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STUDY THE EFFECT OF AN INERT GAS ISOLATING ON THE FLAME CHARACTERISTICS WITH A STABILIZER IN A VERTICAL GAS BURNER

Lubna Abdulwahid Abdulwahhab [1*], Fouad Alwen Saleh [2],

[1] Mechanical Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq.

[2] Mechanical Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq.

* Corresponding author's e-mail: mustafanabeel1991@uomustansiriyah.edu.iq

ABSTRACT

Under laboratory conditions (298 K and 1 bar) and using a wide range of air-to-fuel mixing ratios, an experimental combustion test was performed with ILPG. Combustion has been critical to human life since ancient times for practical applications. Accurate data is always required since laminar combustion speed is one of the most critical characteristics of premixed flames. The laminar combustion velocities of an LPG/air flame under atmospheric conditions were calculated using a vertical-diameter burner (with and without N2). In addition, the effects of nitrogen gas separation of the flame from the outside environment were investigated both with and without the use of a flame stabilizer, and in a 12mm cylinder diameter. In addition, Schlieren imaging equipment was ready to measure and investigate (flame stabilization limitations) to obtain comprehensive data by analyzing a Schlieren flame forward image of a 12 mm diameter flame. This experiment obtained results for the valence ratio using different flame stabilizer angles to obtain valence ratios with and without N2.

Keywords: LPG; laminar burning velocity; Vertical flames; Flame stability; Schlieren; N2; Flame stabilizers of different angles.

1. Introduction

In order to produce energy in the form of heat and light, a fuel must combine chemically with an oxidizer, such as air or oxygen, to produce combustion [1]. Fuels can be liquid, gaseous, or solid. The International Energy Agency (IEA) estimates that the energy consumed globally due to burning fuels like natural gas and petroleum is around 88% [2]. The combustion process is currently utilized in various sectors, including transportation, power generation, heating, steam boilers, and others [3]. Because of this, the percentage of pollutants emitted by combustion processes, including nitrogen oxides, sulfur oxides, volatile organic compounds, carbon dioxide, and soot, has increased in all their uses. These contaminants directly affect both the environment and human health. Thus, to lessen these, fuel needed to be burned more precisely and effectively [4]. Four main categories can be used to categorize flames:

- First, there is stability. It is said to be unstable when the flame front shifts concerning the function or anything else. In any case, the capacity to witness the flame front move steadily inside the system is what a steady flame front means.
- Second, one thing to consider is the kind of gas flow through the reaction zone: Flames come in two different varieties: turbulent and laminar.
- Third, mixing and reaction-diffusion. A premixed flame, or a flame that simultaneously burns and mixes, is utilized (a diffusion flame). Fourth, the physical conditions of the significant reactants are as follows: solid-liquid-gas [5, 6].

The burning velocity has been estimated using a variety of techniques. These techniques may be divided into two groups:

1. A steady flame is achieved by injecting a stream of gas into a burning flame at a rate proportional to that of combustion [7]. Many researchers have used several techniques that fall within this category, such as Bunsen, flat flame methods [8, 9], nozzle burning [10, 11], slot [12, 13], and other methods.
2. Non-stationary flame: This technique passes through the initially quiescent mixture using this technique. [7] The techniques categorized as class (2) include the tube method [14, 15], the constant volume bomb method, which was used by several researchers [16, 17], and lastly, the Lewis and Von Elbe-developed soap-bubble technique [18].

Fuel gas, known as liquefied petroleum gas (LPG or LP gas), comprises a volatile combination of hydrocarbon gases, notably propane, propylene, butylene, isobutene, and n-butane. Heating appliances, kitchenware, and automobiles use LPG as a fuel gas. As a propellant for aerosols, it is increasingly used[19]. During Snelling's research on the volatility of gasoline, LPG was first obtained in 1910. LPG has many uses, such as fuel, home appliances, building materials, heating, and light sources. LPG is cheaper than similar products since it is a by-product with multiple uses. Despite its many benefits, LPG raises some valid safety concerns in commercial and domestic contexts [20, 21]. With enhanced fuel efficiency, fewer emissions of pollutants, and diminished fuel consumption, these alternative fuels make it easier to achieve environmentally friendly combustion. The laminar burning velocity is a key metric that describes several characteristics relating to the reactivity, diffusivity, and exothermic nature of a particular fuel-air mixture. The ability to predict the operational characteristics and emissions of various fuel systems, including internal combustion engines, industrial furnaces, and gas turbine engines, as well as to validate various chemical kinetic mechanisms connected to the fuel, underscores the paramount importance of the burning mixture of combustible fuel.

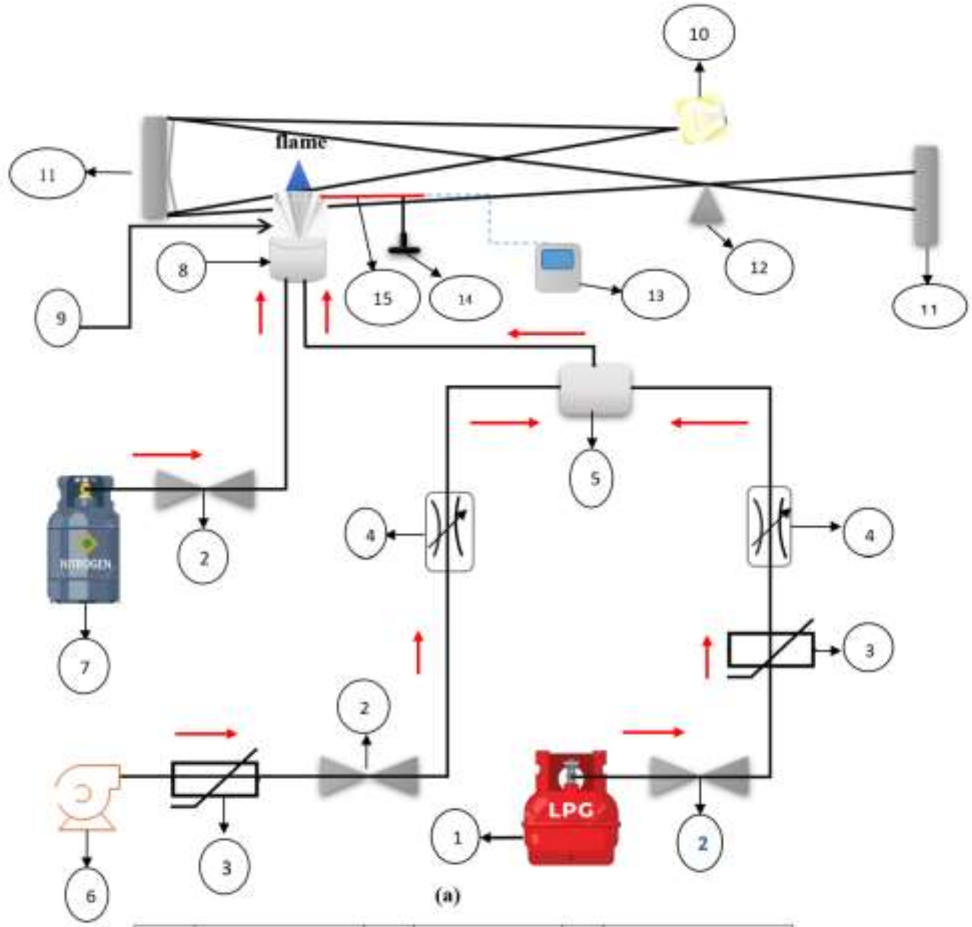
The truthful. Laminar burning velocity (LBV) is one of the crucial characteristics utilized to comprehend precisely how to investigate the viability of using LPG as an alternative fuel in various burning systems [22]. The evaluation of various chemical kinetic processes of the fuel and the anticipation of operational and emission characteristics of various combustion systems, such as industrial furnaces, internal combustion engines (IC), and jet engines, is made easier by the laminar burning velocity of a flammable mixture [23].

2. Device Parts and Experimental Method

The test rig for this investigation consists of four units: a Schlieren photography setup, an LPG distribution system, an air delivery system, a vertical burner unit, and an N_2 delivery system. The first unit is an LPG cylinder, an LPG flow meter, and a flow regulator. These comprise the LPG delivery system. The second unit is a vertical burner consisting of a vertical burner long enough to develop entirely and a mixing chamber. The third unit is an air delivery system, including an air compressor, airflow meter, and regulator. The fourth unit is the delivery system cylinder of N_2, a regulator to control the flow of N_2. A concave mirror, a plane image, and a light source, a knife edge are among the components of the Schlieren photography system's fifth unit.

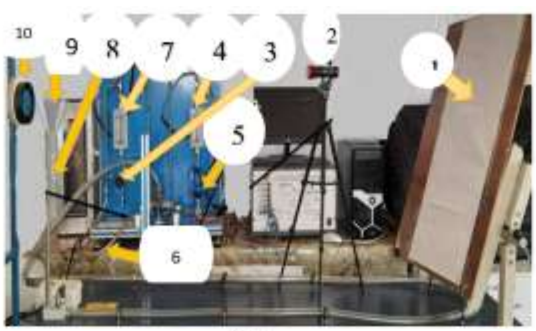
Figure 1. Illustration of the experimental device used for the control and control system for the amount of flow and gas distribution air and gas are mixed before the mixture enters the vertical burner, and the amount of gas entering the mixing chamber is regulated by a gas flow meter that receives gas from a gas cylinder. The amount of air entering the mixing chamber before being fed to the burner is controlled by an airflow meter. The amount of nitrogen is controlled and supplied by a readily accessible cylinder that contains nitrogen with a purity of 99% while air is drawn through an air compressor. The reactants can be quickly combined in the mixing section (premixing flow). The laboratory conditions were 308K and 1 atm for experimental work. The device parts are:

1. A fuel regulator valve.
2. Volumetric flow of the fuel.
3. Sensor for fuel temperature.
4. Regulating valve for air.
5. Volumetric flow of air.
6. Sensors for air temperature.
7. The air compressor.
8. LPG cylinder.
9. Nitrogen cylinder.
10. Nitrogen jacket.
11. Chambers for mixing.
12. Thermocouple.
13. Vertical burner.
14. Schlieren system.



(a)

No.	Name of part	No.	Name of part	No.	Name of part
1	LPG cylinder	6	Blower air	11	plane
2	Solenoid valve	7	N2 cylinder	12	Knife edge
3	Temperature sensor	8	Nitrogen jacket	13	Data Logger
4	Flowmeter gas	9	flame stabilizers	14	Holder
5	Mixing chamber	10	Light source	15	Type K-thermocouple



(b)

No.	Name of part	No.	Name of part
1	Plane	6	Line air
2	Light source &knife Edge	7	Flow meter air
3	Regulation valve	8	Burner
4	Flowmeter gas	9	flame stabilizers
5	Regulation valve	10	Concave mirror

Figure. 1.(a) System Diagram. (b) The Device System image.

2.1 Experimental Tools

The burner tube model consists of a single copper burner tube fashioned into a test section. The burner has a diameter of 12 mm. A standard burner length was selected using the conventional (50xd) approach to guarantee the achievement of fully developed laminar flow at the burner's perimeter on every occasion. A key factor in determining flame stability is the selection of such pipes. To envelop the vertical burner with nitrogen gas and create a nitrogen jacket at the burner terminus, a new component was developed by a technician and added to the upper end of the tube burner. This element is depicted in Figure 2. This design features an open cylinder from the top and a burner tube connected from the bottom, ensuring the burner orifice aligns with the nitrogen cylinder aperture. This cylinder extends to a height of 62 mm and has an external diameter of 96 mm. The base on which the tube ignites from the bottom is made of stainless steel and yields a consistent flow. Nitrogen exit holes are outfitted with 2-, 3-, 4-, and 6-mm dimensions.

Figure.2. Manufacturing steps (nitrogen jacket)

2.2 Schlieren Technology Layout

In order to provide high-resolution contrast to the Schlieren technique, optical components like mirrors or lenses can be utilized. This will enable the case being investigated with the unaided eye or photography film to be differentiated. Based on some geometrical optics and wave considerations, the Schlieren system is an optical system [5]. In this study, the mirror was employed to display the specifics of the system installation, Schlieren visual processing, and the necessary optical picture. The concept and elements of the system are described as follows: Installed in close proximity to the flame, the parabolic mirror's 76 mm diameter and 70 cm focal length cover the flame. At the same time, the light source is hidden behind the mirror. Following that, the light bounces off a vertical beam or the camera and requires a sharp edge to scatter the beam and display the Schlieren image. The measuring method used here is the methodology of flame cone angle [24]. This technique is very helpful for flame cones with straight sides, as shown in Fig. 3 and Fig. 4.

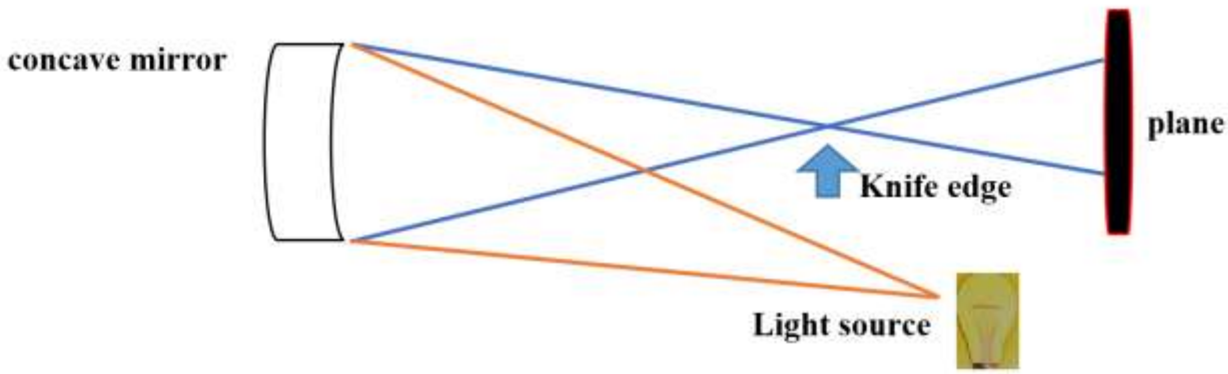


Figure 3. The Schlieren method's organizational structure.

Figure 4. The flame form using the Schlieren method.

Figure 5. The flame retainers at different angles.

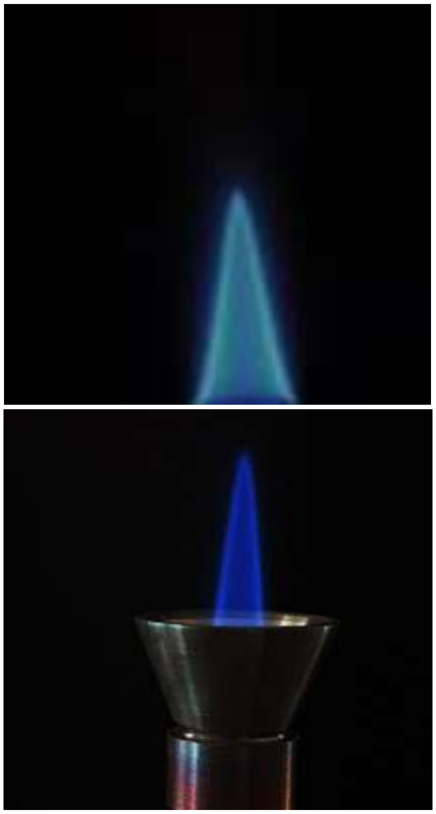


Figure 6. (a) photo of flame without stabilizer. (b) photo of flame with stabilizer.

Figure 7. Concave mirror forms.

The flame retainer is placed on the upper edge of the burner and is made of brass in a V pattern. And at different angles. The diameter of the tube is 12 mm. The stabilizer increases the combustion area and stabilizes the flame. The results of this study were obtained for a tube with a diameter of 12 mm. A photo of the flame with and without stabilizer is shown in Figures 7a and 7b. The stability of the LPG flame at lower equivalency ratios was tested to see whether the pilot flame might improve.

3. Calculations and experimental technique

The following methods were used to determine the mixing ratios for the mixture (ILPG) with air that provides the burner with its optimal performance while operating at a diameter of 12 mm. The mixture preparation process is critical in accurately calculating the flame propagation velocity by optimizing operating conditions (0.5-1.4).

1. Operation of the system (air/fuel): This phase includes the activation of the fuel (LPG) system, which is governed by a manually operated valve, and the activation of the air compressor, which is controlled by a valve located on the air-fuel flowmeter board.
2. The airflow and fuel flow are expressed in volume units (L/S) to ensure precision in measurements. The indication on the flowmeter must be confirmed to be steady and constant throughout the reading operation.
3. An external ignition source (a lighter) is used to ignite the combination of fuel and air, which is then allowed to burn for a long time until the flame stabilizes.
4. Under all circumstances, Place the camera in a fixed position and at a fixed distance from the image board.

5. Capturing an image of the flame profile and using the Schlieren optical technique to create a high-resolution depiction of the flame's morphology and project it onto a whiteboard in front of the flame.
6. Follow the same procedure as before, changing the volumetric values of the fuel and air to, respectively, Vf and Va.
7. Use the flame retainers at various angles to repeat the previous action.
8. Repeat the preceding processes while adding and using the nitrogen system as an insoluble gas. Below are equations used to find experimental results.

3.1 Equivalence Ratio.

$$\Phi = ((A/F)stoic)/((A/F)act) \quad (1)$$

Where:

(A/F) stoic is the air-to-fuel ratio of the LPG

(A/F) **act** Air–fuel ratio is the mass ratio of air to a fuel.

Stoichiometric evaluation of liquid petroleum gas (LPG) fuel allows for the following (A/F) stoic evaluation:

$$“C_xH_y+a(O_2+3.76N_2)\rightarrow xCO_2+y/2(H_2O)+3.76N_2” \quad (2)$$

$$“C3.671H9.342+6.0065(O_2+3.76N_2)\rightarrow 3.671CO_2+4.671(H_2O)+22.58444N_2”$$

$$“(A/F)\ a = \dot{m}a/\dot{m}f” \quad (3)$$

$$“(A/F)\ s = 4.76 * a * \frac{\mathcal{M}wa}{\mathcal{M}wf}” \quad (4)$$

$$a = x + y/4 \qquad \text{For Stoichiometry} \quad (5)$$

For simplicity's sake, it will be assumed that the air constitution contains 21% O_2 and 79% N_2 (by volume), signifying that there are 3.76 moles of N_2 for every mole of O_2 present in the air.

$$\rho a=P/RT \quad (6)$$

ρ_a =1.18 kg $/m^3$ at (laboratory condition =1, T = 298 K)

$$\dot{M}F = \rho FQF \quad (7)$$

$$QF=UF\rho F \quad (8)$$

$$\dot{M}F=UF\rho FAF \quad (9)$$

$$\dot{M}A= \rho AQA \quad (10)$$

$$QA=UA\rho A \quad (11)$$

$$\dot{M}A=\rho AUAAa \quad (12)$$

$$mmix= \dot{m}a+ \dot{m}f \quad (13)$$

$$mmix = Qmix \quad (14)$$

3.2 Reynolds Number of Mixture

$$Re\ mix = \frac{\rho mix*U*D}{\mu MIX} \quad (15)$$

Where:

D=diameter of tube

D=12 mm

3.3 Density of Mixture

$$\mu mix = \mu F\ \%\ fuel+ \mu air\ \%\ air \quad (16)$$

$$\rho_{mix} = \rho_{air}\ \%\ air + \rho_{fuel}\ \% \quad (17)$$

$$Q_{mix} = \frac{\mathring{m}_{mix}}{\rho_{mix}} \quad (18)$$

The precision of calculating the equivalent ratio depends significantly on the purity of the gas fuel utilized. The purity of LPG was reported to be 98.42 percent by refiner laboratories in Baghdad

(AL-Doura). The components of LPG are ethane (C_2H_6) at 0.6%, propane (C_3H_8) at 33.7%, pentane (C_5H_{12}) at 2%, and butane (C_4H_{10}) at 63.7%. The LPG equivalence hydrocarbon mixture could be estimated as C3.671H9.342.

3.4 Equivalent Carbon Atoms Number method

$$(C_xH_y) = \frac{\% * x}{100}$$

$$\text{ethane } (C_2H_6) = \frac{0.6*2}{100} = 0.012$$

$$\text{propane } (C_3H_8) = \frac{33.7*3}{100} = 1.011$$

$$\text{Butane } (C_4H_{10}) = \frac{63.7*4}{100} = 2.548$$

$$\text{pentane } (C_5H_{12}) = \frac{2*5}{100} = 0.1$$

Carbon atoms number (x)
=2.548+1.011+0.1+0.012 = 3.671

3.5 Equivalent Hydrogen Atoms Number Method

$$(C_xH_y) = \frac{\% * y}{100}$$

$$\text{ethane } (C_2H_6) = \frac{0.6*6}{100} = 0.024$$

$$\text{propane } (C_3H_8) = \frac{33.7*8}{100} = 2.696$$

$$\text{Butane } (C_4H_{10}) = \frac{63.7*10}{100} = 6.37$$

$$\text{pentane } (C_5H_{12}) = \frac{2*12}{100} = 0.24$$

H_2 atoms number (y)

=2.696+6.37+0.036+0.24=9.342

The LPG equivalence hydrocarbon mixture would be C3.671 H9.342.

4. Results

The rate of the chemical reaction and, thus, the speed of the flame may be increased by raising the flame's temperature to the corresponding ratio in the free portion of the mixture. The Schlieren system gives high accuracy in the measurements based on the refractive index of the laser beam that passes through the interaction area of the light beam. The geometric dimensions of the front of the flame for every one of the burners under study were obtained via experimental evaluations, and this effect is seen in the analysis of the Schlieren sample of optical images.

The equivalence ratio also affects the laminar combustion speed, as the combustion velocity increases when the equivalence ratio is approximately ($\Phi = 1.1$). The combustion speed after that starts to decrease with a parity ratio of less than 1.1 until the occurrence of the explosion because the amount of air has become greater than the steady state with the same amount of fuel. Following the cone formed by Schlieren's images led researchers to discover that the portion of the flame with the smallest surface area had the quickest burning rate.

It can be seen that the increase in combustion speed is due to the use of flame stabilizers at different angles on the burners. In addition to the use of N2 gas, the utilization of a flame insulator that is separate from its surroundings helps to preserve the stability of the combination (air and fuel). It prevents the air in the external environment from affecting the reaction and combustion process. The increase in the combustion speed is the reason for the use of N_2 as a result of obtaining an equivalent mixture between the reactants and not allowing air to participate, as the highest value of the combustion speed is 55.7 cm/s with stabilizers and 44.3 cm/s without a flame stabilizers.

The flame is at an angle of 32 degrees with a burner diameter of 12 mm. One of the most critical parameters in burner efficiency is temperature, among other parameters like combustion speed. A flame stabilizer mounted on the burner raises the temperature, increasing thermal efficiency. The results showed that the flame temperature was higher than without a flame stabilizer.

The higher the thermal efficiency, the higher the temperature a flame stabilizer achieves when installed on the burner. The results showed that increasing the flame temperature more than without a flame stabilized.

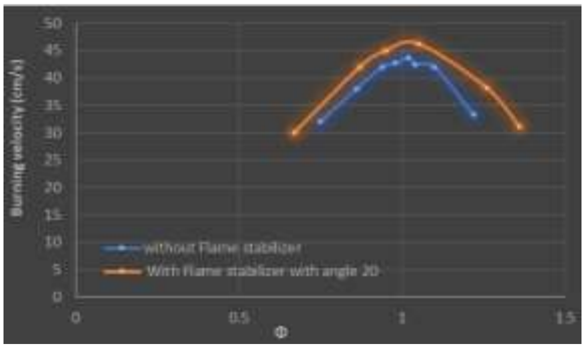


Figure 9. Impact of burning velocity on the equivalence ratios ϕ 12mm D (without and with Flame stabilizer with 20° angle and without N_2).

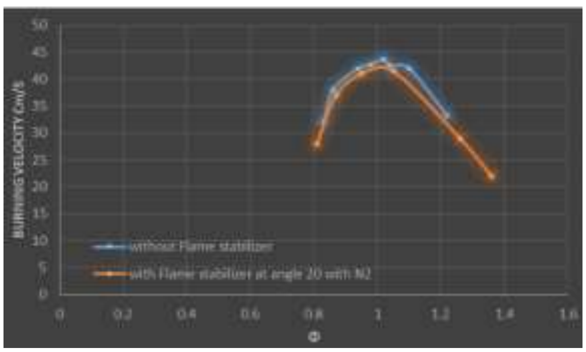


Figure 10. Impact of burning velocity on the equivalence ratios ϕ 12mm D (without and with Flame stabilizer with 20° angle and without N_2).

The flame stabilizer angle's value rose, resulting in a rise in the flame's temperature. Burning a significant quantity of the mixture causes the flame temperature to rise. The highest temperature was 1126 without the flame stabilizer and N_2 and 1145, 1190, 1250, 1330, and 1335 with a flame stabilizer for the flame interface for different angles; the values of the angles are 20, 26, 32, 38, and 41 with a parity ratio of 1.06, 1.05, 1.03, 1.02, and 1.1 for a diameter of 12 mm.

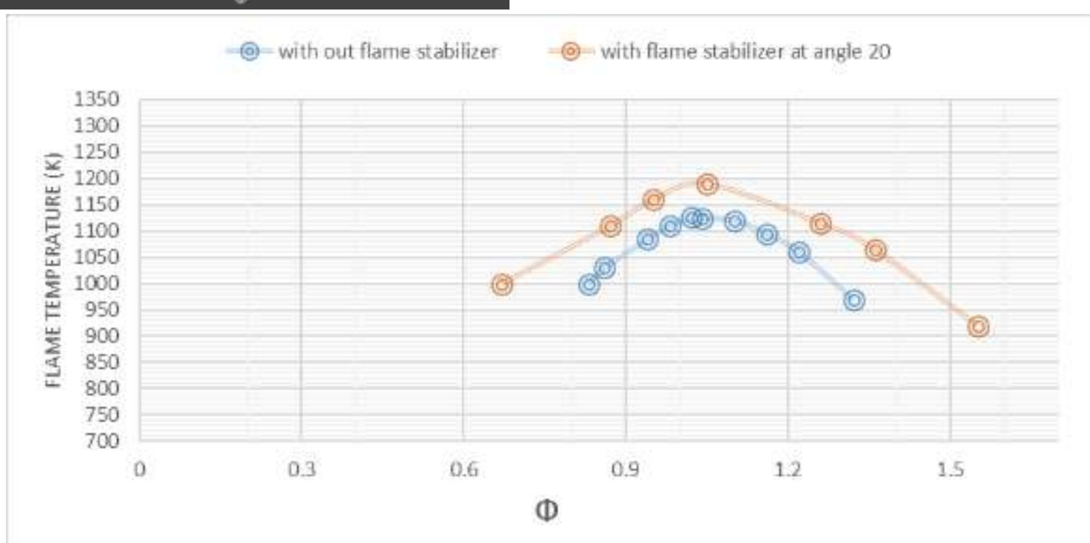


Figure 11. Impact of flame temperature distribution on Φ at 12 mm D with and without Flame stabilizer at angle 20.

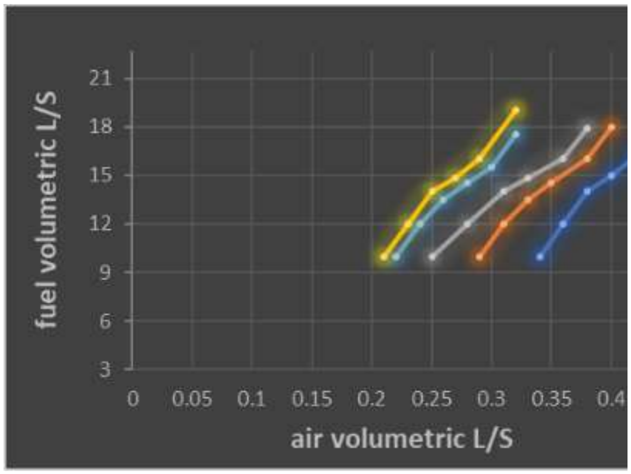


Figure. 12. Premixed vertical flame stability limits at(12mm) without N_2

5. Conclusions

Flame temperature, flame structure, and laminar burning velocity were examined as the three critical characteristics of laminar premixed LPG or air flames. Photographs were obtained of the flame structure. The laminar burning velocity was calculated using the angle technique employing Schlieren images.

Calculate angles by converting images to the Solid Work application. Based on the measurements described above, the following conclusions were drawn:

1. Schlieren images show the laminar burning velocity (Su) of premixed LPG/air flames determined using the angle technique at 310 K laboratory temperature and 1 atm atmospheric pressure. With and without a flame stabilizer, the maximum velocity was achieved in both situations with a 12 mm burner diameter.
2. The stability zone is decent, although the maximum stability zone was attained with a 12mm burner diameter.
3. Because it is the primary factor boosting the effectiveness of the per-mixing process between air and fuel, the burner diameter plays a significant role in the mechanism of flame stability.

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Conflict of interest

"The authors declare that there are no conflicts of interest regarding the publication of this manuscript."

Author Contribution Statement

"M. Nabeele proposed the research problem, developed the theory, and performed the computations. F. A. Saleh verified the analytical methods and supervised the findings of this work. Both authors discussed the results and contributed to the final manuscript."

References

1. Turns, S., R., (1996). *An Introduction to Combustion Concepts and Applications*. 3rd ed. New York, USA: McGraw-Hill, Inc. ISBN: 0073380199.
2. IEA, (2019). *A 26-member-states policy-advice cooperative agency*. International Energy Agency. Isuue.
3. Kohse-Höinghaus, K., (2021). *Combustion in the future: The importance of chemistry*. Proceedings of the Combustion Institute. Vol. 38, Isuue 1, pp. 1-56. https://doi.org/10.1016/j.proci.2020.06.375.
4. Yu, B., S. Lee, and C.-E. Lee, (2015). *Study of NOx emission characteristics in CH4/air non-premixed flames with exhaust gas recirculation.* Energy. Vol. 91, Isuue, pp. 119-127. https://doi.org/10.1016/j.energy.2015.08.023.
5. Omar, S.T., (2019). *Investigation of Flame Propagation Characteristics for Premixed and Diffusion Combustion in Vertical Counter Burners with N2 Shell.* Mechanical Engineering Department, Mustansiriyah University Baghdad, Iraq.

6. Esquiva-Dano, I., H.T. Nguyen, and D. Escudie, (2001). *Influence of a bluff-body's shape on the stabilization regime of non-premixed flames.* Combustion and Flame. Vol. 127, Isuue 4, pp. 2167-2180. https://doi.org/10.1016/S0010-2180(01)00318-2.
7. Daly, C.A., et al., (2001). *Burning velocities of dimethyl ether and air.* Combustion and Flame. Vol. 125, Isuue 4, pp. 1329-1340. https://doi.org/10.1016/S0010-2180(01)00249-8.
8. Gomez, A. and D.E. Rosner, (1993). *Thermophoretic Effects on Particles in Counterflow Laminar Diffusion Flames.* Combustion Science and Technology. Vol. 89, Isuue 5-6, pp. 335-362. 10.1080/00102209308924118.
9. Egolfopoulos, F.N., H. Zhang, and Z. Zhang, (1997). *Wall effects on the propagation and extinction of steady, strained, laminar premixed flames.* Combustion and Flame. Vol. 109, Isuue 1, pp. 237-252. https://doi.org/10.1016/S0010-2180(96)00152-6.
10. Liu, D.D.S. and R.R. Macfarlane, (1983). *Laminar burning velocities of hydrogen-air and hydrogen-airsteam flames.* Combustion and Flame. Vol. 49, Isuue 1, pp. 59-71.
11. Kobayashi, H. and M. Kitano, (1989). *Extinction characteristics of a stretched cylindrical premixed flame.* Combustion and Flame. Vol. 76, Isuue 3, pp. 285-295. https://doi.org/10.1016/0010-2180(89)90111-9.
12. Smyth, K.C., et al., (1985). *Soot inception in a methane/air diffusion flame as characterized by detailed species profiles.* Combustion and Flame. Vol. 62, Isuue 2, pp. 157-181. https://doi.org/10.1016/0010-2180(85)90143-9.
13. Xiao, X., C.W. Choi, and I.K. Puri, (2000). *Temperature measurements in steady two-dimensional partially premixed flames using laser interferometric holography.* Combustion and Flame. Vol. 120, Isuue 3, pp. 318-332. https://doi.org/10.1016/S0010-2180(99)00100-5.
14. Odgers, J., I. White, and D. Kretschmer, (1980). *The Experimental Behavior of Premixed Flames in Tubes: The Effects of Diluent Gases.* Journal of Engineering for Power. Vol. 102, Isuue 2, pp. 422-426. https://doi.org/10.1115/1.3230273.
15. Karim, G.A., I. Wierzba, and S. Boon, (1985). *Some considerations of the lean flammability limits of mixtures involving hydrogen.* International Journal of Hydrogen Energy. Vol. 10, Isuue 2, pp. 117-123. https://doi.org/10.1016/0360-3199(85)90044-8.
16. Bradley, D., et al., (1998). *The Measurement of Laminar Burning Velocities and Markstein Numbers for Iso-octane–Air and Iso-octane–n-Heptane–Air Mixtures at Elevated Temperatures and Pressures in an Explosion Bomb.* Combustion and Flame. Vol. 115, Isuue 1, pp. 126-144. https://doi.org/10.1016/S0010-2180(97)00349-0.
17. Al-Shahrany, A.S., et al., (2006). *DARRIEUS–LANDAU AND THERMO-ACOUSTIC INSTABILITIES IN CLOSED VESSEL EXPLOSIONS.* Combustion Science and Technology. Vol. 178, Isuue 10-11, pp. 1771-1802. https://doi.org/10.1080/00102200600788734.
18. Lewis, B. and G. Von Elbe, (1987). *Combustion, flames and explosions of gases*. 3rd ed. New York, USA: Academic Press. ISBN: 0123958881.

19. Alvi, M.u.-D. (2016).*“Aerosol Propellant Aerosol Propellant Gas | Aerosol Supplies*. [cited 2023; Available from: www.brothersgas.com.
20. D.P Mishra and A. Rahman, (2003). *An experimental study of flammability limits of LPG/air mixtures.* Fuel. Vol. 82, Isuue 7, pp. 863-866. https://doi.org/10.1016/S0016-2361(02)00325-3.
21. Huzayyin, A.S., et al., (2008). *Laminar burning velocity and explosion index of LPG–air and propane–air mixtures.* Fuel. Vol. 87, Isuue 1, pp. 39-57. https://doi.org/10.1016/j.fuel.2007.04.001.
22. Razus, D., et al., (2010). *Burning Velocity of Liquefied Petroleum Gas (LPG)−Air Mixtures in the Presence of Exhaust Gas.* Energy & Fuels. Vol. 24, Isuue 3, pp. 1487-1494. 10.1021/ef901209q.
23. Yamamoto, K., et al., (2009). *Burning velocity and OH concentration in premixed combustion.* Proceedings of the Combustion Institute. Vol. 32, Isuue 1, pp. 1227-1235. https://doi.org/10.1016/j.proci.2008.06.077.
24. Khudhair, M. and F.A. Saleh, (2023). *Experiment study on LPG flame stability of vertical burner.* AIP Conference Proceedings. Vol. 2787, Isuue 1, pp. 030032-030042. 10.1063/5.0155688.