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Research Article

The Characterization of Liquefied Petroleum Gas (LPG) Using a Modified Bunsen Burner

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The equivalence ratio ranges were found between 22.77 and 42.93 for the Saudi LPG/air mixture using a traditional Bunsen burner. An operation problem was found with a traditional Bunsen burner for the Saudi LPG/air mixture, especially in a lean mixture. Therefore, a Bunsen burner was successfully modified to overcome the limits of operation with different mixtures of Saudi LPG/air and a stable flame was obtained. The equivalence ratio ranges were found between 0.68 and 1.30 using the modified Bunsen burner. A premixed flame was used for the modified Bunsen burner. A MATLAB algorithm was successfully applied to flame image processing and measurement of laminar burning velocity. The laminar burning velocity was determined to be approximately 35 ± 0.91 cm/s under stoichiometric conditions using the modified Bunsen burner for the Saudi LPG/air mixture. The half-cone angle of the flame was found to be $16.20 \pm 0.76^{\circ}$. The minimum flame height was observed to be 21.50 ± 0.22 mm above the Bunsen burner exit.

1. Introduction

The laminar burning velocity is an important parameter for the understanding of the structure of the flame and combustion characteristics. It can be useful to determine fuel combustion characteristics, optimize combustion processes, and studying premixed combustion [1–4]. Laminar burning velocity is essential to study the properties of the reacting premixed mixture in combustion applications. Additionally, an increase in the laminar burning velocity leads to an increase in combustion efficiency.

Many factors impact the laminar burning velocity [3, 4]: the equivalence ratio (Φ) and the properties of the fuel are chemical factors, while pressure, flame temperature, and particle size (such as soot, dust, or coal particles) are physical factors. For example, Lee et al. added coal particles with methane/air mixtures in the lean fuel. They obtained that the laminar burning velocity was increased [5]. However, an important factor is the equivalence ratio. The equivalence ratio is defined as the ratio between the oxidizer-to-fuel ratio at stoichiometric condition and the actual oxidizer-to-fuel ratio. The laminar burning velocity depends on the equivalence ratio (Φ) [6, 7]. Laminar burning velocity will increase when the equivalence ratio is increased in lean mixtures (less than one), while the decrease in the laminar burning velocity was found with increasing the equivalence ratio in rich mixtures (greater than one). As a result, a high laminar burning velocity is found near the stoichiometric condition, which is around the equivalence ratio of 1 ($\Phi \sim 1$). The highest flame temperature is also found around the stoichiometric condition [3, 6]. Khudhair et al. mentioned that an increase in the laminar burning velocity will result in an increased thermal energy and chemical reaction. They found that the highest laminar burning velocity was obtained in rich and stoichiometric mixtures [3]. The stability performance was investigated using porous medium burners [8]. The heat transfer coefficient was also improved. However, the properties of the fuel influence the laminar burning velocity. A multiple opposing jets' burner was developed by Kamal [9]. He extended the flame stability limits using 12 fuel/air jets. A cross-flow was also used to control combustion performance with measuring NOx emissions [10].

The effect of NOx emissions for the natural gas (NG) and liquefied petroleum gas (LPG) was also investigated [11]. The laminar burning velocity has been determined for different fuels, such as natural gas/air [12], H_2/air [2], and C_3H_8/air [6]. Khudhair and Shahad [3] reported that the laminar burning velocity would decrease with an increase in the number of carbon atoms in the fuel molecule due to changing thermal diffusivity. The thermal diffusivity can be changed by increasing the number of carbon atoms. Laminar burning velocity for many alkanes was measured by Farrell et al. [13]. They found that methane had the lowest laminar burning velocity, which has the lowest number of carbon atoms in this study, due to chemical kinetic mechanisms, especially the flux of fuel atoms. In addition, Fu et al. [2] found that the properties of fuels impact the laminar burning velocity. The fuels, which have a large number of hydrogen atoms, had a high laminar burning velocity. O_2 gas is also important for increasing laminar burning velocity [3]. A sensitivity of the laminar burning velocity around the stoichiometric condition was found for fuels with a large number of hydrogen atoms [14]. Fuel combustion characteristics of the LPG/air were studied by Lee and Ryu [15]; they optimized combustion processes under different engine conditions. An increase in laminar burning velocity indicates an improvement in the burner designs and explosion protection in combustion units. The laminar burning velocity was found to be 16 to 40.3 cm/s for the LPG/air mixture under stoichiometric conditions [16].

Bunsen burners have been extensively used to measure laminar burning velocity in many studies [2, 17, 18]. The Bunsen burner is used to maintain a stable flame for different conditions (e.g., pressure, temperature, and equivalence ratios). In addition, it can be easily used to determine laminar burning velocity [2, 19]. Wei et al. [20] determined the minimum flame height above the burner exit under stoichiometric conditions. They obtained a lower flame height under stoichiometric conditions using biogas/hydrogen fuel. They also obtained a laminar burning velocity of approximately 32 cm/s. Moreover, Bouvet et al. [19] found that the laminar burning velocity depends on the composition of each mixture. They also obtained good flame stabilization with a fine-edge burner. The laminar burning velocity for flames of propane, n-butane, and their mixtures was measured by using a Bunsen burner [21]. Chu et al. studied the effects of N_2 dilution on the laminar burning velocity for CH_4-air premixed flames by using a Bunsen burner [22]. Goey et al. [23] used the Bunsen-type flames on multislit burners for understanding heat release. They investigated experimentally and numerically. A Bunsen burner was manufactured for high-performance hydrocarbon fuels by Hwang et al. [24]. They used a Bunsen burner to measure laminar burning velocity. A lab-scale Bunsen burner was used to measure the laminar burning velocity of oxy-CH_4 flames [25]. The authors used Schlieren photography to measure the laminar burning velocity using a Bunsen burner. The laminar burning velocity of premixed CH_4-air flames was investigated by using the Bunsen burner method [5]. John [17] studied different kinds of Bunsen burners for natural gas. He compared these burners to determine the limits of the operation when some gas mixtures are used. However, a straight tube with a flame burner was mostly used. The Bunsen burner properties are a port area of 70.97 mm^2, a port diameter of 9.53 mm, a burner height of 139.70 mm, a mixing tube length of 88.90 mm, and an orifice of 0.74 mm. This orifice port was designed for natural gas [17]. Barakat et al. [26] used multiple air ports of the burner to enhance the diffusion flame. They found that pollutant emissions were reduced by using the burner with multiple air ports. Cyclonic burners were numerically investigated to reduce combustion emissions [27, 28]. However, the laminar burning velocity was easily measured using the Bunsen burner to match other techniques such as the spherical flame propagation technique [29]. A high-speed camera is required. For example, 3-D measurements of flame structure were achieved by using chemiluminescence imaging with six CMOS cameras operating at 5 kHz [30].

Table 1: The mixture of Saudi LPG/air for the Bunsen burner.

Flow rate of LPG (l/min)	Flow rate of air (l/min)	AFR*	Φ*
0.47	0.18	0.38	22.77
0.51	0.17	0.33	26.16
0.54	0.16	0.30	29.43
0.58	0.15	0.26	33.72
0.61	0.14	0.23	37.99
0.64	0.13	0.20	42.93
0.67	0.12	0.18	48.69
0.70	0.11	0.16	55.49
0.73	0.10	0.14	63.66

*Air-fuel ratios (AFR) and equivalence ratio (Φ).

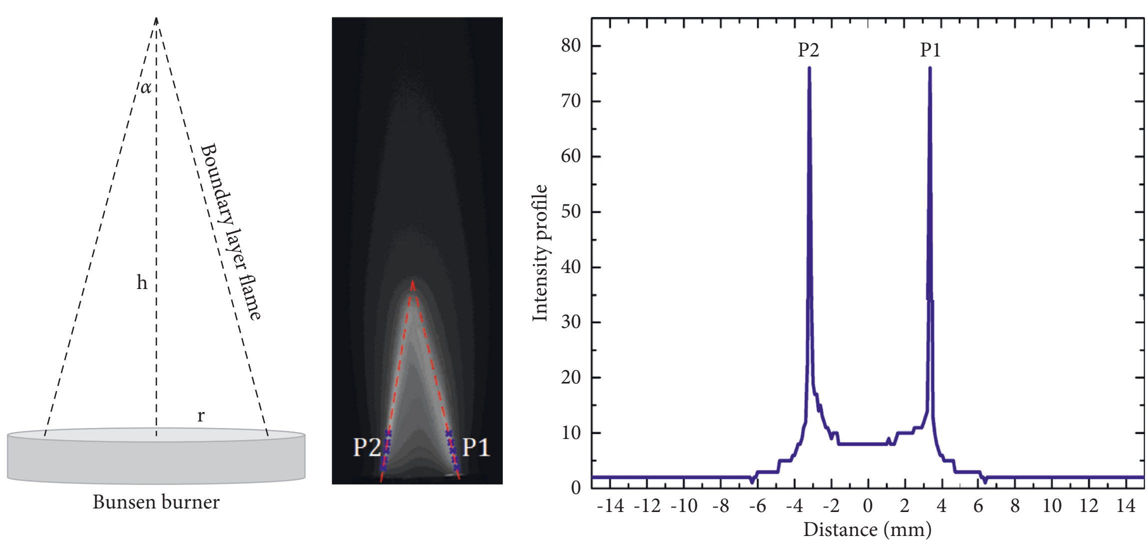
In this study, the laminar burning velocity was obtained from the composition of various mixtures of Saudi LPG and air, as listed in Tables 1 and 2. A straight tube Bunsen burner was used. The mixture of Saudi LPG and air was mixed after injecting the orifice port (primary port) in the mixing tube. Furthermore, the Bunsen burner was modified to measure the laminar burning velocities of Saudi LPG/air mixtures. The mixture of Saudi LPG and air was mixed in the mixing tube. The laminar burning velocities were also compared using original and modified Bunsen burners for different flow rates of the Saudi LPG/air mixture. Batch processing was successfully applied to improve the images of the flame. A MATLAB algorithm was also used to determine height and angle of the half-cone of the flame, as well as the laminar burning velocity. Our aim of this research is to study the characteristic of Saudi liquefied petroleum gas (LPG)/air flames by using a Bunsen burner and a modified Bunsen burner.

2. Materials and Methods

2.1. Laminar Burning Velocity Measurements. A Bunsen burner is extensively used to measure laminar burning velocity. The flame shape is pronounced as a conical flame under most of the conditions, as shown in Figure 1. The Bunsen burner maintains a stable flame for different conditions. The laminar burning velocity can be easily measured using a Bunsen burner.

Table 2: The mixture of Saudi LPG/air for the modified Bunsen burner.

Flow rate of LPG (l/min)	Flow rate of air (l/min)	AFR*	Φ*	Flow rate of LPG (l/min)	Flow rate of air (l/min)	AFR*	Φ*	Flow rate of LPG (l/min)	Flow rate of air (l/min)	AFR*	Φ*
0.72	4.81	6.68	1.31	0.72	7.51	10.43	0.84	0.76	5.81	7.64	1.14
0.72	5.01	6.96	1.25	0.72	7.61	10.57	0.83	0.76	6.21	8.17	1.07
0.72	5.03	6.98	1.25	0.72	7.71	10.71	0.82	0.76	6.41	8.43	1.04
0.72	5.05	7.02	1.24	0.72	7.81	10.85	0.8	0.76	6.61	8.7	1
0.72	5.07	7.05	1.24	0.72	7.91	10.99	0.79	0.76	6.81	8.96	0.97
0.72	5.1	7.08	1.23	0.72	8.01	11.13	0.78	0.76	7.01	9.22	0.95
0.72	5.51	7.65	1.14	0.72	8.11	11.26	0.78	0.76	7.21	9.49	0.92
0.72	5.51	7.65	1.14	0.72	8.21	11.4	0.77	0.76	7.41	9.75	0.9
0.72	5.71	7.93	1.1	0.72	8.31	11.54	0.76	0.76	7.61	10.01	0.87
0.72	5.91	8.21	1.06	0.72	8.41	11.68	0.75	0.76	7.81	10.28	0.85
0.72	6.01	8.35	1.05	0.72	8.61	11.96	0.73	0.76	8.01	10.54	0.83
0.72	6.11	8.49	1.03	0.72	8.71	12.1	0.72	0.76	8.21	10.8	0.81
0.72	6.31	8.76	1	0.72	8.81	12.24	0.71	0.76	8.41	11.07	0.79
0.72	6.51	9.04	0.97	0.72	9.01	12.51	0.7	0.76	8.61	11.33	0.77
0.72	6.71	9.32	0.94	0.72	9.21	12.79	0.68	0.76	8.81	11.59	0.75
0.72	6.81	9.46	0.92	0.76	4.81	6.33	1.38	0.76	9.01	11.86	0.74
0.72	6.91	9.6	0.91	0.76	5.01	6.59	1.32	0.76	9.21	12.12	0.72
0.72	7.11	9.88	0.88	0.76	5.21	6.86	1.27	0.76	9.41	12.38	0.71
0.72	7.25	10.07	0.87	0.76	5.41	7.12	1.23	0.76	9.61	12.64	0.69
0.72	7.41	10.29	0.85	0.76	5.61	7.38	1.18	0.76	9.81	12.91	0.68



(a) (b) (c)

Figure 1: Illustration of the parameters of the Bunsen flame: (a) schematic of flame height h flame half-cone angle α, and flame radius r; (b) the contour of the flame; and (c) flame intensity profile.

Measurement of the surface area of the flame is one of the main problems in determining the laminar burning velocity [3, 19, 31]. The flame surface area can be determined using the surface area of a cone by measuring the height of the flame and the radius of the flame. The contour of the flame was used to compute many parameters of the flame (for example, the height of the flame (h), the angle of the half-cone angle of the flame (α), and the radius of the flame (r)), as shown in Figure 1(a). The flame contour for the boundary layer flame was obtained by using the function profile in the MATLAB software. The function profile is the function between the intensity profile of the image and the distance on the x-axis, as shown in Figure 1(b). The flame of the boundary layer was determined on the x-axis for each flame height using the peaks (P2 and P1) of the intensity profile for five points above the exit of the burner, as shown in Figure 1(c). The resolution of the camera was calculated to be 0.07 mm/pixel. The flame height ranges were used at distances above the burner exit of 1 to 5 mm to avoid turbulent flame regions or lower illuminance of the layer flame in the top flame, as indicated by the blue points in Figure 1(b). The blue points are obtained using peaks (P1 and P2). Then the entire contour of the surface of the flame was fitted by using the Polyfit function for the degree of the first polynomial in the MATLAB software, as indicated by the red dashed line for P1 points and P2 points. The total contour is shown by the red dashed line in Figure 1(b). The MATLAB algorithm was developed to calculate the half-cone angle of the flame, the flame height, the flame surface area, and the laminar burning velocity for each image. The MATLAB algorithm was written to trace the boundary layer flame. The mean Bunsen flame images were used using Vargas et al. [32]. In this study, we obtained the mean Bunsen flame images with a good fitting of the contour of the surface. A good approximation was obtained to avoid the error of the laminar burning velocity measurements in this study. This process involves automated analysis.

The laminar burning velocity (S_L) can be calculated as a function of the velocity of the unburned mixture (U_o) and the half-cone angle of the flame (α) [18, 20, 33, 34]. It is given by

$$S_L = U_o \sin(\alpha). \quad (1)$$

U_o can be expressed by (2). It is associated with the total volumetric flow rate of unburned gases (such as air and Saudi LPG) and the surface area of the flame.

$$U_o = \frac{\dot{V}_{air} + \dot{V}_{LPG}}{A}, \quad (2)$$

where $\dot{V}_{air}$ is the volumetric flow rate of air, $\dot{V}_{LPG}$ is the volumetric flow rate of LPG, and A is the flame surface area. The velocity of the unburned mixture is the rate of the total volumetric flow rate of the unburned gases with respect to the flame surface area (A). The flame surface area can be expressed by (3). As an approximation, the boundary layer flame was detected using the MATLAB program. Then the height and radius of the flame were obtained from the flame in the boundary layer.

$$A = \pi r \left(r + \sqrt{h^2 + r^2} \right), \quad (3)$$

where r is the radius of the flame and h is the height of the flame.

2.2. Experimental Details. The LPG cylinder contained a 26.5-liter mixture consisting of 50% propane (C_3H_8) and 50% butane (C_4H_{10}) mixture. This gas cylinder was a commercial gas cylinder in Saudi Arabia. The pressure regulator of the gas cylinder was set to be 50 mbar in the outlet [33, 35]. The air was provided by an air compressor through a pressure of 7 bar.

Original and modified Bunsen burners were used. For the original Bunsen burner, the mixture of Saudi LPG and air was mixed before getting injected into the orifice port (primary port), as presented in Figure 2(a). A 6-mm diameter tee fitting was used to mix Saudi LPG and air before injecting them into the orifice port. For the modified Bunsen burner, Saudi LPG was injected into the orifice port (primary port), while air was injected into the air hole (secondary port) using the ring, which was carried out as presented in Figure 2(b). This ring was placed around the air hole, which was near the bottom and outside of the mixing tube, as shown in Figure 2(c). As a result, the mixture of Saudi LPG/air was mixed after injecting the orifice port (primary port) into the mixing tube in the modified Bunsen burner. The diameter and height of the mixing tube were 9.4 and 87.8 mm, respectively.

The experimental setup used for the laminar burning velocity measurement is shown in Figure 3. Laminar burning velocity was obtained from the mixture of Saudi LPG and air for mixing both before injection into the orifice port and in the mixing tube. The orifices port diameter was 0.74 mm. The air and Saudi LPG flow rates were controlled by a mass flow controller (Bronkhorst Hi-Tec). Each gas was controlled by an El flow meter. Each El flow meter was connected to a mass flow controller (MFC). The range of mass flow for the El flow meter was 0 to 30 l/min (accuracy <1%). The Bunsen flame images were successfully improved to measure laminar burning velocity by using batch image processing. A CCD FlowMaster II camera (LaVision) was used to capture 500 Bunsen flame images for each air-fuel ratio. The luminous flame technique was used to determine the laminar burning velocity. The CCD camera resolution is 1280×1024 pixels at 5 Hz. The average of 100 accumulations was found to produce a better flame shape with a lower standard deviation in the laminar burning velocity measurements, using batch processing in DaVis 7. The flame images were also improved by using the average of 100 accumulations. The standard deviation of laminar burning velocity measurements corresponded to five Bunsen flame images after image processing, with each image being the average of 100 accumulations.

3. Results and Discussion

A premixed flame was used for both the Bunsen burner and the modified Bunsen burner. An average of 100 accumulations of the Bunsen flame images were used. The contour of the Bunsen flames was created by using a MATLAB algorithm; it was useful to determine the flame height, the half-cone angle of the flame, and the flame radius for laminar burning velocity measurements using original and modified Bunsen burners.

3.1. Laminar Burning Velocity Measurements Using Bunsen Burner. Nine flow rates of Saudi LPG/air mixtures were used, as listed in Table 1. Air-fuel ratios (AFR) were determined to be between 0.14 and 0.38. Fuel volume fractions were used. The air-fuel ratio is 8.73 under stoichiometric conditions for the Saudi LPG/air mixture and could not be achieved using a traditional Bunsen burner. Images of Saudi LPG/air flames for different air-fuel ratios (AFR) with mixing before the orifice port using a traditional Bunsen burner are shown in Figure 4.

The limits of operation were determined using the traditional Bunsen burner for the Saudi LPG/air mixtures mixed before the orifice port. An increase in the airflow decreased the flow rate of Saudi LPG. The flow rate of the Saudi LPG/air mixture was difficult to control for passage through the orifice port because the density of Saudi LPG was greater than the air density. According to Poiseuille's law, the resistance of flow increases with increasing viscosity. It also decreases the port area. The viscosity of the Saudi LPG was greater than that of the air. Hence, the resistance to flow for Saudi LPG is greater than that of air in the same port area, as an air barrier. When

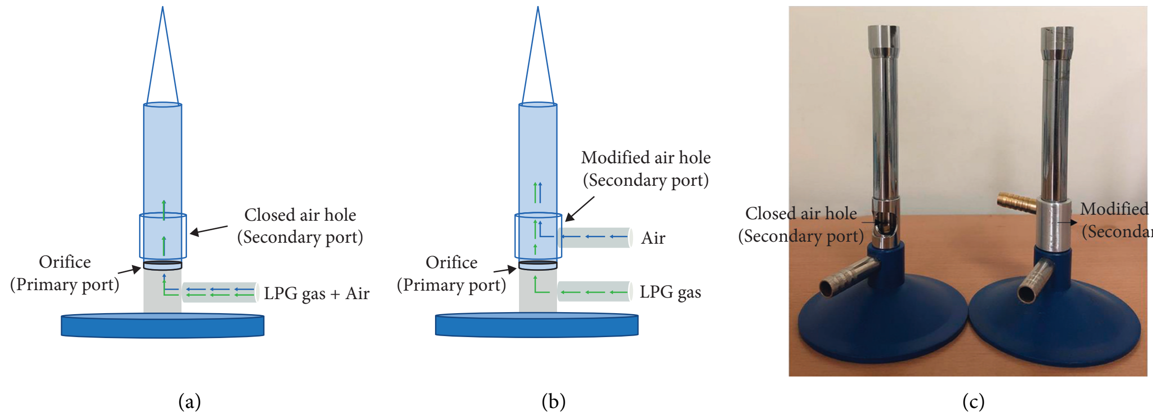


Figure 2: Illustration of Saudi LPG and air inlet connections of the Bunsen burner for the mixture of LPG and air (a) the Bunsen burner, (b) the modified Bunsen burner, and (c) photograph of the modified Bunsen burner.

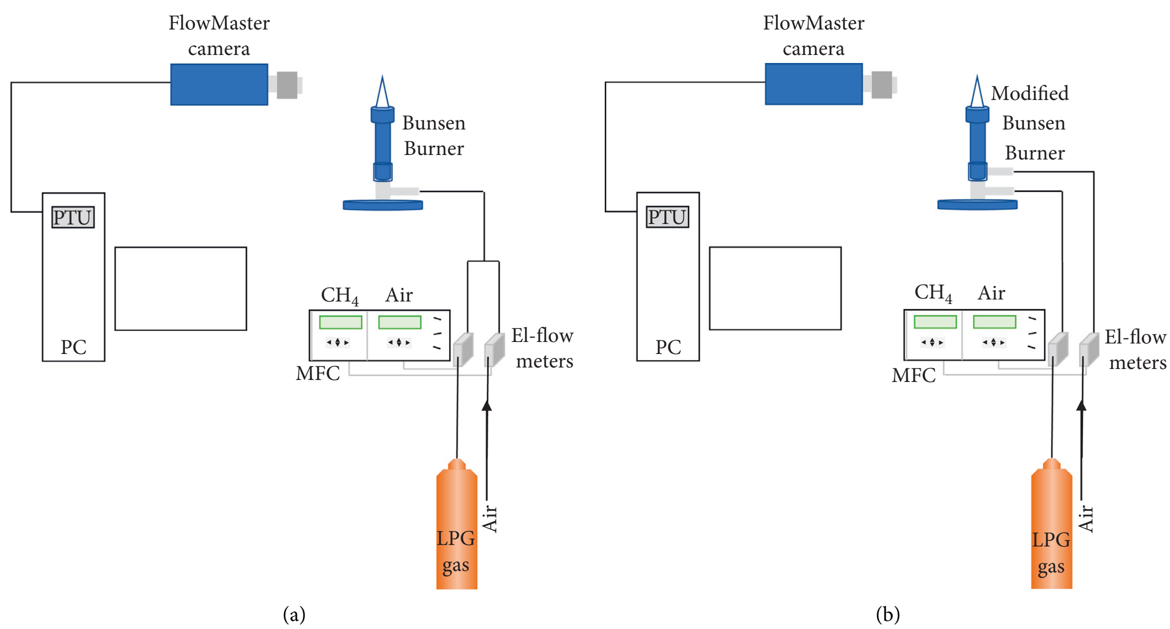


Figure 3: The experimental setup used for laminar burning velocity measurement. MFC, the mass flow controller; PC, personal computer; PTU, programmable timing unit.

the Saudi LPG/air mixture was mixed before the orifice port, the Saudi LPG/air mixture was injected into the orifice port, which had a diameter of 0.74 mm. In addition, the volumetric flow rate can be decreased by increasing the resistance of the flow. The flow rate of air was less than the flow rate of Saudi LPG, which passed through the orifice port using the traditional Bunsen burner. A flame flashback was generated when the traditional Bunsen burner was used. Because the flow rate of Saudi LPG was decreased unit 0.47 l/min when airflow was increased unit 0.18 l/min, as listed in Table 1. The total volumetric flow rate of the unburned gases was too small (less than 0.65 l/min). In addition, the diameter of the mixing tube can lead to the flashback of the flame, when the total volumetric flow rate is small [19].

The laminar burning velocity was found to be less than 12.27 cm/s, as shown in Figure 5. For example, laminar burning velocities were determined to be less than 2.69 cm/s for a higher equivalence ratio. The shape of the flames was not similar to a conical flame because the half-cone angle of the flame was found to approach zero (α~0), as shown in Figure 5(a).

A high standard deviation of laminar burning velocity can be obtained by changing the asymmetrical boundary layer flame [19]. Many factors impact the flame shape. Exhaust gases, heat losses, and changing pressure could be caused by unburnt mixture; this effect will increase the laminar burning velocity error. The laminar burning velocity error can also be produced by changing pressure or exhaust gas [3].

3.2. Laminar Burning Velocity Measurements Using Modified Bunsen Burner. The mixtures of Saudi LPG and air were mixed after the orifice port in the mixing tube using the

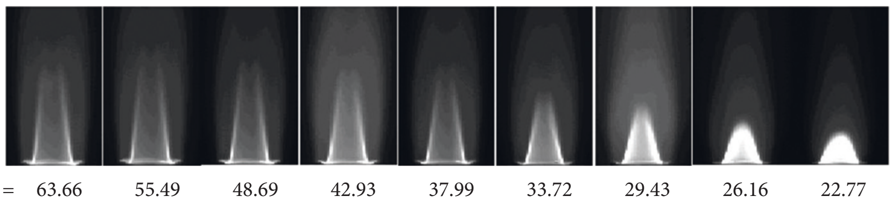


Figure 4: Images of the Saudi LPG/air flames for different equivalence ratios with mixing before the orifice port using the traditional Bunsen burner.

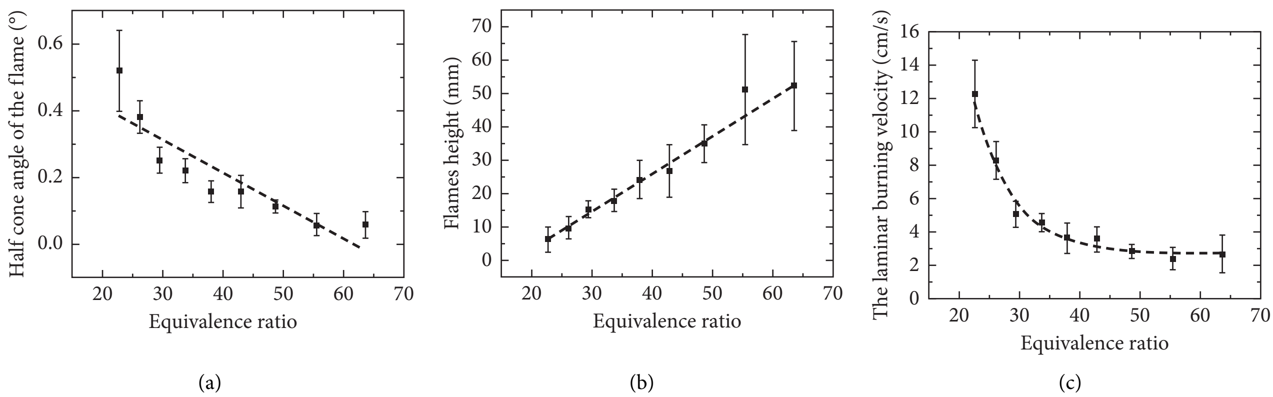


Figure 5: Flame parameters: half-cone angle of flame (a), flame height (b) and laminar burning velocity (S_L) (c) using Bunsen burner (S_L) for the Saudi LPG/air mixture mixed before the orifice port.

modified Bunsen burner. The resistance to air flow was decreased by increasing the port area, which was 6 mm in diameter. Various air flow rates and a fixed 0.72 l/min flow rate of Saudi LPG were used, as listed in Table 2, to determine the laminar burning velocity. Various air flow rates and a fixed 0.76 l/min flow rate of Saudi LPG were also used, as listed in Table 2, to measure the laminar burning velocity.

In Figure 6, the minimum flame height was found to be around the stoichiometric condition. This result was in good agreement in the literature. The air-fuel ratio was found to be 8.73 under stoichiometric conditions for the Saudi LPG/air mixture for the modified Bunsen burner. The flame heights were not significantly different for the Saudi LPG flow rates of 0.72 and 0.76 l/min.

In many studies, a high flame temperature was found to occur under stoichiometric conditions [3, 15]. In addition, the flame thickness was found to be a function of the flame temperature. As a result, it was clear that the flame thickness was higher under stoichiometric conditions than under other air-fuel ratios. The flame thickness effect can negatively influence laminar burning velocity measurements. Some flame images for Saudi LPG/air were observed to be slightly the flame asymmetry images using the modified Bunsen burner, especially above the equivalence ratio of 0.85, as shown in Figure 6. The contour of the flame surface was more precisely fitted using the MATLAB algorithm with a layer flame for a flow rate of 0.76 l/min for Saudi LPG than for a flow rate of 0.72 l/min for Saudi LPG. The flame asymmetry images can be processed to set the flame images at the central image plane [30, 36]. As a result, the measurement of the laminar burning velocity will be improved, with less error (less than 2.6%), and overcome the effect of flame thickness by using the peaks of the intensity profile of the flame image, as shown in Figure 1(c). However, a good linear relationship was found between the half-cone angle of the flame and the air-fuel ratio in the combustion regions of the rich and lean mixture, as shown in Figure 7(a). The highest half-cone angle of the flame was found to be $16.20 \pm 0.76^{\circ}$ at the stoichiometric condition, at an air-fuel ratio of around 8.73. No significant differences were found in the half-cone angle of the flame measurements for the flow rates 0.72 and 0.76 l/min of Saudi LPG in different air-fuel ratios, especially in the region of combustion of the lean mixture.

The lowest flame height was found to be 21.5 mm above the modified Bunsen burner exit when using Saudi LPG flow rates of 0.72 and 0.76 l/min, as shown in Figure 7(b). The type of gas mixture will affect the laminar burning velocity and flame height measurements around the stoichiometric condition. For example, the laminar burning velocity was found to be sensitive to stretching around the stoichiometric condition such as between 0.8 and 1.2, as when there was shown in Figure 8 a greater number of hydrogen atoms in the fuel molecule [14, 39]. In addition, the flame height did not change significantly in an equivalence ratio ranging from 0.8 to 1.15, because the mixture of Saudi LPG and air has a large number of hydrogen atoms. In Figure 8, the increase in laminar burning velocity was obtained with a lean mixture with increasing equivalence ratio, while the laminar burning velocity was decreased by increasing the equivalence ratio in a rich mixture. The maximum value of the laminar burning

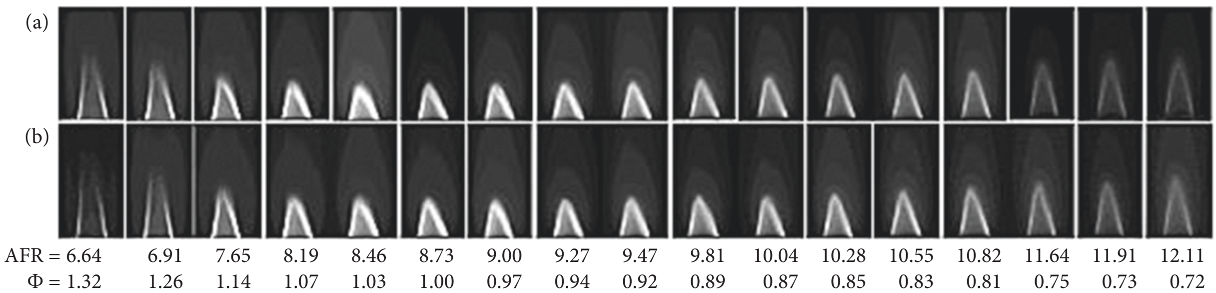


FIGURE 6: Images of the Saudi LPG/air flames for different air-fuel ratios (AFR): (a) at fixed 0.72 of the Saudi LPG flow rate and (b) at fixed 0.76 l/min of the Saudi LPG flow rate, mixing in the mixing tube using the modified Bunsen burner.

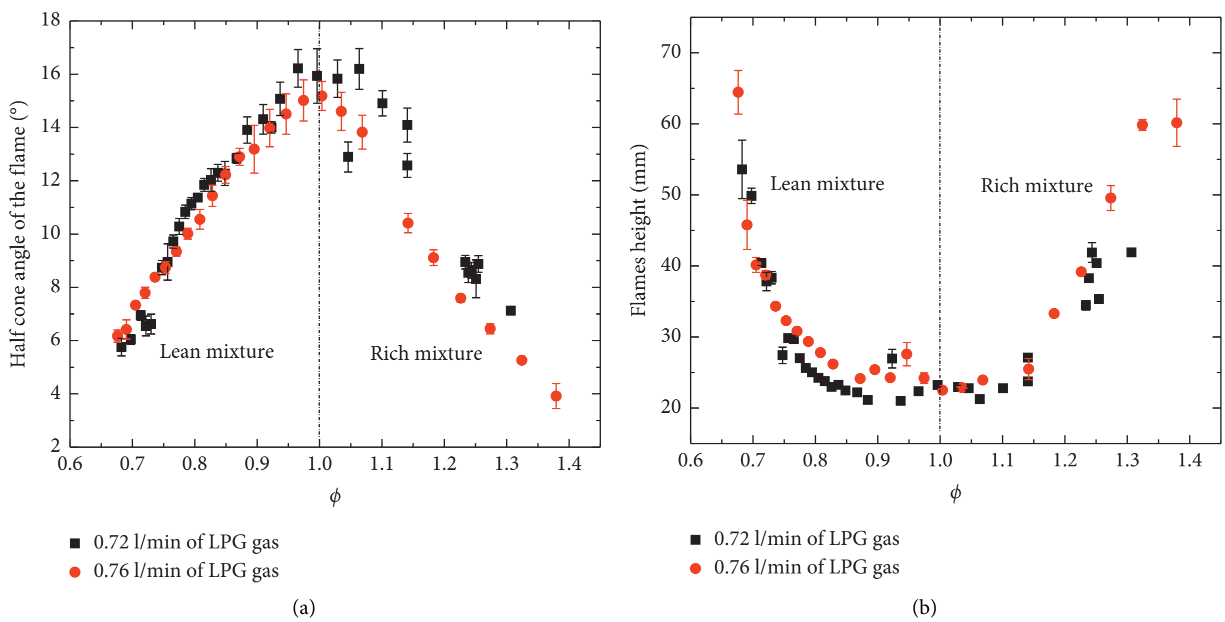


FIGURE 7: Half-cone angle of the flame measurements (a) and flame height (b) for different equivalence ratios at different Saudi LPG flow rates: (■ black solid square) for 0.72 l/min and (● red solid circle) for 0.76 l/min LPG flow rates using the modified Bunsen burner.

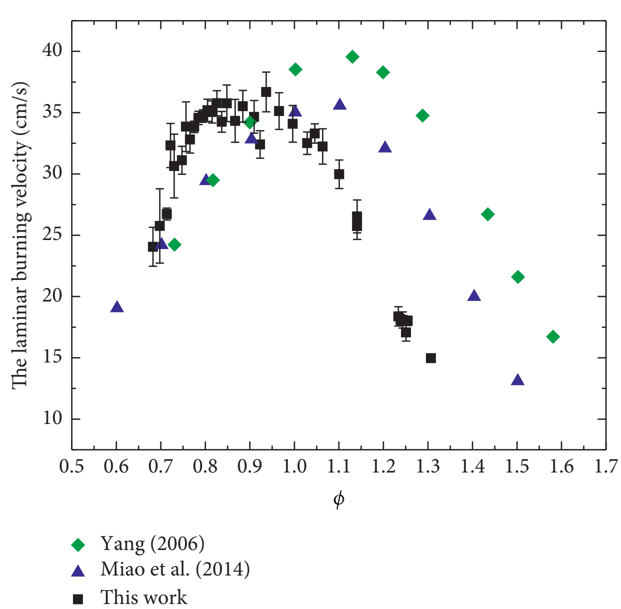


FIGURE 8: Comparison laminar burning velocity (SL) between present work with previous work in literature: (◆ green solid diamond) for 50% of C_3H_8 + 50% of n-C_4H_{10}/air mixture by Yang [37], (▲ blue solid triangle) for LPG gas by Miao et al. [38], and (■ black solid square) for Saudi LPG/air using the modified Bunsen burner in this work.

velocity was calculated to be approximately 35 ± 0.91 cm/s, as shown in Figure 8. About 0.72 and 0.76 l/min Saudi LPG flow rates were used to obtain a laminar burning velocity of approximately 35 cm/s, while the laminar burning velocity was found to be lower than 2.69 cm/s at a flow rate of 0.73 l/min for Saudi LPG using a traditional Bunsen burner. As a result, the high performance of the Bunsen burner was found using the modified Bunsen burner for the Saudi LPG/air mixture. The highest laminar burning velocity was found under stoichiometric conditions. The behavior of the laminar burning velocity was validated as the highest under stoichiometric conditions in many studies. Laminar burning velocities were also not significantly different for Saudi LPG flow rates of 0.72 and 0.76 l/min at different equivalence ratios. This is in good agreement with the dependence of the laminar burning velocity on the equivalence ratio. Wei et al. found that the laminar burning velocity of biogas/hydrogen fuel was 32 cm/s using a Bunsen burner [20]. In addition, the laminar burning velocity was found to be 35 cm/s and 32 cm/s for Saudi LPG-air and biogas-hydrogen, respectively.

The laminar burning velocities (SL) were observed to be more sensitive to the equivalence ratio in rich mixtures compared to lean mixtures; this is because exhaust gas is produced in rich mixtures more than in lean mixtures. This is one of the problems that leads to a decrease in laminar burning velocity [3]. The laminar burning velocity was improved using the modified Bunsen burner compared to the traditional Bunsen burner for Saudi LPG/air mixtures. The laminar burning velocity of the Saudi LPG/air flame was increased from 12.27 cm/s to 35 cm/s using the modified Bunsen burner.

The laminar burning velocity, the height, and the half-cone angle of the flame measurements had very similar values at the same value of the air-fuel ratio for Saudi LPG/air mixtures mixed in the modified Bunsen burner mixing tube. Flame stability was monitored using 100 Bunsen flame images. Additionally, the laminar burning velocity error was found to be less than 2.6%. A stable flame and a conical flame were obtained using the modified Bunsen burner when mixed in the mixing tube for Saudi LPG.

4. Conclusion

In this study, a traditional Bunsen burner had an operational problem in a lean mixture of Saudi LPG/air mixtures. A modified Bunsen burner was developed to overcome the limits of operation of the traditional Bunsen burner when using different mixtures of Saudi LPG/air. The equivalence ratio range between 0.6 and 1.3 can be operated using the modified Bunsen burner. The laminar burning velocity was experimentally measured using traditional and modified Bunsen burners for different ranges of Saudi LPG/air flow rates. The effect of mixing Saudi LPG and air on the performance of the Bunsen burner was studied. A MATLAB algorithm was developed to compute the half-cone angle of the flame, the height of the flame, and the surface area of the flame. The layer flame was precisely fitted using the MATLAB algorithm. The laminar burning velocities were successfully determined. The maximum value of the laminar burning velocity was calculated to be approximately 35 ± 0.91 cm/s for Saudi LPG using the modified Bunsen, while the laminar burning velocity was found to be lower than 2.69 cm/s for Saudi LPG using a traditional Bunsen burner. A stable flame of the Saudi LPG mixture was also obtained using the modified Bunsen burner.

Data Availability

The results are experimentally obtained in this study that have not been previously published.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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