm), respectively. When hydrogen blending was 50% at stoichiometric condition, the critical velocity gradient at flashback increased from (469.9-650.8 1/s) with 10 mm diameter, and the critical velocity gradient at blow-off increased from (1538-2936 1/s). It was observed that the flashback limits decreased with increasing burner diameter. Its limit increased with increasing hydrogen addition to the ILPG. The blow-off limit increased with increasing fuel concentration. This paper further presents the stability zone for ILPG/air combustion for a non-swirling burner with a 10-mm diameter and different hydrogen blends. It was found that the stability zone was narrow on the lean combustion side and enhanced with increasing diameter and hydrogen addition.

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1 Introduction

The conditions for stable flames are bounded between the limits of the flame flashback and blow-off phenomena. If the velocity of the unburned mixture is greater than the laminar flame speed, the flame will be detached from the burner rim. The flame in this case is called a lift-off flame. If the velocity of the unburned mixture is increased significantly, flame blow-off occurs. However, if the velocity of the unburned mixture becomes lower than the laminar flame speed, the flame will be detached from the burner rim and moves in the reverse direction of the mixture flow. This phenomenon is called flame flashback. The determination of the limits of these phenomena (flashback and blow-off) is very significant for the safe operation of combustion systems using liquefied petroleum gas (LPG) as a primary fuel and hydrogen as a secondary fuel. Several papers related to flame stability have been published. Lewis and Elbe [1] first conducted an experimental test and produced a prediction model for boundary layer flashback. Syred, *et al*. [2] investigated the stability zone of combustion flames by determination of the flashback propensity and the flame blow-off limit of a swirl burner with a group of gaseous fuel blends. The fuel mixtures included methane, methane/H_2 blends, pure H_2 and (COG) coke oven gas.

Kurdyumov, *et al*. [3] experimentally and theoretically investigated the flame flashback propensity of premixed flames in a propane/air duct with a constant equivalence ratio. They presented a model for premixed flame propagation in the boundary layer. Sayada, *et al*. [4] investigated the flame stability zone when changing the swirl number of the burner of various syngas compositions in an atmospheric premixed flame. Lean blow-out and flashback experiments were performed using fuel mixtures containing variable amounts of H2, and CH_4 at two swirl numbers. They also investigated the effect of swirl number on flashback propensity and found that when the swirl number was reduced from 0.66 to 0.53, the flashback propensity of various syngas/air mixtures was reduced but it did not greatly affect the blow-off limit. Syred, *et al*. [5] used two swirl burners with various gaseous fuels such as (natural gas, CH_4, and coke oven gas COG). Open and confined flames were both investigated to detect the impact of confinement on the flame stability zone. Dam, *et al*. [6] used a burner unit with Pyrex tubes of different diameters (10.4 mm, 7 mm, and 6 mm). The critical velocity gradient at flashback (g_f) for 25% H_2 to 75% CO was measured. It is interesting to note that the effect of the burner diameter was smaller for lean mixtures. Their experimental result for rich conditions showed that the (10.4) mm diameter burner had g_f values lower than the 6.0-mm and 7.0-mm diameter burners. Ebi and Clemens [7] investigated the boundary layer flashback of swirling turbulent lean premixed flames of methane/H_2/air in a model combustor featuring a mixing tube. The focus of their work was on improving the understanding of the flow-flame interface during flashback. Shaffer, *et al*. [8] studied the changeability in the composition of syngas and its effect on flashback propensity. To address this phenomenon they used a jet burner structure to advance regular data for a wide range of compositions under turbulent flow conditions. Aravind, *et al*. [9] studied the effect of hydrogen addition on the combustion characteristics of different LPG-air mixture compositions.

Abdulsada 10] experimentally and numerically studied flashback in a tangential entry swirl burner originally designed for the combustion of poor-quality fuels. He found that the velocity gradient at flashback was similar to the critical velocity gradient of Lewis and Elbe [1]. Mishra [11] found that the flame blow-off increased with an increase of the concentration of fuel for CNG-air premixed combustion. Similar ways of increasing the flame blow-off limit were found with an increase of the burner diameter, as shown in Figure 1.

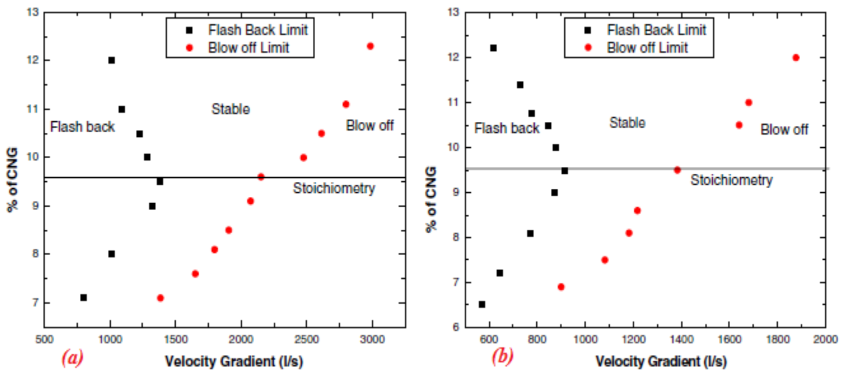

Figure 1 Critical velocity gradient at flashback and blow-off of $CNG-air$ premixed combustion: (a) 12-mm burner diameter, (b) 15-mm burner diameter [11].

Patel and Shah [12] experimentally investigated the flame appearance, flame stability, soot free length fraction (SFLF) and CO emission of LPG diffusion flames. They found that SFLF increased with increasing air velocity at a constant fuel velocity and they also found that the blow-off velocity of the diffusion flame increased as the fuel velocity increased.

Flame stability is an important concept in burner design and operation because burners must stay ignited through a reasonable range of fuel and oxidizer mixtures and flow characteristics. This study aimed to shed light on this stability for ILPG-H2 air mixture flames.

2 Calculation Methodology

Kalantari and McDonell [13] showed that flame flashback and flame blow-off can occur as a result of at least four mechanisms: (1) core flow flashback, (2) combustion instability induced flashback, (3) combustion induced vortex breakdown (CIVB), and (4) boundary layer flashback. The present study concentrated on the fourth mechanism using a non-swirling burner in the experimental rig. To investigate this concept in more detail, a glass tube burner was constructed in which the flame stabilizes downstream of the burner edge.

The critical velocity gradient model neglects the flame flow interaction and assumes that the flow velocity remains undisturbed. Figure 2 shows that the flame front is stabilized inside the burner, close to the wall. The velocity profile of the unburned mixture *u(y)* represents a laminar flow approaching the flame front. The flame speed denoted by $S_L(y)$ decreases close to the wall due to heat loss and the quenching of radicals [14].

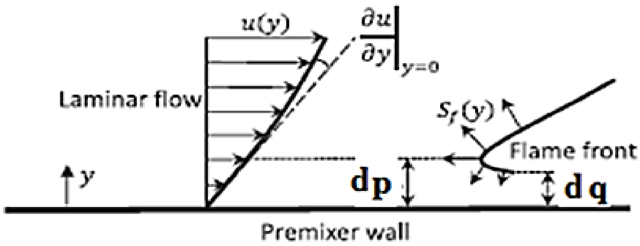

Figure 2 Schematic of the critical velocity gradient prediction model [14].

Kroner, *et al*. [15] used the flame quenching approach or Peclet number approach. They defined the quench parameter in terms of the laminar flame speed and characteristic length scale [15] as follows:

$$C_{quench} \leq \frac{\alpha}{S_L^2}\frac{U}{D} \quad (1)$$

Eq. (1) can be modified to show that:

$$\frac{UD}{\alpha} \sim C_{quench}\left(\frac{S_L D}{\alpha}\right)^2 \quad (2)$$

$$\mathrm{Pe}_{\mathrm{flow}} \propto (\mathrm{Pe}_{\mathrm{flame}})^2 \quad (3)$$

In this study, the definition of the critical velocity gradient in the boundary layer flashback mechanism by Lewis and Elbe [1] was adopted, as expressed in Eq. (4):

$$g_f = \frac{4Q}{\pi R^3} \quad (4)$$

where Q is the volumetric flow rate (cm^3/s) and R is the tube radius (cm). The value of g_f decreases with the decrease of the velocity of the unburned fuel and the flame is stabilized at a location close to the burner rim. When the unburned gas velocity becomes smaller than the laminar flame speed, S_L, the flame propagates upstream of the mixture flow. This state is referred to as boundary layer flashback and the critical velocity g at which the flashback condition is detected is denoted by g_f.

The flashback and blow-off limits are determined experimentally. The critical velocity gradient at flashback g_f primarily depends on the laminar flame speed and can be expressed as follows:

$$g_f = \frac{S_L}{d_P} \tag{5}$$

where d_p is the flame penetration distance, which normally correlates with the quenching distance, d_q, as follows:

$$d_P = c_1 . d_q \tag{6}$$

where c_1 is a burner constant. The quenching distance again generally depends on the laminar flame speed and the mixture thermal diffusivity by [14]:

$$d_q = 2\sqrt{c_2}\,\frac{\alpha}{S_L} \tag{7}$$

where C_2 is a constant that depends on the burner configuration. Combining Equations (5-7) yields:

$$g_f = c\,\frac{SL^2}{\alpha} \tag{8}$$

where:

$$c = \frac{1}{2c_1\sqrt{c_2}} \tag{9}$$

If the laminar flame speed and thermal diffusivity α are identified it is possible to calculate the critical velocity gradient at flame flashback of the mixture when the value of constant *C* is available. However, the critical velocity at flashback for some fuel blends is unknown and the value of *C* for the fuel mixture is not freely available.

Dam, *et al*. [6] found that the trend of variation of the term of C_{quench} is not affected by the swirl number of the burner and the type of fuel mixture. Interestingly, a relative Peclet number approach in comparison with the critical gradient theory by Lewis and von Elbe [1] has also been applied to describe the flashback and blow-off in the boundary layer.

The background of the mathematical analysis of the Peclet number approach is identical for the boundary layer mechanism of the flashback process, as can be seen from comparing Eqs. (2) and (8). The present study is concerned with flame flashback and blow-off for ILPG-H_2 blends with hydrogen blending ratios ranging from 0 to 50%.

3 Experimental Rig and Test Procedure

All experiments were conducted in the Mechanical Engineering Department Laboratories of the University of Babylon in Iraq on a rig constructed specially for this purpose. This consisted of a burner unit, an ignition circuit and a control unit, a mixture preparing unit, a high-speed photography unit and safety precautions (flame arrestor and flame trap) to prevent flame flashback to the mixer as shown in Figure 3 (a) and (b).

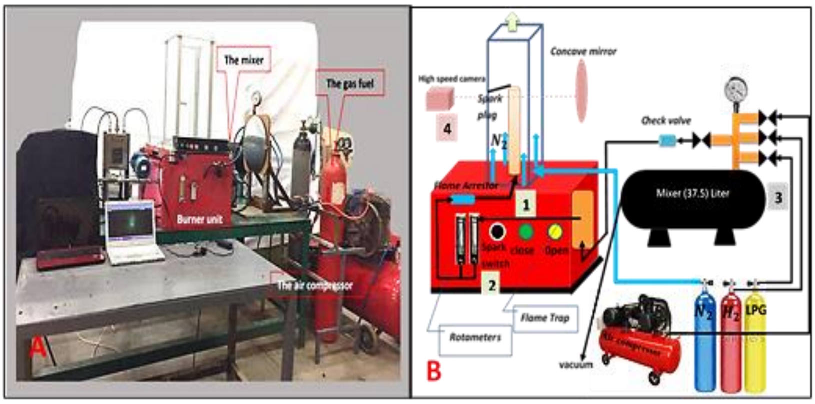

Figure 3 The experimental apparatus used in the present study: (a) photograph of rig, (b) schematic diagram of rig.

Figure 3(b) shows a schematic representation of the ILPG-H_2-air flame test rig. The ILPG for this experimental study was supplied from a commercially available ILPG cylinder, while the H_2 was supplied from a special bottle. The ILPG composition was obtained by gas chromatography. It consisted of 0.7% ethane, 55.8% propane, 41.5% butane, and 2% pentane. The preparation of the ILPG/H_2-air mixture depended on the partial pressure principle of each component in a 37.5-liter mixing tank at 4 bar total pressure, as shown in Figure 3.

The air for this experiment was supplied from a reciprocating air compressor. The ILPG and hydrogen were measured by regulator and needle valves, as shown in Figure 3, depending on the partial pressure. The flow rate of the unburned mixture was metered using a calibrated rotameter. The test procedure steps were as follows:

1. Set the ILPG/H_2 blending ratio.
2. Set the equivalence ratio.
3. Prepare the required mixture in the mixing tank.
4. Open the valve and supply the mixture to the burner at the required flow rate.
5. Ignite the mixture by the spark plug.
6. Adjust the flow rate to obtain a stable flame.
7. Increase the mixture flow rate slowly to obtain flame lift off and continue until blow-off occurs and record the flow rate.
8. Repeat steps 1-6.
9. Reduce the mixture flow rate until the flame is not able to anchor on the burner port rim and moves upstream of the burner and record the flow rate.
10. Repeat the above steps for other equivalence ratios from (0.6 to 1.4) and other blending ratios from (0 to 50%).

For each equivalence ratio and blending ratio the experiment was repeated at least five times; the average values were used in the subsequent analysis.

In the present study, the data of flame flashback and flame blow-off were obtained by visual observation using an AOS-Q-PRI portable high-speed camera and a large concave mirror with a diameter of 40.5 cm and a focal length of 68 cm depending on the principles of the Schlieren photography technique (Bunjong, *et al.* [16]), as shown in Figure 4.

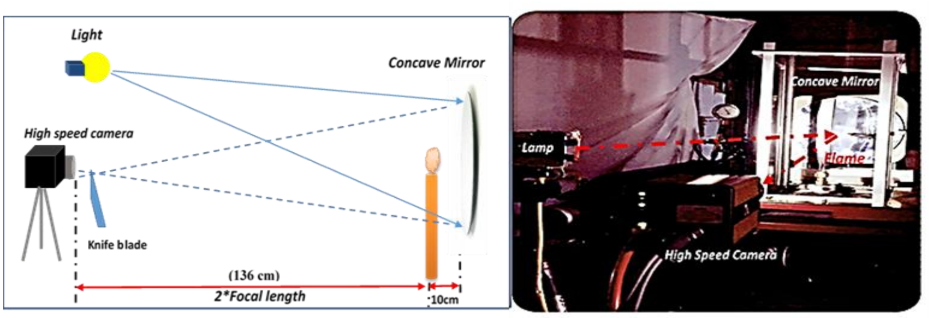

Figure 4 Capturing unit setup.

The mixing process used was based on Gibbs-Dalton Law of the partial pressure for each mixture component to obtain an accurate equivalence ratio. The preparation of the mixture was done inside a mixing tank that was designed for this purpose. The total pressure in the mixing tank was set at 4 bar for each test. The procedure of each test is summarized in the flowchart shown in Figure 5.

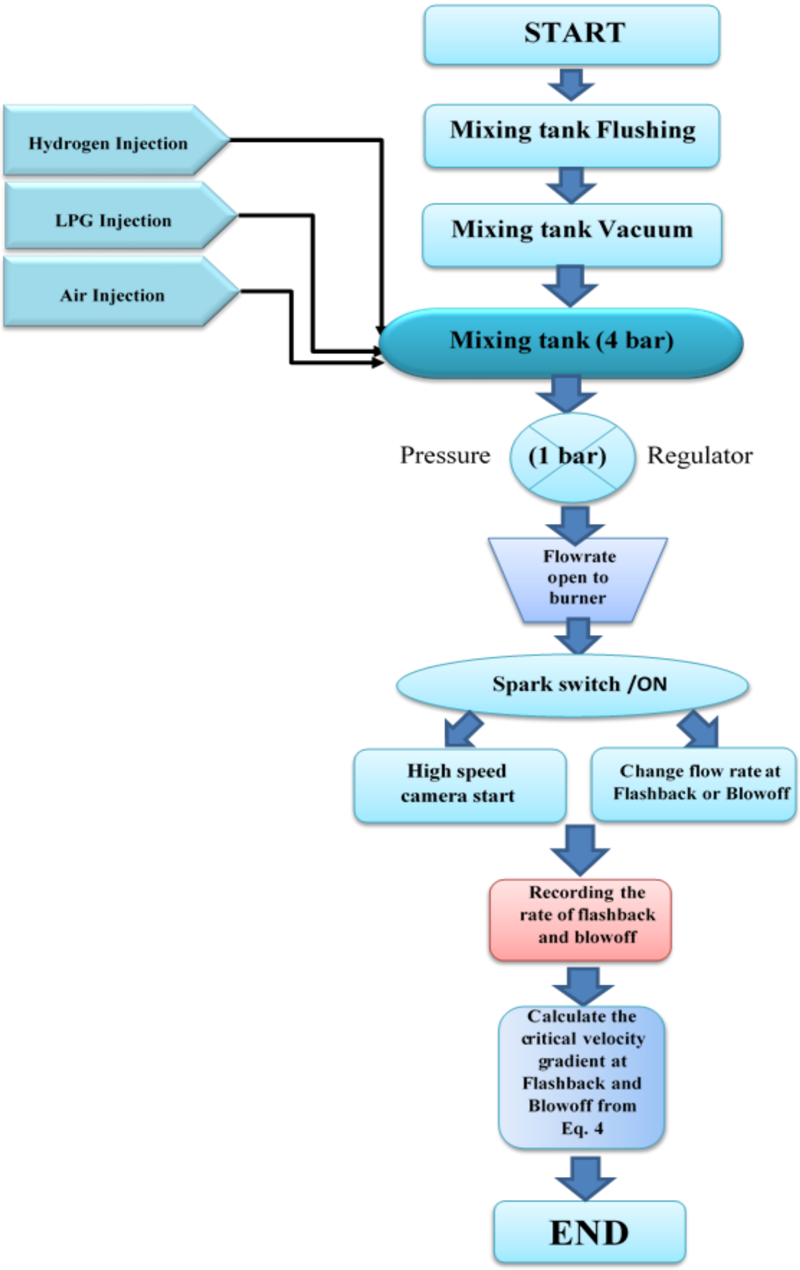

Figure 5 Flowchart with each experimental test.

4 Results and Discussions

In the present study, experiments were conducted to determine the flame flashback and blow-off for ILPG-air combustion at laminar premixed condition with different blending ratios of hydrogen and a wide range of equivalence ratios. Figure 6 shows the stability zone for a range of ILPG-H_2 blending ratios. It can be seen in this figure that the region of stability is narrow in lean condition and diverges in rich condition. The divergence of the stability zone in rich condition is due to the increasing blow-off limit with increasing fuel concentration, while the flashback limit decreases with increasing fuel concentration, as shown in Figure 6, due to the high flammability of hydrogen, [18]. It is also noticed that flame flashback increased by increasing the blend of hydrogen due to the high flame speed of hydrogen compared with ILPG [18]. The flame flashback limit for any burner has its maximum value at a mixture slightly richer than stoichiometric [13]. On both sides of this maximum value, the flashback limit decreases by varying the fuel concentration around the stoichiometric condition. The results of the present study are comparable with the laminar flame speed of CH_4/air combustion obtained by [17].

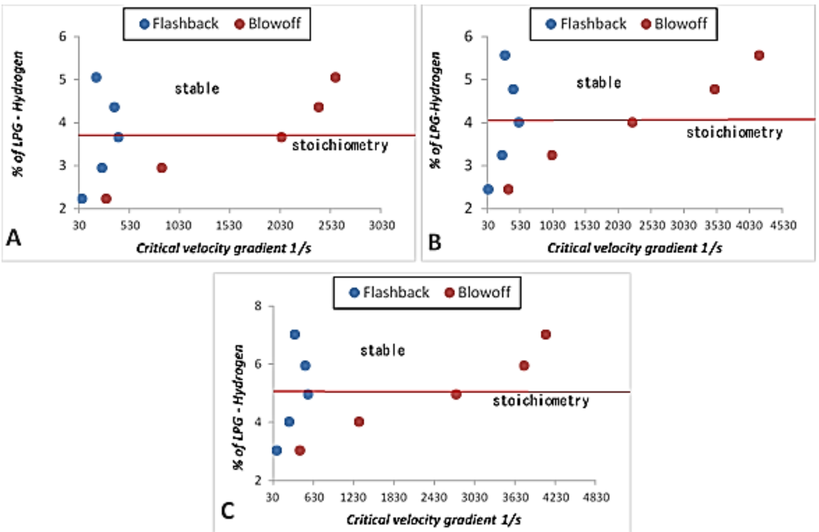

Figure 6 Blow-off and flashback limits as a function of critical velocity gradient for 10-mm burner diameter: (A) 0% H_2-100% ILPG, (B) 10% H_2-90% ILPG, (C) 30% H_2-70% ILPG.

Figure 7 shows the effect of the hydrogen blending ratio on the stability zone of ILPG-air combustion, indicated by the critical velocity gradient at flashback and blow-off. It can be seen that the critical velocity gradient at blow-off increased with increasing blending of hydrogen due to the high flammability of hydrogen compared with ILPG [18]. It can also be seen that the critical velocity gradients at flashback increased with increased blending of hydrogen due to the high flame speed of hydrogen [18]. The figure also indicates that the stability zone was enhanced with increasing blending ratio of hydrogen for all equivalence ratios, which is important for safe operation of the combustion system as in a gas turbine [11].

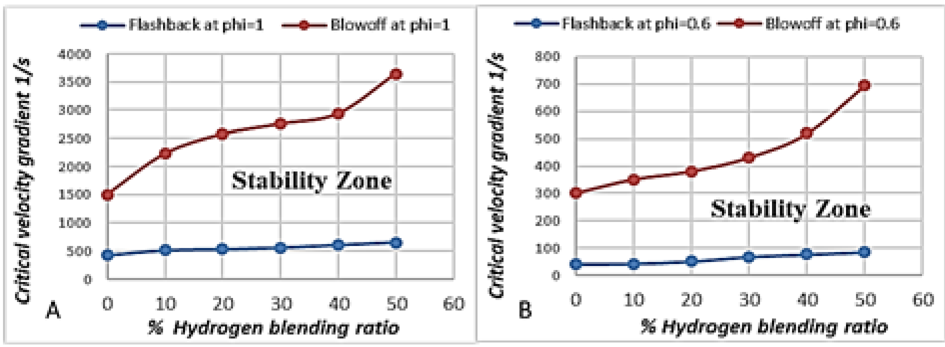

Figure 7 Blow-off and flashback limits for the 10-mm diameter burner.

The effect of equivalence ratio on total mixture flow rate at the flashback limit for different burner diameters is shown in Figure 8. It can be seen that a large diameter implies a higher flow rate at flame flashback due to the reduction of the boundary layer effect [18]. It can also be seen that the hydrogen blending ratio increased the flow rate at which flashback occurred due to the high burning temperature and high hydrogen flame speed which increases the flame flashback limit. The maximum increase of flow rate occurred at slightly richer than stoichiometric (φ = 1.05).

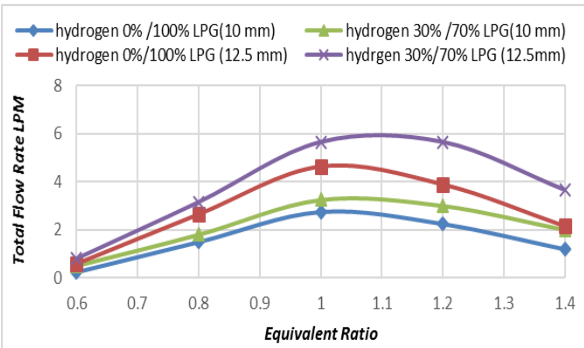

Figure 8 Flow rate at flame flashback for different burner diameters.

The values of g_f were calculated for different flow rates at different burner diameters for pure ILPG and a 30% H_2 blending ratio, as presented in Figure 9. It was observed that the maximum flame flashback occurring in the neighborhood of the stoichiometric mixture decreased with increasing burner diameter and increased with an increasing percentage of hydrogen blending due to the quenching effects at the burner rim and the high burning temperature of hydrogen [18].

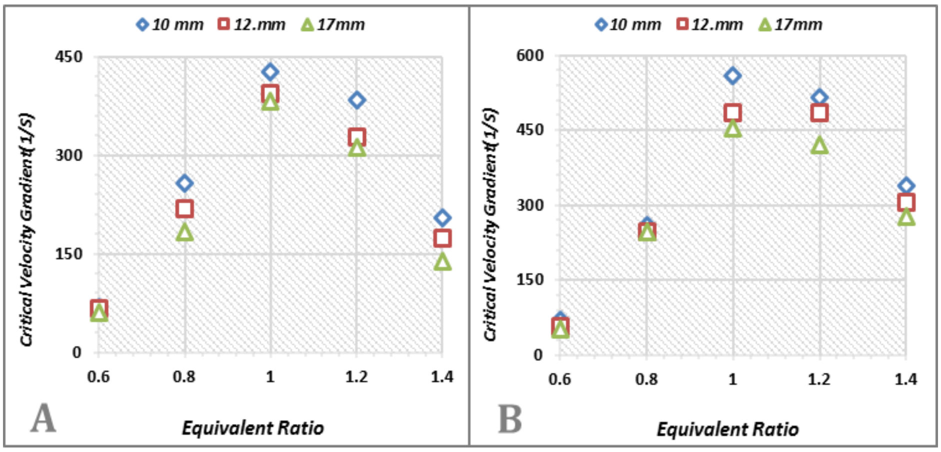

Figure 9 Critical velocity gradients of mixtures for different burner diameters: (A) pure ILPG, (B) 30% H_2-70% ILPG.

One of the biggest challenges to flame stability is to prevent the occurrence of flame flashback. Figures 10, 11 and 12 show the analysis of flame flashback as a function of velocity gradient for different burner diameters with different blending ratios of hydrogen. It can be seen that flame flashback increased with increasing blending ratio of hydrogen due to the high flame speed of hydrogen gas and the high burning temperature [18]. It can also be seen that maximum flashback occurred at stoichiometric condition due to the high burning temperature, which produces a high laminar flame speed.

The other phenomenon that affects the stability of the flame in addition to the phenomenon of flashback is blow-off. An experimental test was conducted to study the flame blow-off limit. Flame blow-off is determined by increasing the flow rate of the unburned mixture to a value that is greater than the laminar flame speed where the flame moves away from the burner tube port or rim. This movement of the flame away from the burner rim causes air entrainment at the base of the flame, which reduces the equivalence ratio and hence affects flame blow-off. Thus, if the blend of hydrogen is increased, the flame blow-off limit is increased due to the high flammability of hydrogen compared with ILPG.

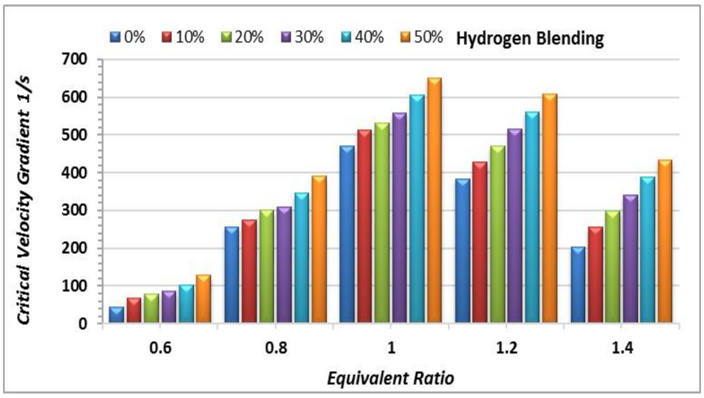

Figure 10 Critical velocity gradient at flashback at 10-mm burner diameter.

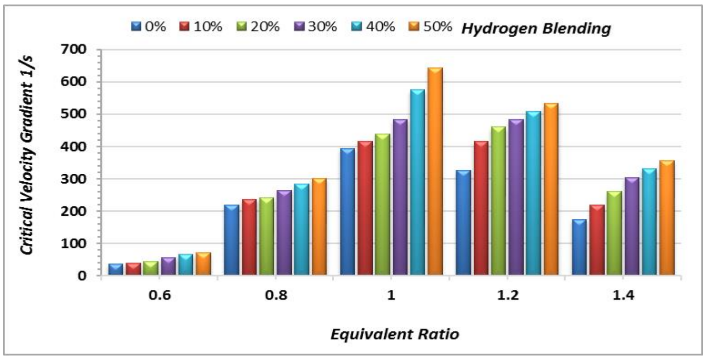

Figure 11 Critical velocity gradient at flashback at 12.5-mm burner diameter.

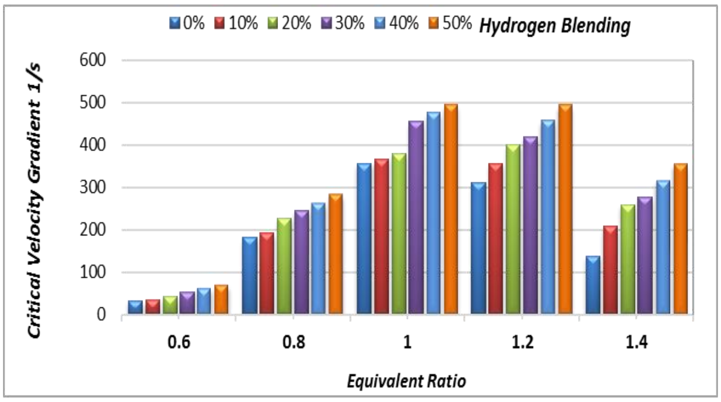

Figure 12 Critical velocity gradient at flashback at 17-mm burner diameter.

The experimental test of flame blow-off in terms of the velocity gradient for a 10-mm burner diameter is shown in Figures 6 and 7 above. Similar to flame flashback, the critical velocity gradient at blow-off was calculated by using Eq. 4. Thus, the flame must be kept between the flame flashback and the blow-off zone for smooth and safe operation of the combustion system.

Figure 13 shows photographs of the stable flame, flame blow-off, and flame flashback for ILPG/H_2/air combustion in the present work. As mentioned above, flame flashback and blow-off occur due to the separation of the boundary layer, as shown in Figure 2. Figure 14 shows a photograph of flashback occurrence and the propagation of the flame upstream of the 10-mm burner diameter and 50% ILPG, 50% H_2 with a 1.2 equivalence ratio. This phenomenon affects safe operation of the combustion system and harms the burner structure.

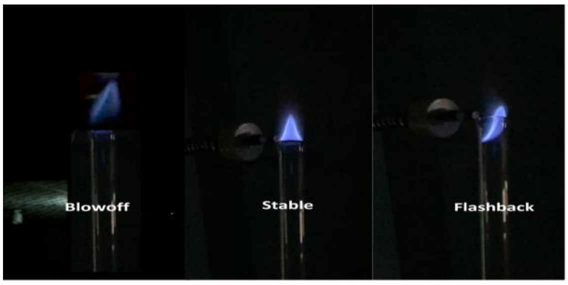

Figure 13 Stable flame, blow-off and flashback for ILPG/H_2/air combustion in the present work.

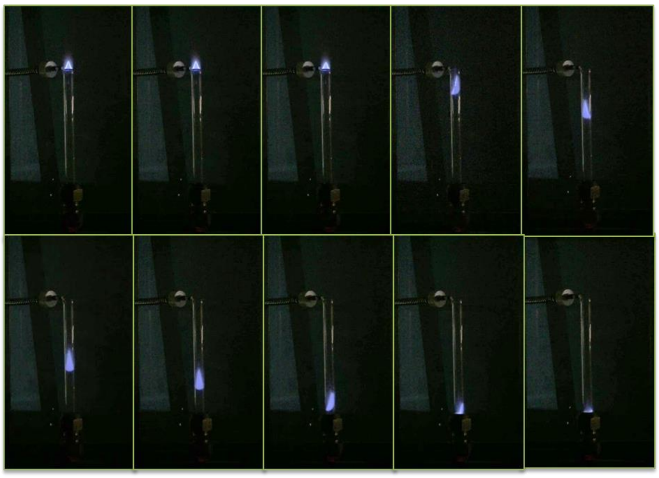

Figure 14 High-speed camera images from the present study of flame flashback.

5 Conclusions

This paper describes a range of experiments conducted for the analysis of the flame stability zone of ILPG premixed combustion in a non-swirl burner at different burner diameters for a range of hydrogen blend ratios and a range of equivalence ratios. The following conclusions could be drawn.

The flashback limits and blow-off limits of premixed ILPG-air flames with different hydrogen blend ratios (0%-50%) for different burner diameters, namely (10, 12.5, and 17) mm, and a range of equivalence ratios (0.6-1.4) were measured. All tests were conducted at atmospheric pressure and ambient burner inlet temperature. It was found that the maximum flame flashback limit occurred at approximately stoichiometric equivalence ratio and decreased on both sides of the stoichiometric condition.

Flame blow-off increased by increasing the fuel concentration in a range of equivalence ratios, its value depending on the flammability of the mixture. Flame separation from the burner rim causes air entrainment at the base of the flame, which reduces the equivalence ratio and hence affects the mixture flammability limit. When the hydrogen blend ratio was increased, the stability zone was enhanced. In more detail, the flashback limits were slightly increased due to high the flame speed of hydrogen, while the blow-off limit was increased significantly so the flame stability zone was expanded, which is an important trend for the safe operation of the combustion system.

The stability zone of combustion flames in terms of critical velocity gradient for different burner diameters was presented. From this it can be seen that the flame stability zone was enhanced at large burner diameter due to the decrease of the flame flashback limit.

Nomenclature

Symbol	**Descriptions**	**Unit**
S_L	Laminar flame speed	cm/s
C_q	Constant of the flame quench parameter	$-$
g_f	Critical velocity gradient at flame flashback	$1/s$
g_B	Critical velocity gradient at flame blow-off	$1/s$
R	Burner tube radius	mm
d_p	Penetration distance	mm
d_q	Quenching distance	mm
S	Swirl number	-
Pe	Peclet number	-
Pe_{flow}	Flow Peclet number	-

Symbol	Descriptions	Unit
Pe_{flame}	Flame Peclet umber	-
D	Characteristic length	mm
U	Mean burner exit velocity	m/s
d	Burner tube diameter	mm
α	Thermal diffusivity	m^2/s

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