Journal of Applied Fluid Mechanics, Vol. 17, No. 3, pp. 616-627, 2024.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
https://doi.org/10.47176/jafm.17.3.2175

Study of the Impact of LPG Composition on the Blowoff and Flashback Limits of a Premixed Flame in a Swirl Burner

A. S. Mahmood[1,2†] and F. A. Saleh[1]

[1] *Mustansiriyah University, College of Engineering, Mechanical Engineering Department, Baghdad, Iraq*
[2] *Environment Research Center, University of Technology, Iraq*

†Corresponding Author Email: EHph004@uomustansiriyah.edu.iq

ABSTRACT

Liquefied petroleum gas (LPG) is considered one of the gases widely used in many industrial and residential sectors. Still, due to its different compositions, mainly propane (C_3H_8) and butane (C_4H_{10}), it can have other combustion characteristics. This paper aims to conduct an experimental analysis to study the impact of LPG composition on the stability map (limits of blowoff and flashback) of the premixed flame in a tangential swirl burner. Four LPG mixtures were used with different proportions of ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12}). Three burner nozzles at diameters of 20, 25, and 30 mm have been used, which gave three swirl numbers of 0.918, 1.148, and 1.377, respectively. The results indicate that increasing the swirl number (S) from 0.918 to 1.377 for all LPG mixtures accelerated the flashback propensity (getting worse) while the blowoff resistance improved; thus, a rising S gave a better stability map. As for the effect of the LPG composition, it was found that the maximum flame temperature was for the LPG mixture containing high percentages of butane (C_4H_{10}), while the lowest was for the mixture containing fewer percentages of butane. Changing the LPG composition had an apparent effect on the flashback limits and a slight effect on the blowoff limits; it was found that mixtures containing high percentages of butane increased flame speeds and increased the flashback propensity. Compared to LPG mixtures, the flame stability map was widest for LPG mixtures containing lower percentages of butane. Therefore, LPG with propane (C_3H_8) proportions higher than butane (C_4H_{10}) reduces flame temperature, flame speeds, and flashback propensity, thus improving the stability map.

Article History

Received July 8, 2023
Revised October 14, 2023
Accepted October 29, 2023
Available online January 1, 2024

Keywords:

Flame stability
LPG
Swirl number
Flashback
Blowoff

1. INTRODUCTION

For many years, fossil fuel was the most common fuel in most combustion devices. Still, due to its combustion, it emits nitrogen oxides (NO_X) and carbon dioxide (CO_2), causing the effects of climate change and global warming. Therefore, to decrease these impacts (climate change and global warming) and the consumption of fossil fuels, there was a movement toward employing alternative fuels in combustion devices, including gas turbines. (Syred et al., 2012; Lewis et al., 2014). However, alternative fuels with a higher content of hydrogen (H_2) in gas turbine combustors can cause combustion instabilities, especially flashback and blowoff (Shaffer et al., 2013). Flashback refers to the flame retreating upstream and propagating fully into the mixing chamber. At the same time, blowoff occurs as the flame separates from the burner nozzle and is physically blown out of the combustor (AbdulAmeer et al., 2020). For enhancing flame stability and, at the same time, decreasing emission levels of NO_X and CO in gas turbine combustors, the swirling flow method for premixed combustion mode has been proven to be the better approach (Syred et al., 2012; Hossain et al., 2015; Nemitallah et al., 2022). The major characteristic of swirling flows is the creation of central recirculation zones (CRZ) that recirculate the active reactants to enhance flame stability (Baej et al., 2018). Therefore, determining the flame stability region that represents the limits of blowoff and flashback is considered one of the most important issues for the safe operation of combustors (AbdulAmeer et al., 2020). Many factors can cause these two phenomena (flashback and blowoff) to occur, such as the combustion mode (premixed, partially

NOMENCLATURE

A_t	total area for the tangential inlets	*FB*	flashback
BLF	Boundary Layer Flashback	H_2	hydrogen
BLO	blowoff	*LCV*	Lower Calorific Value
CH_4	methane	*LPG*	Liquefied Petroleum Gas
C_2H_6	ethane	m	total mass flow rate
C_3H_8	propane	NO_X	nitrogen oxides
C_4H_{10}	butane	S	swirl number
C_5H_{12}	pentane	S_g	geometric swirl numbers
CIVB	Combustion-Induced Vortex Breakdown	T_f	flame temperature
CO_2	carbon dioxide	$Ø$	equivalence ratio
CRZ	Central Recirculation Zone		

mixed, and non-premixed), fuel type, swirl number, burner geometry, ambient pressure and temperature, etc. (Valera-Medina et al., 2009; Nemitallah et al., 2019; Wan & Zhao, 2020). Among these factors, emphasis will be placed on the influence of the swirl number (S) as well as the type of fuel.

The swirl number is considered a key parameter in the characterization of swirling flows, where it represents “the ratio between the axial flux of angular momentum (G_θ) divided by the product of the axial flux of axial momentum (G_x) and the nozzle radius (R)”, as shown in Equation 1 (Lefebvre, 1999):

$$S = \frac{G_\theta}{G_x * R} \tag{1}$$

However, the complex swirling flow patterns make it difficult to determine the swirl number. Therefore, depending on the geometry of the burner, the geometric swirl number (S_g) can be used (Alsaegh, 2022)

$$S_g = \frac{\pi\, r_e\, R_{eff}}{A_t} \tag{2}$$

Where R_{eff}, r_e, and A_t represent the radius to which the tangential inlets connect with respect to the burner's central axis, the exit nozzle radius, and the tangential inlets total area, respectively.

Many researchers have investigated the swirl number effect. The swirl number impact on the structure of a premixed butane-propane flame has been studied by (Gorelikov et al., 2021). They found that the shape and length of the flame and the formation of the central recirculation zone were significantly affected by the change in swirl number. Also, the influence of swirl number on the limits of flame flashback and blowoff has been studied. It was found that as the swirl number increases, the flame flashback limits get worse (Abdulsada et al., 2011; Syred et al., 2014; Yellugari et al., 2020), while the blowoff limits improve (Syred et al., 2014; Zubrilin et al., 2016). However, it was observed that the stability map is clearly influenced by the swirl number (Saediamiri et al., 2014), and it was discovered that the flame stability map gets better as the swirl number increases (Jerzak & Kuźnia, 2016; Carneiro Piton et al., 2020).

On the other hand, the fuel type is one of the factors affecting the combustion process. In gas turbine combustors, the style or composition of fuel can play an essential role in determining the safe operating range represented by the flashback and blowoff limits (Liu et al., 2014). When the type or composition of fuel is different, this, in turn, leads to a difference in flame speed and chemical kinetic rates. However, a blowoff happens when a chemical reaction takes longer than the combustion zone's residence time. Regarding the flashback, it happens when the velocity of the incoming mixture is less than the flame speed (Lieuwen et al., 2008). Flashback is considered the most serious problem that can damage the combustion device severely. Therefore, it is necessary to avoid fuel types that have a high flame speed, especially those that contain highly hydrogenated mixtures (Heeger et al., 2010). The propagation of flames in the low velocity zone of the boundary layer of the wall is a significant manifestation of the flashback phenomenon. Several previous studies have studied boundary layer flashback (BLF) using different types and compositions of gaseous fuels. Lewis and Von Elbe (1987) were the first to study the BLF for a laminar flame, where they proposed a relation to predict the boundary layer flashback. (Syred et al., 2012) experimentally investigated the limits of flame blowoff and flashback using different fuel mixtures, methane (CH_4), hydrogen (H_2), CH_4/H_2 blends, and coke oven gas (COG: 25%CH_4/65%H_2/6%CO/4%N_2). They reported that with hydrogen-containing mixtures, there is a rapid acceleration of BLF. They also found that COG had completely different behavioral patterns. A flashback of premixed flames using different fuel mixtures of carbon monoxide, hydrogen, and natural gas was verified by (Shaffer et al., 2013). They noticed that the type of flashback that occurred was boundary layer flashback. They discovered that the higher flashback propensity had been related to a higher content of H_2, and the mixture of H_2/CO (50/50% by vol.) gave reactions with a higher propensity for flashback compared to a similar ratio of H_2/CH_4. (Ebi & Clemens, 2016) experimentally examined the boundary layer flashback using a CH_4/H_2 mixture in a swirl burner. They reported that the increase in H_2 content in the mixture gave a larger and more convoluted flame compared to CH_4.

In addition, many previous studies have used liquefied petroleum gas (LPG) as a fuel alone or by mixing it with other gases. LPG can be mainly either propane (C_3H_8) or butane (C_4H_{10}) or mostly a mixture of these two gases (Liu et al., 2014). (Gorelikov et al.,

2021) investigated the premixed swirl flame characteristics utilizing LPG (60% propane and 40% butane by volume). (Elbaz et al., 2019) experimentally verified the flame stability map and NO emission using LPG (30% C_3H_8 and 70% C_4H_{10} by volume) in a swirl burner. Also, flame stability was studied in a vertical non-swirl burner using premixed LPG of 3.3% ethane, 57.08% propane, 38.38% butane, and 1.24% pentane by (Saleh & Alwan, 2021). (Alfarraj et al., 2022) used an LPG of 50% propane and 50% butane as fuel to estimate the premixed flame's combustion velocity in a Bunsen burner. The impact of adding CO_2 to LPG on the premixed flame characteristics of two swirling and non-swirling burners was studied by (Al-Tayyar et al., 2023). They found that adding CO_2 to the LPG increased flame length, significantly improved flame flashback, and increased flame stability limits. (Aravind et al., 2015) performed a numerical model to examine the effect of adding hydrogen (H_2) to LPG (50% propane–50% butane) on the combustion characteristics. They noticed that the change in flame speeds was slight for only the LPG-air mixture, while the flame speed increased with adding H_2. Thus, they reported that adding H_2 to the air-fuel mixture could improve its burning ability. The influence of adding H_2 (0%–50%) to LPG (0.7% C_2H_6, 55.8% C_3H_8, 41.5% C_4H_{10}, and 2% C_5H_{12}) on the premixed flame stability map was investigated by (AbdulAmeer et al., 2020).They found that the type of flashback that occurred was boundary layer flashback (BLF). They also found that when increasing the percentage of H_2 in the LPG-air blend, the flashback propensity increased slightly while the blowoff limits improved significantly. Thus, the stability map was enhanced with the raise of H_2 in the blend due to the significant improvement in the blowoff limits. (Al-Naffakh et al., 2022) studied the impact of mixing acetylene gas (0–50%) with LPG on the premixed flame stability in a swirl burner. They reported that as the percentage of acetylene gas increased, the critical velocity gradient during flashback increased slightly, whereas at blowoff it increased significantly. The stability map was observed to improve as the acetylene gas percentage was raised.

However, the different compositions of LPG, mainly propane (C_3H_8) and butane (C_4H_{10}), may result in various combustion characteristics. For such fuels, auto-ignition, burning velocity, flashback, blowoff, and emissions are significant challenges (Liu et al., 2014). Increased levels of these higher-order hydrocarbons can cause an increase in flame speeds and, thus, a flashback propensity (Dirrenberger et al., 2011). There is a difference in flame speeds, where C_2H_6, C_3H_8, and C_4H_{10} have higher flame speeds than CH_4 (Dirrenberger et al., 2011). However, through my review of previous studies in the field of this study, I did not find any studies about the impact of varying LPG compositions on the characteristics of combustion. Therefore, the aim of this paper is to perform an experimental investigation on the influence of LPG composition on the limits of blowoff and flashback (stability map) of the premixed flame in a tangential swirl burner at three various swirling numbers (S = 0.918, 1.148, and 1.377). Four mixtures of LPG (C_2H_6, C_3H_8, C_4H_{10}, and C_5H_{12}) were used in different proportions for all compositions.

2. MATERIALS

LPG is one of the most widely used alternative gases, as it is a non-renewable energy source. LPG is produced by refining petroleum, where it can be either propane (C_3H_8) or butane (C_4H_{10}), or mostly a mixture of these two gases (Liu et al., 2014). In Iraq, LPG consists of a mixture of several gases (ethane, propane, butane, and pentane); propane and butane are considered to have the largest proportions, while ethane and pentane are in very small proportions (AbdulAmeer et al., 2020; Mjbel et al., 2021). The proportions of propane and butane in the LPG mixture change depending to the seasons and temperature changes. In summer, butane is in higher proportions than propane, and vice versa in winter (Janna & Abdulsada, 2019). Therefore, despite the increasing use of LPG in household uses and internal combustion engines because of its good combustion efficiency, emissions, and low cost in Iraq, it is possible to use it as a fuel in operating burners (Janna & Abdulsada, 2019; Raheemah, 2020).

This study used Iraqi liquefied petroleum gas (ILPG) with different composition proportions as a fuel. It was obtained from the Gas Company of Al-Dora in Baghdad, Iraq. The used ILPG consists of a mixture of several components, namely methane (CH_4), ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12}). The proportions of components and properties of ILPG can be illustrated in Table 1.

3. EXPERIMENTAL SETUP

In this work, experiments have been performed at atmospheric conditions (P = 1 bar and T = 298 K) in the combustion laboratory of the Mechanical Engineering Department, College of Engineering, Al-Mustansiriya University, Iraq. The experimental setup consists of a

Table 1 Component proportions and properties of ILPG used

No. of mixture	Composition Quantity by volume (%)					Chemical formula for ILPG mixture	Density (kg/m^3)	Lower calorific value (kJ/m^3)
	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}			
Mix.1	0	0.34	21.67	77.84	0.15	$C_{3.778}H_{9.556}$	2.224	101296.5
Mix.2	0	0.5	35.01	63.63	0.85	$C_{3.648}H_{9.2958}$	2.143	97922.2
Mix.3	0.05	0.39	52.24	46.79	0.53	$C_{3.4736}H_{8.9472}$	2.048	93976.6
Mix.4	0	0.11	67.00	32.86	0.04	$C_{3.3286}H_{8.6574}$	1.976	90983

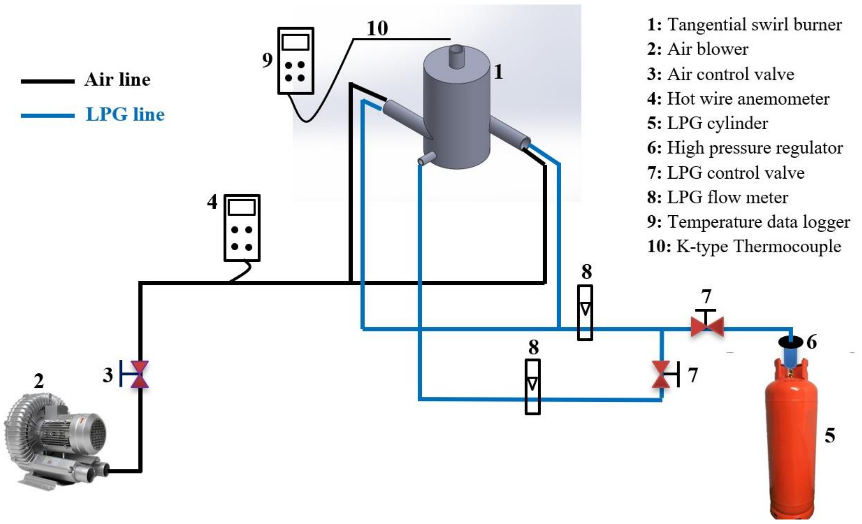


Fig. 1 Schematic of an experimental test rig

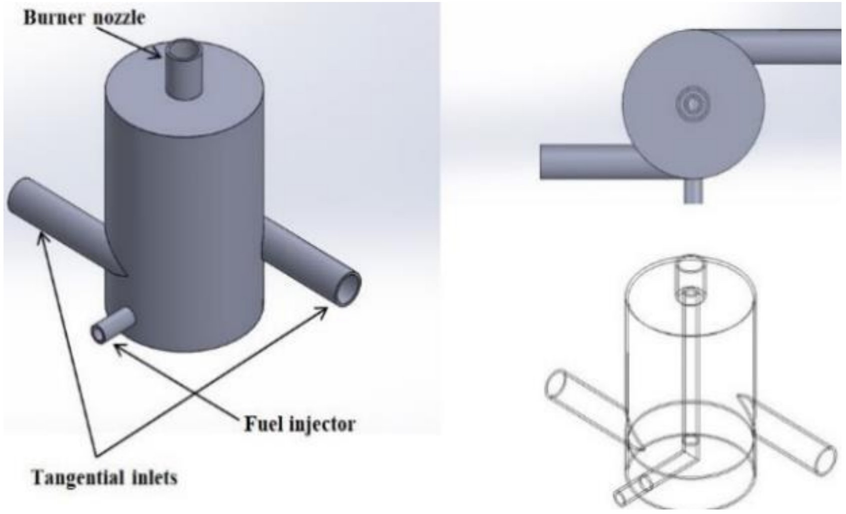


Fig. 2 Tangential swirl burner used

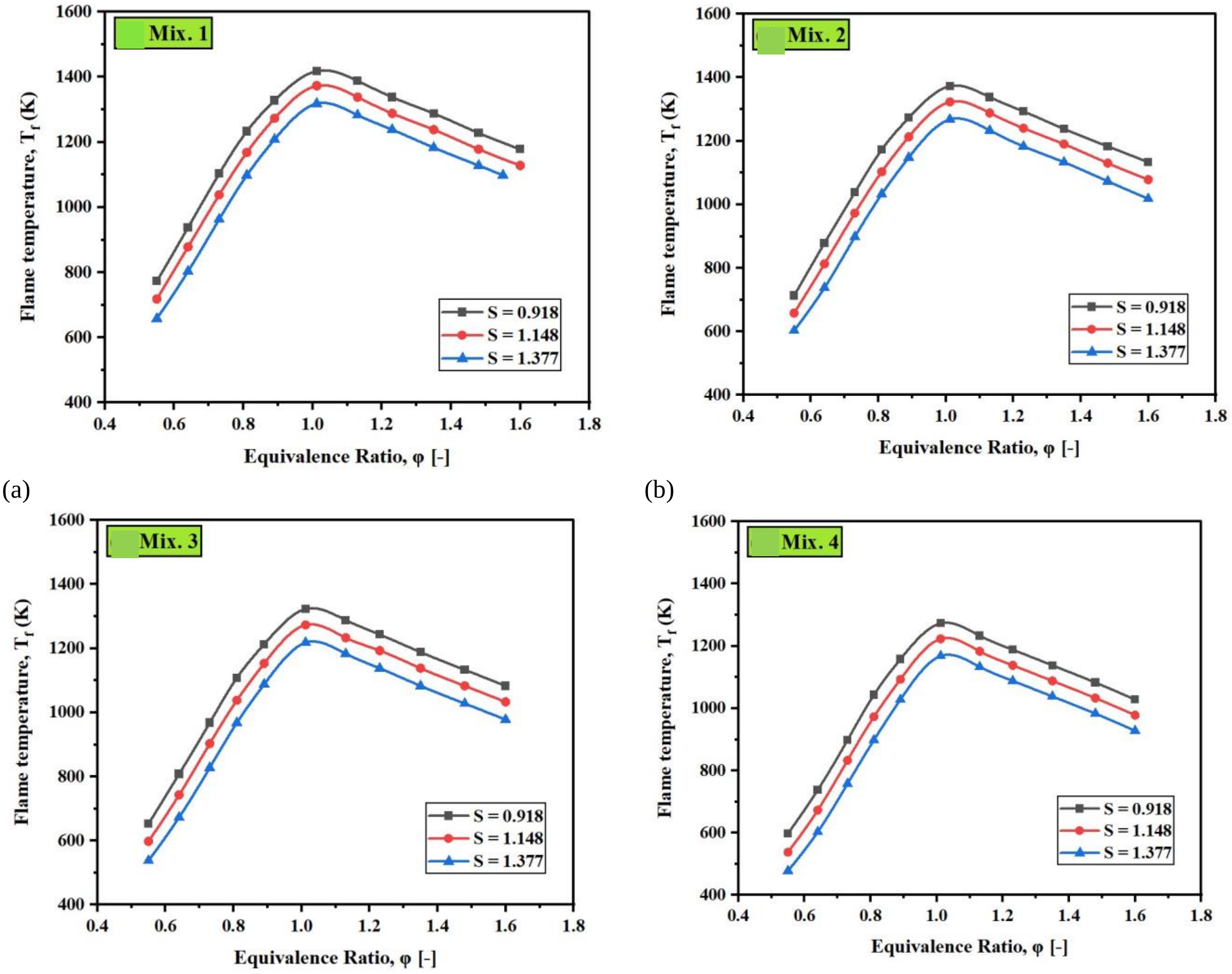
tangential swirl burner (20 kW), air and gas flow meters, air and gas control valves, flexible tubing for connections, an air blower, a gas cylinder, and a camera for imaging, as shown in Fig. 1.

To ensure the creation of swirling flows, the present tangential swirl burner has been designed with two tangential inlets, as shown in Fig. 2. All burner parts were manufactured from stainless steel, and the burner consists of a cylindrical mixing chamber that is 100 mm in diameter and 140 mm in length. At a distance of 3 mm below the mixing chamber, two tangential inlets with inner diameters of 28 mm were installed. A central fuel injector with an outer diameter of 8 mm was used as a bluff body, where it was installed through a hole in the burner baseplate. Whereas the burner nozzle was installed at the top of the mixing chamber, three nozzles with diameters of 2, 2.5, and 3 cm and a height of 3 cm were used. Therefore, by Equation 2, these three nozzles (2, 2.5, and 3 cm) gave different geometric swirl numbers (S_g = 0.918, 1.148, and 1.377), respectively.

The burner was provided with air through an air blower and LPG from a gas cylinder via flexible hoses. In the air supply line, a gate valve was installed to control the airflow rates, and a hot wire anemometer type (GM8903) with a speed range of 0-45 m/s was installed to measure flow rates. Also, a solenoid valve was installed in the gas supply line to control the LPG flow rates, and one LPG flow meter with a volumetric flow range of 0–20 L/min was used to measure the flow rates. The specifications, resolution, and accuracy of the measuring instruments used can be shown in Table 2. A thermocouple of the K-type was used to measure the flame's temperature.

Table 2 The range, resolution, and accuracy of the measuring instruments

Instruments	Range	Resolution	Accuracy
Hot wire anemometer	0 – 30 m/sec	0.001 m/s	±3%
LPG flow meter	0 – 20 L/min	0.25 L/min	±4%



(a) (b)

(c) (d)

Fig. 3 Flame temperatures (T_f) versus equivalence ratio (Ø) at different swirl numbers for (a) LPG mixture 1, (b) LPG mixture 2, (c) LPG mixture 3, and (d) LPG mixture 4

The designed tangential swirl burner can operate in all combustion modes (premixed, partially premixed, and non-premixed), but the premixed combustion mode was used in this study. To operate the burner, a small amount of LPG is injected through the fuel injector. Once the flame is obtained, the premixed mixture is fed via the tangential inlets, with the central fuel injection reduced until it is closed. At this moment, it has achieved a stable premixed flame.

After a stable flame is obtained, the state of flame blowoff is achieved when the fuel flow through the tangential inlets is reduced, and the airflow remains constant. The flame blowoff is identified when the flame is clearly lifted away from the burner's mouth. Once the flame area is lifted out of the burner's mouth, the flow rates of LPG and air at that moment are recorded. In contrast to a flame blowoff, a flame flashback is achieved when the flow rate of fuel (LPG) is increased with constant airflow. As the fuel flow rate is increased, the base of the flame propagates and is connected to the burner nozzle, and by continuing to increase the fuel flow, the flame propagates inside the burner. At this moment, the flow rates of both LPG and air are recorded. To obtain more points for the flashback and blowoff conditions, these steps are repeated for other values of the flow rate that are higher than the previous one. This procedure is considered for any burner nozzle (i.e., any swirl number). Therefore, the procedure followed previously is repeated for the other swirl numbers, as well as for the four LPG mixtures used in this study.

4. RESULTS AND DISCUSSION

4.1 Flame Temperature

Flame temperature is considered an important property during the combustion process, where it plays a major role in the development, efficiency, and pollution of all types of combustion systems. The flame temperature (T_f) can be determined through the energy balance between the reactants and products. In this study, a K-type thermocouple installed on a metal stand at a height of 70 mm from the burner outlet was used to measure the flame's temperature.

4.1.1 Effect of Swirl Number on Flame Temperature

Figures 3 a, b, c, and d show the flame temperatures (T_f) versus equivalence ratio (Ø) at three swirl numbers (S = 0.918, 1.148, and 1.377) and for the four LPG mixtures used, respectively. In general, from figures 3 a, b, c, and d, it was noticed that the flame temperature's behavior with the change in the equivalence ratio was similar for all swirl numbers and the LPG mixtures. The maximum flame temperature was found at a stoichiometric ratio of slightly richer side (Ø = 1.012), while it decreased on both the lean and rich sides of the mixture. This can be explained by the fact that under stoichiometric conditions, the mixing process of the reactants is ideal (the completion of the chemical reaction), and this results in an effective combustion process under conditions of chemical and thermal balance and thus leads to an increase in heat transfer by convection and radiation, which in turn gives an additional amount of energy that works to raise the flame's temperature. On both the mixture's lean and rich sides, the flame temperature decreases due to the poor mixing of the reactants. On the lean side (Ø < 1), the amount of air in the mixture is greater, which causes greater heat loss from the flame and, thus a lower flame temperature. On the rich side (Ø > 1), the amount of air is small and insufficient to burn the fuel, which results in an incomplete combustion process, which leads to less heat release from combustion and, thus, a lower flame temperature.

As for the effect of the swirl number, Figs 3 a, b, c, and d illustrate this. For all LPG mixtures used, it was noticed that the flame temperature reduced as the swirl number increased. The main feature of swirling flows is the creation CRZ that transport hot combustion products to the flame root and recirculate them with the incoming reactants (Baej et al., 2018). However, with the increase in swirl number, the width and intensity of the CRZ increase. Increasing the intensity of the CRZ leads to the introduction of more incoming reactants into the CRZ, which leads to a more significant loss of heat from the reaction zone as a result of heating the incoming mixture to re-ignite it and thus reduce the flame temperature; this is consistent with (Yellugari et al., 2020).

4.1.2 Effect of LPG Composition on Flame Temperature

Changing the type or composition of fuel is considered one of the most important factors affecting the combustion process. With the change in fuel composition, the chemical and thermo-physical properties of the mixture may change, and changing these properties affects the combustion process.

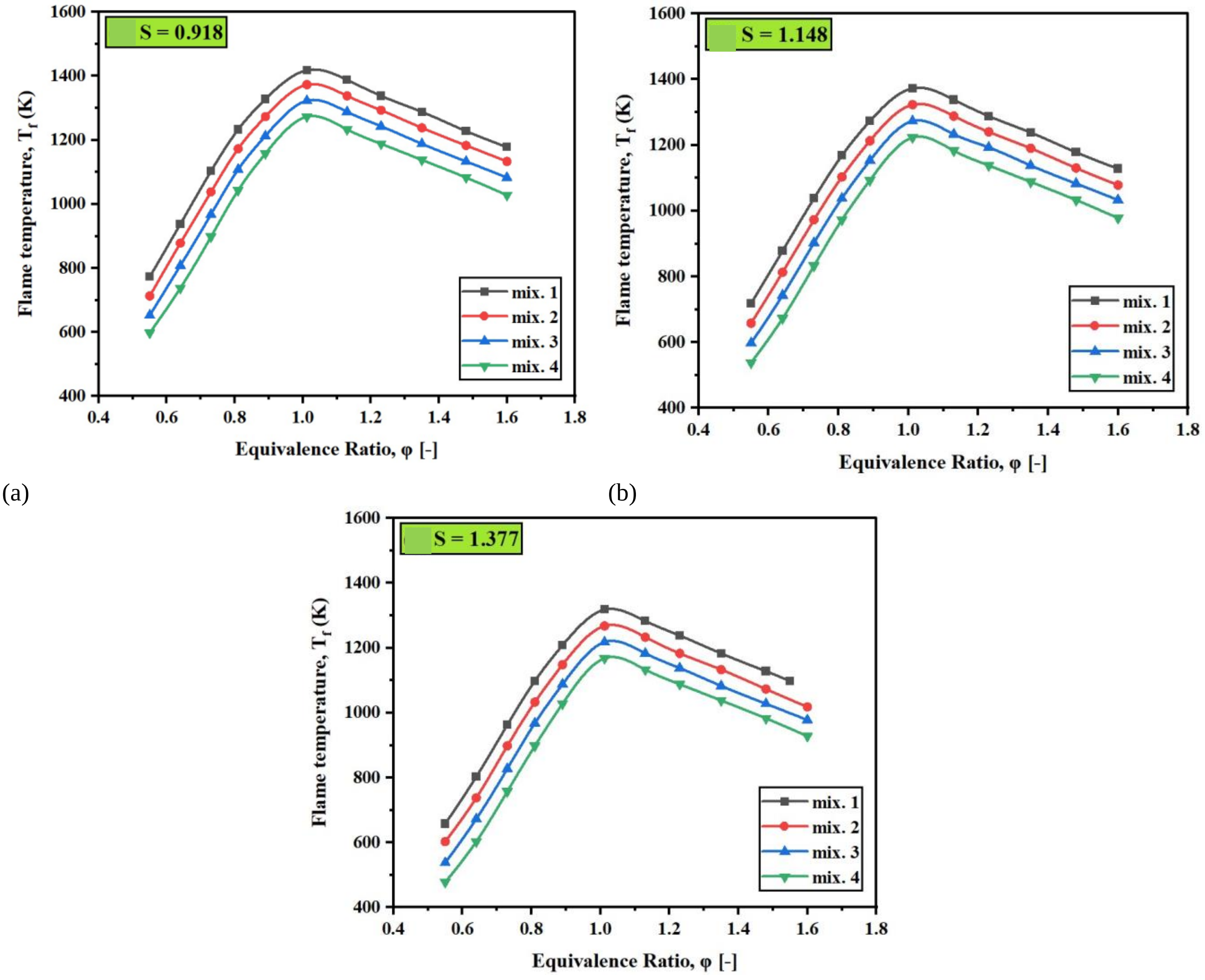
Figures 4 a, b, and c show the variation of flame temperature versus equivalence ratio for all LPG mixtures for swirl numbers of 0.918, 1.148, and 1.377, respectively. For all swirl numbers, it was noticed that the maximum flame temperature was with Mix.1, while the lowest was with Mix.4. This can be explained by two reasons: (1) As shown in Table 1, Mix.1 has a greater number of H atoms (9.556) compared to the other mixtures: Mix.2 has (9.2958), Mix.3 has (8.9472), and Mix.4 has (8.6574). This could be a major reason, as increasing the number of H atoms enhances the combustion process and accelerates the flame propagation, which increases the flame speed and temperature, and this is consistent with (Xiao et al., 2020). (2) The difference in volumetric calorific value of LPG compositions is also considered an influencing factor, and it can give different flame temperatures. In this study, the volumetric calorific values of the LPG mixtures are $LCV_{Mix.1}$ = 101296.5 kJ/m^3, $LCV_{Mix.2}$ = 97922.2 kJ/m^3, $LCV_{Mix.3}$ = 93976.6 kJ/m^3, and $LCV_{Mix.4}$ = 90983 kJ/m^3. Therefore, an LPG mixture that has a high LCV gave an increase in combustion temperatures and, thus, the flame temperature.

4.2 Flame Stability Map

Flame stability is considered a significant issue during the combustion process, through which the safe operation of combustors can be determined. The flame stability map represents the region that lies between the limits of blowoff and flashback. The tests have been performed on the swirl burner used, and the flame stability map was determined at three various swirl numbers and using four different mixtures of LPG, as shown in Table 1. In swirling flows, combustion induced vortex breakdown (CIVB) is considered the dominant type of flashback, even if the velocity of the flame is lower than that of the fresh mixture (Hatem et al., 2018). In this study, due to the central fuel injector (as a bluff-body) is present, it gave a high resistance and prevented the occurrence of CIVB, but led to an increase in the tendency of the other mechanism of flashback, which is the boundary layer flashback (BLF). Some real photos taken during practical tests with the Nikon D5300 camera showing the cases of flame stabilization, boundary layer flashback (BLF), and just before blowoff can be illustrated in Fig. 5.

4.2.1 Effect of Swirl Number on Stability Map

Beginning with the influence of swirl number (S), as mentioned in the introduction, swirl number is one of the factors affecting flow structures and combustion characteristics and, thus, the flame stability map. Therefore, the effect of the swirl numbers (S = 0.918, 1.148, and 1.377) on the limits of flame flashback (FB) and blowoff (BLO) as a function of total mass flow rate ($\dot{m}$) versus equivalence ratio for the four mixtures of LPG (Mix.1, Mix.2, Mix.3, and Mix.4) can be illustrated in Figs 6 a, b, c, and d, respectively. For all LPG mixtures, it was observed that the flame flashback propensity is accelerated (getting worse) while the blowoff resistance improves with the increase of S from 0.918 to 1.377. Increasing the S increases the CRZ intensity and the turbulence level. Increasing the turbulence level increases the flame speed, which increases the flashback tendency. In addition, according to Equation 2, in which the swirl number has been calculated, an increase in the swirl number means an increase in the burner nozzle diameter. Therefore, at a certain level of mixture flow rate, an increase in the burner nozzle diameter leads to a decrease in the mixture flow velocity and thus an increase in the flashback propensity. As for the improvement in blowoff resistance, increasing the CRZ intensity greatly improves flame stability by recirculating fresh reactants and hot combustion products, which improves the flammability of the fresh mixture.



(a) (b)

(c)

Fig. 4 Flame temperatures (T_f) versus equivalence ratio (Ø) at different LPG mixtures for (a) S = 0.918, (b) S = 1.148, and (c) S = 1.377

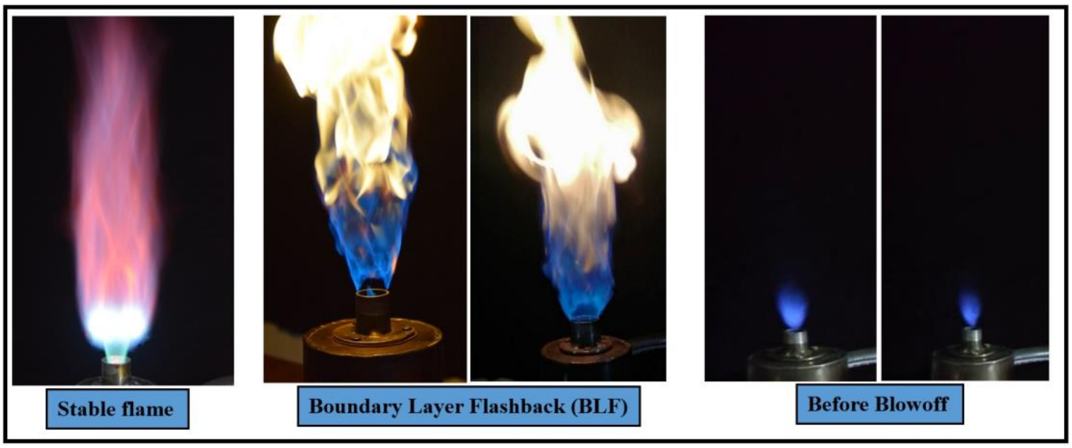
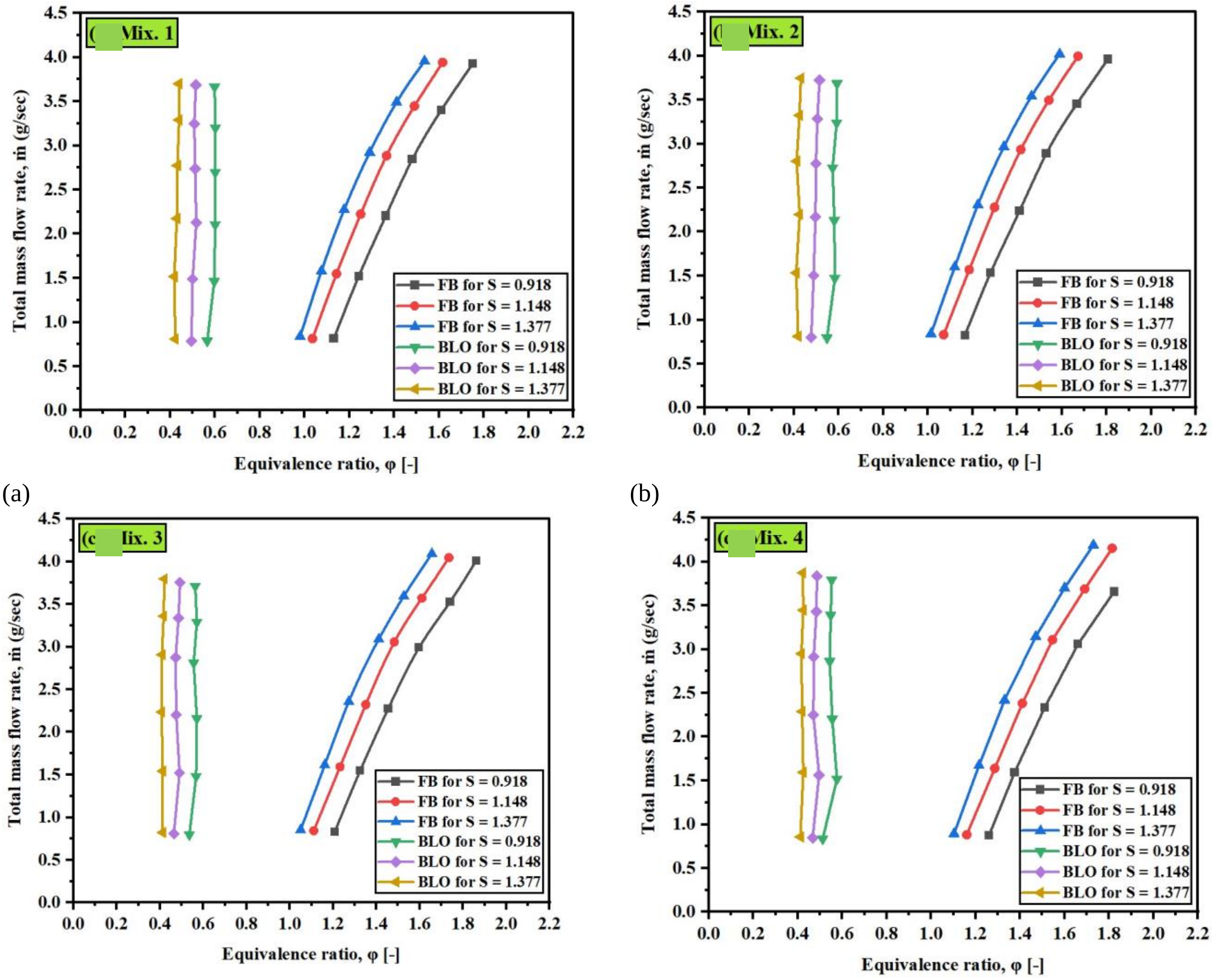


Fig. 5 Real images for cases of flame stability, BLF, and just before blowoff

Figures 6 a, b, c, and d show that the smaller swirl number (0.918) gave better flashback resistance, but its resistance to blowoff was lower compared to the larger swirl number (1.377). However, the flame stability map was not significantly affected by the change in swirl number due to both the limits of flashback and blowoff being affected. Increasing the swirl number (S) led to moving the equivalence ratio limits for both flashback and blowoff towards the lean regions. Consequently, it can be said that the flame stability map improves with the increase of the S as a result of the equivalence ratio limits moving towards the lean regions as well as the improvement of the mixing and combustion processes, and this is beneficial to meet low-emissions requirements.



(a) (b)

(c) (d)

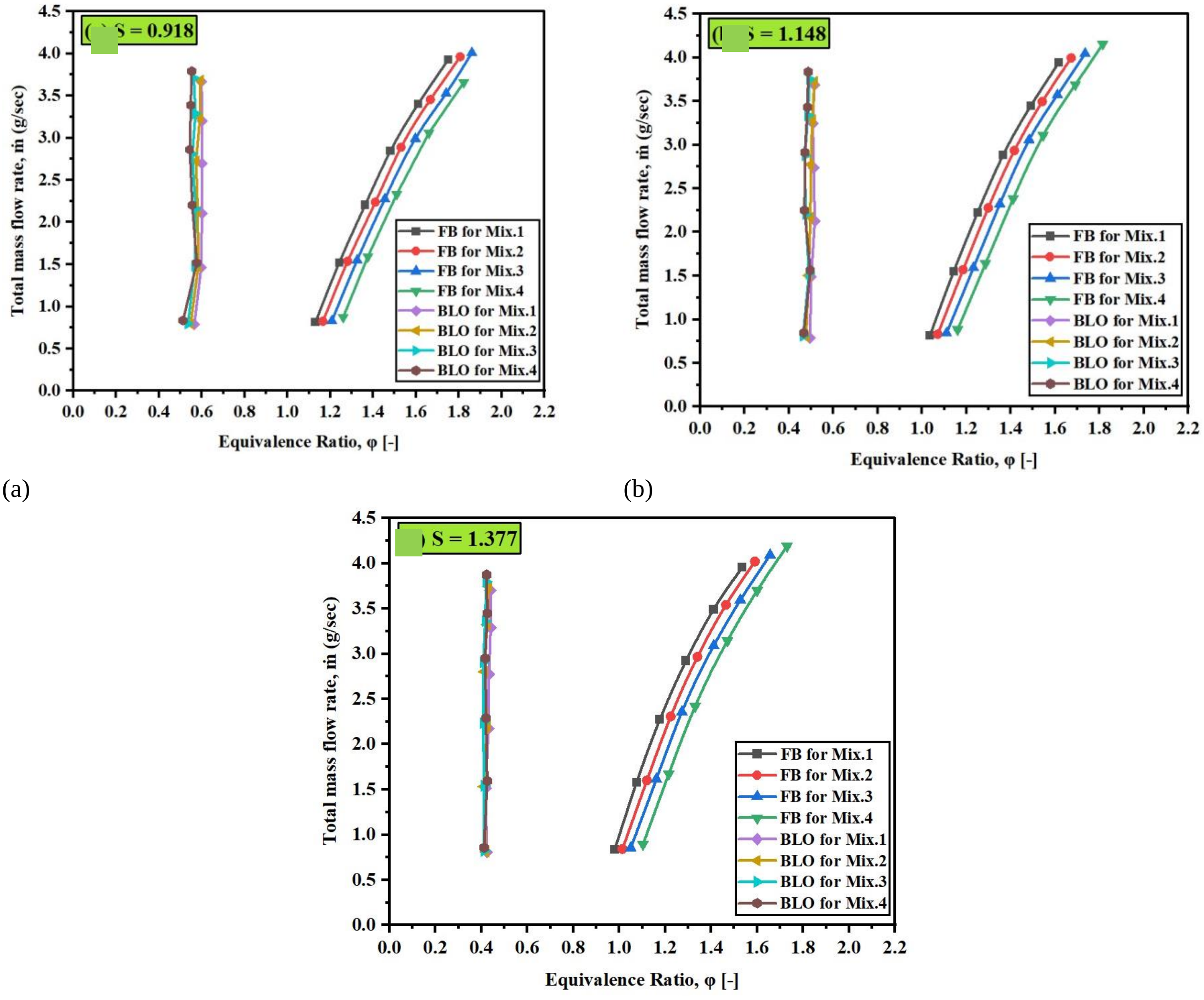
Fig. 6 Flashback and blowoff limits (flame stability map) at different swirl numbers for (a) LPG mixture 1, (b) LPG mixture 2, (c) LPG mixture 3, and (d) LPG mixture 4

4.2.2 Effect of LPG Composition On Stability Map

In addition to the swirl number's impact, changing the fuel type or composition is one of the most significant factors affecting the flashback and blowoff of the flame and, thus, the stability map. Figures 7 a, b, and c show the effect of changing the LPG composition on the limits of flame blowoff (BLO) and flashback (FB) as a function of total mass flow rate ($\dot{m}$) versus the equivalence ratio for swirl numbers 0.918, 1.148, and 1.377, respectively. From the figures, changing the LPG composition had an apparent effect on the FB limits and a slight effect on the BLO limits for each swirl number. Mixture 1 ($C_{3.778}$ $H_{9.556}$) had an increase in the flashback propensity, while the flashback propensity decreased for mixture 2 ($C_{3.648}$ $H_{9.2958}$), mixture 3 ($C_{3.4736}$ $H_{8.9472}$), and the best decrease was for mixture 4 ($C_{3.3286}$ $H_{8.6574}$). One of the reasons related to the increase in flashback propensity is the high flame speeds. However, it can be noted that the number of H atoms in mixture 1 is greater compared to mixtures 2, 3, and 4, so increasing the number of H atoms in the mixture leads to an acceleration of the flame propagation and an increase in its temperature, which increases the flame speed and increases the flashback propensity but the difficulty of the flame blowoff. Also, the lower calorific value (LCV) is considered one of the fuel properties affecting the combustion process. The LCV of LPG mixtures 1, 2, 3, and 4 is 101296.5, 97922.2, 93976.6, and 90983 kJ/m^3, respectively, as shown in Table 1. Therefore, an LPG mixture that has a high LCV gave an increase in combustion temperatures and, thus, a flashback propensity.

On the other hand, when the LCV of the mixture decreases, an increase in the fuel flow rate is required to maintain the same power output level. Thus, increasing the fuel flow rate increases the flow of the unburned mixture, resulting in a decrease in the flashback propensity. This can be seen in Figures 7 a, b, and c, where the flame flashback of LPG mixtures 2, 3, and 4 occurred at higher flow rates than LPG mixture 1.

In addition to the effect of the calorific value of the LPG mixture, the change in the proportions of propane (C_3H_8) and butane (C_4H_{10}), which are the two main components in the LPG mixture, also has an impact on the combustion characteristics. Increased levels of these higher-order hydrocarbons can cause an increase in flame speeds and, thus, a flashback propensity (Dirrenberger et al., 2011). Therefore, the mixture containing high percentages of butane (C_4H_{10}) has higher flame speeds, which is consistent with (Yasiry & Shahad, 2016). In this study, the proportions of (C_3H_8–C_4H_{10}) for Mix.1 were



(a) (b)

(c)

Fig. 7 Flame stability map (flashback and blowoff limits) at different LPG mixtures for (a) S = 0.918, (b) S = 1.148, and (c) S = 1.377

(21.67%–77.84%), Mix.2 (35.01%–63.63%), Mix.3 (52.24%–46.79%), and Mix.4 (67%–32.86%). Thus, the flame flashback propensity increases in Mix.1 and Mix.2 was clear due to the high proportions of C_4H_{10}, which increased flame speeds. Whereas, the flashback propensity decreased in Mix.3 due to the low C_4H_{10} proportion becoming less than C_3H_8, and in Mix.4 the best reduction in the flashback propensity was achieved due to the increase in the high C_3H_8 proportion.

Although there was a slight change in the blowoff limits for all LPG mixtures, the flashback limits had a clear effect on the flame stability map. From Figures 7 a, b, and c, it can be seen that LPG Mix.4 gave the best flashback resistance for all swirl numbers and thus the widest stability map. The change in the stability map ($Ø_{FB}$ - $Ø_{BLO}$) of the burner used for LPG Mix.4 was found at S = 0.918, 1.148, and 1.377, which were (1.26 - 0.51), (1.16 - 0.466), and (1.10 - 0.41), respectively.

5. CONCLUSION

Experimental tests were performed on a tangential swirl burner, and the influence of changing the LPG composition on the limits of flame blowoff and flashback (stability map) at swirl numbers (S = 0.918, 1.148, and 1.377) was studied. Four LPG mixtures were used with different proportions of ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12}). The flame flashback and blowoff limits were determined for each LPG mixture and swirl number. The following is a summary of the current study's conclusions:

1. For all LPG compositions and swirl numbers, the maximum flame temperature was found to be at a stoichiometric ratio of slightly richer side (Ø = 1.012), while decreasing on both the lean and rich sides of the mixture.

2. For all LPG mixtures, it was observed that the flame temperature decreases as the swirl number increases.

3. It was found that the maximum flame temperature was for the LPG mixture containing high percentages of butane (C_4H_{10}), while the lowest was for the mixture containing fewer percentages of butane.

4. For all LPG mixtures, it was observed that the flame flashback propensity is accelerated (getting worse) while the blowoff resistance improves with the increase of S from 0.918 to 1.377. Thus, a rising S gave a better stability map.

5. It was observed that changing the LPG composition clearly affected the flashback limits and slightly affected the blowoff limits for each swirl number. It was found that mixtures containing high percentages of butane increase flame speeds and increase flashback propensity.

6. For all swirl numbers, the flame stability map was widest for LPG mixture containing lower percentages of butane.

Therefore, it is preferred to use LPG with propane (C_3H_8) proportions higher than butane (C_4H_{10}) to reduce the flame temperature, flame speeds, and flashback propensity, thus improving the stability map.

ACKNOWLEDGEMENTS

The authors would like to thank Mustansiriyah University, College of Engineering, Mechanical Engineering Department, Iraq- Baghdad, for its support of this work.

The authors would like to thank the Gas Company of Al-Dora in Baghdad, Iraq, who helped us in this work in supplying liquefied petroleum gas (ILPG) with different composition proportions.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

AUTHORS CONTRIBUTION

Abdulrahman Shakir Mahmood: Material preparation, data collection, Investigation, Methodology, and Writing - original draft. **Fouad Alwan Saleh**: conceptualization, supervision, review and editing.

REFERENCES

AbdulAmeer, M. T., Shahad, H. A. K., & AbdulHaleem, S. M. (2020). Experimental investigation of lpg/h2/air premixed flame stability zone. *Journal of Engineering and Technological Sciences*, *52*(5), 691. https://doi.org/10.5614/j.eng.technol.sci.2020.52.5.7

Abdulsada, M., Syred, N., Griffiths, A., & Bowen, P. (2011, January 4). Effect of swirl number and fuel type upon the flashback in swirl combustors. *49th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*. https://doi.org/10.2514/6.2011-62

Alfarraj, B. A., Al-Harbi, A. A., Binjuwair, S. A., & Alkhedhair, A. (2022). The characterization of liquefied petroleum gas (LPG) using a modified bunsen burner. *Journal of Combustion*, *2022*, 1–9. https://doi.org/10.1155/2022/6977930

Al-Naffakh, J. T., Al-Qassab, M. R., Neamah, B. T., & Al-Makhzoomi, Z. M. H. (2022). Experimental investigation of blending acetylene with iraqi lpg to determine a flame stability map. *Journal of Petroleum Research and Studies*, *12*(1), 350–363. https://doi.org/10.52716/jprs.v12i1.607

Alsaegh, A. (2022). *Fundamental characterisation of coherent structures for swirl combustors*. [Doctoral dissertation, Cardiff University]. https://orca.cardiff.ac.uk/id/eprint/148132

Al-Tayyar, M. A., Alkhafaji, D., & Shahad, H. A. K. (2023). An Investigation into Burner Configuration Effects on Premixed Flame Characteristics for LPG Diluted with CO_2. *Applied Mechanics and Materials*, *914*, 53–66. https://doi.org/10.4028/p-gu777j

Aravind, B., Ratna Kishore, V., & Mohammad, A. (2015). Combustion characteristics of the effect of hydrogen addition on LPG–air mixtures. *International Journal of Hydrogen Energy*, *40*(46), 16605–16617. https://doi.org/10.1016/j.ijhydene.2015.09.099

Baej, H., Akair, A., Diyaf, A., Adeilla, S., & Kraiem, A. (2018). Modeling effects of outlet nozzle geometry on swirling flows in gas turbine. *First Conference for Engineering Sciences and Technology*. http://dspace.elmergib.edu.ly/xmlui/handle/123456789/67

Carneiro Piton, L., Senra Pessanha Rios Nobrega, G., Figueira da Silva, L. F., Scouflaire, P., & Darabiha, N. (2020). Experimental study of the influence of the swirl number on lean premixed combustion regimes. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *42*(4), *210.* https://hal.science/hal-03313670

Dirrenberger, P., Glaude, P. A., Le Gall, H., Bounaceur, R., Herbinet, O., Battin-Leclerc, F., & Konnov, A. A. (2011). laminar flame velocity of components of natural gas. *Volume 2: Combustion, Fuels and Emissions, Parts A and B*, 1079–1085. https://doi.org/10.1115/GT2011-46312

Ebi, D., & Clemens, N. T. (2016). Experimental investigation of upstream flame propagation during boundary layer flashback of swirl flames. *Combustion and Flame*, *168*, 39–52. https://doi.org/10.1016/j.combustflame.2016.03.027

Elbaz, A. M., Moneib, H. A., Shebil, K. M., & Roberts, W. L. (2019). Low NOX - LPG staged combustion double swirl flames. *Renewable Energy*, *138*, 303–315. https://doi.org/10.1016/j.renene.2019.01.070

Gorelikov, E., Litvinov, I., & Shtork, S. (2021). *Aerodynamics and characteristics of the premixed swirl flame*. 030082. https://doi.org/10.1063/5.0052337

Hatem, F. A., Alsaegh, A. S., Al-Faham, M., Valera-Medina, A., Chong, C. T., & Hassoni, S. M. (2018). Enhancing flame flashback resistance against Combustion Induced Vortex Breakdown and Boundary Layer Flashback in swirl burners. *Applied Energy*, *230*, 946–959.

https://doi.org/10.1016/j.apenergy.2018.09.055

Heeger, C., Gordon, R. L., Tummers, M. J., Sattelmayer, T., & Dreizler, A. (2010). Experimental analysis of flashback in lean premixed swirling flames: upstream flame propagation. *Experiments in Fluids*, *49*(4), 853–863. https://doi.org/10.1007/s00348-010-0886-0

Hossain, M. M., Lu, G., Hatem, F. A., Valera-Medina, A., Marsh, R., & Yan, Y. (2015). *Temperature measurement of gas turbine swirling flames using tomographic imaging techniques.* 2015 IEEE International Conference on Imaging Systems and Techniques (IST), 1–5. https://doi.org/10.1109/IST.2015.7294541

Janna, H., & Abdulsada, M. (2019). Experimental investigation of the confinement effect on flashback in multi combustion modes tangential swirl burner. *Al-Qadisiyah Journal for Engineering Sciences*. https://doi.org/10.30772/qjes.v12i3.613

Jerzak, W., & Kuźnia, M. (2016). Experimental study of impact of swirl number as well as oxygen and carbon dioxide content in natural gas combustion air on flame flashback and blow-off. *Journal of Natural Gas Science and Engineering*, *29*, 46–54. https://doi.org/10.1016/j.jngse.2015.12.054

Lefebvre, A. H. (1999). *Gas Turbine. Combustion*. 2nd Edition, Taylor and Francis, Philadelphia. Combustion.

Lewis, B., & Von Elbe, G. (1987). *Combustion, flames and explosions of gases*. 3rd. Edition, London: Academic Press.

Lewis, J., Valera-Medina, A., Marsh, R., & Morris, S. (2014). Augmenting the structures in a swirling flame via diffusive injection. *Journal of Combustion*, *2014*, 1–16. https://doi.org/10.1155/2014/280501

Lieuwen, T., McDonell, V., Petersen, E., & Santavicca, D. (2008). Fuel flexibility influences on premixed combustor blowout, flashback, autoignition, and stability. *Journal of Engineering for Gas Turbines and Power*, *130*(1). https://doi.org/10.1115/1.2771243

Liu, K., Martin, P., Sanderson, V., & Hubbard, P. (2014). Effect of change in fuel compositions and heating value on ignition and performance for siemens SGT-400 dry low emission combustion system. *Journal of Engineering for Gas Turbines and Power*, *136*(3). https://doi.org/10.1115/1.4025682

Mjbel, H. M., Abdulhaleem, S. M., & Shahad, H. A. (2021). A numerical and experimental analysis of laminar flame speed for pre-mixed Iraqi Lpg/Air mixture in a horizontal cylindrical combustion chamber. *Journal of Mechanical Engineering Research and Developments*, *44* (1), 176-189. https://www.semanticscholar.org/paper/bcccca877b1a485d04cddf92c069e186b50fa54e

Saleh, M. A., & Alwan, F. S (2021). *Experimental study of flame propagation and stability of (ILPG).* IOP Conference Series: Materials Science and Engineering, 1088(1). https://iopscience.iop.org/article/10.1088/1757-899X/1088/1/012069/meta

Nemitallah, M. A., Abdelhafez, A. A., Ali, A., Mansir, I., & Habib, M. A. (2019). Frontiers in combustion techniques and burner designs for emissions control and CO $_2$ capture: A review. *International Journal of Energy Research*, er.4730. https://doi.org/10.1002/er.4730

Nemitallah, M. A., Haque, M. A., Hussain, M., Abdelhafez, A., & Habib, M. A. (2022). Stratified and hydrogen combustion techniques for higher turndown and lower emissions in gas turbines. *Journal of Energy Resources Technology*, *144*(2). https://doi.org/10.1115/1.4052541

Raheemah, K. S. H. (2020). *Study operation of steam generation system using different fuels*. [Master Thesis, AL-Furat Al-Awsat Technical University Engineering Technical College- Najaf].

Saediamiri, M., Birouk, M., & Kozinski, J. A. (2014). On the stability of a turbulent non-premixed biogas flame: Effect of low swirl strength. *Combustion and Flame*, *161*(5), 1326–1336. https://doi.org/10.1016/j.combustflame.2013.11.002

Shaffer, B., Duan, Z., & McDonell, V. (2013). Study of fuel composition effects on flashback using a confined jet flame burner. *Journal of Engineering for Gas Turbines and Power*, *135*(1). https://doi.org/10.1115/1.4007345

Syred, N., Abdulsada, M., Griffiths, A., O'Doherty, T., & Bowen, P. (2012). The effect of hydrogen containing fuel blends upon flashback in swirl burners. *Applied Energy*, *89*(1), 106–110. https://doi.org/10.1016/j.apenergy.2011.01.057

Syred, N., Giles, A., Lewis, J., Abdulsada, M., Valera Medina, A., Marsh, R., Bowen, P. J., & Griffiths, A. J. (2014). Effect of inlet and outlet configurations on blow-off and flashback with premixed combustion for methane and a high hydrogen content fuel in a generic swirl burner. *Applied Energy*, *116*, 288–296. https://doi.org/10.1016/j.apenergy.2013.11.071

Valera-Medina, A., Syred, N., & Griffiths, A. (2009). Visualisation of isothermal large coherent structures in a swirl burner. *Combustion and Flame*, *156*(9), 1723–1734. https://doi.org/10.1016/j.combustflame.2009.06.014

Wan, J., & Zhao, H. (2020). Blow-off mechanism of a holder-stabilized laminar premixed flame in a preheated mesoscale combustor. *Combustion and Flame*, *220*, 358–367. https://doi.org/10.1016/j.combustflame.2020.07.012

Xiao, P., Lee, C., Wu, H., & Liu, F. (2020). Effects of hydrogen addition on the laminar methanol-air flame under different initial temperatures. *Renewable Energy*, *154*, 209–222. https://doi.org/10.1016/j.renene.2020.03.037

Yasiry, A. S., & Shahad, H. A. (2016). An experimental study for investigating the laminar flame speed and burning velocity for LPG. *International Journal of Thermal Technologies*, *6*, 7–12. http://inpressco.com/an-experimental-study-for-investigating-the-laminar-flame-speed-and-burning-velocity-for-lpg/

Yellugari, K., Villalva Gomez, R., & Gutmark, E. J. (2020, January 6). Effects of swirl number and central rod on flow in lean premixed swirl combustor. *AIAA Scitech 2020 Forum*. https://doi.org/10.2514/6.2020-0433

Zubrilin, R. A., Zubrilin, I. A., Matveev, S. S., & Matveev, S. G. (2016, June 13). Gaseous fuel flame stabilization in a modular swirled burner. *Volume 4B: Combustion, Fuels and Emissions*. https://doi.org/10.1115/GT2016-57441