JJMIE

Volume 17, Number 4, December. 2023
ISSN 1995-6665
Pages 595– 604
https://doi.org/10.59038/jjmie/170414
Editor-in-Chief: Prof. Ali M. Jawarneh

Jordan Journal of Mechanical and Industrial Engineering

Experimental Study of the Effect of Swirl Number and Bluff Body Size on the Stability Map of Premixed LPG Flames in a Tangential Swirl Burner

Abdulrahman Shakir Mahmood[a,b*], Fouad Alwan Saleh[a]

[a]*Mustansiriyah University, College of Engineering, Mechanical Engineering Department, Iraq- Baghdad*
[b]*Environment Research Center, University of Technology-Iraq, 10066, Baghdad, Iraq.*

Received 20 Jun 2023 *Accepted 16 Sep 2023*

Abstract

This article presents an experimental analysis investigating the impact of swirl number (S) and annular passage area (B) on the stability limits of the premixed flames in a 20-kW tangential swirl burner. Three nozzles with different diameters (D_N = 20, 25, and 30 mm) were used to achieve variable geometric swirl numbers (S_g = 0.918, 1.148, and 1.377).Three central fuel injectors (as a bluff-body) with different diameters (D_{inj} = 6, 8, and 12 mm) were used to obtain different annular passage areas.

In the first part of the study, the results revealed that as swirl number (S) increased, flashback limits (FB) decreased (i.e., worsened), and the flame resistance to blowoff (BLO) improved. Thus, the best flame stability map was obtained with increasing S. In the second part of the study, changing the central fuel injector diameter (bluff-body) led to a change in the annular passage area (B) and had an important role in resisting and preventing flashback from combustion-induced vortex breakdown (CIVB). When B was increased (increasing fuel injector diameter), a significant improvement in flashback resistance was observed due to an increase in the momentum of the unburned mixture, while with a decrease in B (reducing fuel injector diameter), the limits of the flashback decreased and moved towards lean regions. However, it was found that the burner operation map increases with increasing B; the best operation map was found at S = 1.377 and B = 0.4, and it was (φ_{FB} = 1.18 - φ_{BLO} = 0.42) in the inlet tangential velocity range (W_{inlet}= 0.58 to 2.84 m/s).Also, tests were carried out without the use of a bluff-body (central fuel injector), and it was found that there is a great impact on the flow field and the location and shape of the central recirculation zone (CRZ); thus, the stability map was narrower than that using the bluff-body. Consequently, adding bluff-bodies to swirling flows improves the mixing properties, increases the intensity of the CRZ, thus enhances the stable operation map. In addition, the bluff-body's presence greatly helps in eliminating CIVB flashback.

Keywords: Operation map, flashback, blowoff, swirl number, bluff-body.

Nomenclature

A_{inlet}	cross section area of tangential inlet's
B	annular passage area
BLF	boundary layer flashback
BLO	blowoff
CH_4	methane
C_2H_6	ethane
C_3H_8	propane
C_4H_{10}	butane
C_5H_{12}	pentane
$CIVB$	combustion induced vortex breakdown
CO	carbon monoxide
COG	coke oven gas
CRZ	central recirculation zone
D_{inj}	central fuel injector diameter
D_N	nozzles diameter
FB	flashback
H_2	hydrogen
IRZ	inner recirculation zone
LPG	liquefied petroleum gas
$\dot{m}_a$	air mass flow rate
$\dot{m}_f$	fuel mass flow rate
$\dot{m}_{tot}$	total mass flow rate
N_2	Nitrogen
NG	natural gas
PVC	pressing vortex core
Q_a	air volume flow rate
Q_f	fuel volume flow rate
Q_T	total volume flow rate
S	swirl number
S_g	geometric swirl number
W_{inlet}	inlet tangential velocity
$\emptyset$	equivalence ratio
$\emptyset_{BLO}$	equivalence ratio at blowoff
$\emptyset_{FB}$	equivalence ratio at flashback
ρ_a	air density
ρ_f	fuel density
ρ_T	total density

---

* Corresponding author e-mail: EHph004@uomustansiriyah.edu.iq.

1. Introduction

The increasing use of combustion systems in many fields, especially those that operate on fossil fuels, has increased pollutant emissions. This has led to imposing emissions regulations in the energy production market to reduce the level of pollutants in the atmosphere[1-5]. Among these combustion systems, gas turbines are getting particular interest because of their significant contribution in the energy market[2][6]. The use of a premixed combustion mode in gas turbine combustors helps reduce undesirable emissions [7][8]. Flame stability and a wide operating map are the main and most important factors that contribute to the good performance of gas turbine combustors, where manipulation of the flow field is considered one of the most important factors [6]. Therefore, there are several methods to stabilize the flame, including swirling flows and bluff-bodies[9][10].

Swirling flows are the most widely used technique to stabilize flames in the combustors due to their ability to form the so-called coherent structures, the pressing vortex core (PVC), and the central recirculation zone (CRZ). These structures play an important role in recirculating chemical species and heat to the flame root, enabling flame establishment in a region of low-velocity. Thus, the flow and turbulent flame speeds can be matched[11]. However, most swirl combustors, especially those operating in premixed combustion mode, encounter instability problems, the most important of which are blowoff and flashback [12][13]. Flashback is the most serious problem in combustion devices, which occurs when the flame propagates upstream from the combustor to the premixing tube; it leads to severe damage to the combustor[14]. The most common cause is an imbalance between the velocity of the flame and the incoming mixture. Some parameters can affect this equilibrium degree, such as fuel type, mixing degree, burner configuration, swirl number, etc. [15]. The swirl number is considered an important factor on which to focus. It is observed that the structures of the swirling flows, flame stability, and heat transfer characteristics can be greatly affected when the swirl number changes[16][17]. Gorelikov et al. [18] found that the formation of the CRZ, the shape and length of the flame depended on the swirl number. Also, the swirl number has great effects on the operation map represented by the blowoff and flashback limits. It has been observed that when the swirl number increases, the blowoff limits improve[13][19], while the flashback limits worsen [12[[13][20]. Jerzak and Kuźnia [21] reported that there was a significant improvement in the operating range of the burner when S was increased from 0.69 to 1.35.

In swirl burners, flashback can occur as a result of CIVB. This can be due to the CRZs that form, which act as a flame holder and then can lead to the movement of the flame within the premixing zone [22]. On the other hand, as a result of the interaction between swirl burner geometries and swirl structures, this type of flashback (CIVB) can happen even when the velocity of the incoming mixture exceeds the speed of the flame[15]. The flashback of the flame in the swirl burner without the use of a bluff-body was verified byFritz et al. [23]. They reported that the dominant mechanism of flashback is CIVB. They also found that when axial momentum is added around the axis of the mixing tube, it significantly reduces the circumferential velocity gradient and thus prevents flashback. Konle et al. [24] also found that the flashback mechanism that occurred in a swirl burner without the presence of a bluff-body was of the CIVB type. However, many previous studies have added or made some changes to the flow field or burner geometry to mitigate flame flashback, and the flashback mechanism (CIVB) that occurs in swirl burners was of particular interest.

The addition of central fuel injectors, considered a bluff body in swirl burners, is a good technique for anchoring the swirl flame [25][26] and, at the same time, preventing or significantly resisting CIVB flashback. In addition, the existence of the bluff-body leads to the creation of CRZs, which recirculate the hot gases behind them, and this improves the mixing properties, thus enhancing the flame stability. Also, the contact between the bluff-body and the combustible mixture plays an important role in re-igniting the mixture again [27]. Numerous studies have been conducted on flame stability in swirl burners with the use of bluff-bodies. The position and geometry of the bluff-body can influence the length of the recirculation zone and the position of the shear layer [28]. It was also mentioned by [29] that the recirculation zone length can play a main role in the residence time distribution and flame stabilization mechanisms. Tong et al. [30]examined the impact of a bluff-body position on flame stability. They reported that the size and strength of the CRZ were influenced when the bluff-body position was changed; the flame was more stable when it was placed 10 mm above the outlet of the annular channel.Hatem et al. [15]experimentally investigated the influence of the central fuel injector position, the possibility of axially injecting air, and the use of microsurfaces as a lining for the inner nozzle wall on the swirl burner operation map. They found that there was an improvement and increase in the flame stability map when these three techniques were used together. Gao et al. [31]conducted a numerical simulation to examine the impact of changing the swirl number on the swirl flow structure in the bluff-body's presence. They reported that the inner recirculation zone (IRZ) gradually forms as the swirl number increases, and the presence of the bluff-body helps enhance the IRZ. Whereas in low swirls, IRZ does not form unless the bluff-body is existing.

However, the use of swirling flows in combustors is not sufficient to obtain an acceptable operation map. It is possible to add the bluff body to the swirl burner design to resist flame flashback and thus improve the operation map. The presence of the bluff-body not only contributes to the formation or enhancement of the IRZ, but it simultaneously acts as a source of disturbance in the flow field, which results in the formation of a large-scale vortex structure. On the other hand, the fuel type is one of the factors affecting the combustion process. Most of the previous studies studied the flame stability map using natural gas, methane, or hydrogen as fuel. Recently, the use of liquefied petroleum gas (LPG) has increased in Iraq in various uses, such as domestic uses, power generation plants, and internal combustion engines, as a result of its good combustion properties and its low cost and emissions. However, the LPG mixture consists of several components, and these components differ from one country to another and from one season to another depending on the temperatures; hence, the change of these components leads to a change in the LPG properties and the combustion characteristics. Therefore, it was necessary to conduct experiments to determine the limits of flame stability for this mixture.

The aim of the current paper is to conduct an experimental test to examine the impact of the swirl number as well as the annular passage area (represented by the ratio between the outer diameter of the bluff body and the inner diameter of the burner nozzle) on the operation map of the premixed LPG-air flames in a tangential swirl burner. Three nozzles with different diameters (D_N = 20, 25, and 30 mm) for the burner were used to obtain variable swirl numbers, and three central fuel injectors (as a bluff bodies) with different diameters (D_{inj}

= 6, 8, and 12 mm) were also used to obtain different annular passage areas.

2. Experimental Setup

The experimental test rig for this study can be illustrated in Figure 1. The current tangential swirl burner was designed with tangential inlets to ensure the generation of swirling flows, with the possibility of using burner nozzles of different diameters and the ability to replace the central fuel injector with another injector of a smaller diameter. At the same time, this burner can operate in premixed, non-premixed, and partially premixed combustion modes.

The 20-kW tangential swirl burner was manufactured of stainless steel and consists of a cylindrical mixing chamber with 140 mm in length and 100 mm in diameter. Two inlets were installed tangentially in the cylindrical mixing chamber to ensure the generation of swirl flow; these two inlets have an inner diameter of 28 mm and are positioned 3 mm from the bottom of the mixing chamber. From the top, the burner consists of a nozzle with a diameter of 30 mm and a height of 30 mm, with the possibility of replacing it with another nozzle with a smaller diameter. Whereas the baseplate of the burner contains an opening with a diameter of 14 mm to insert the central fuel injector, as well as the possibility of replacing it with another injector of a smaller diameter. The tangential swirl burner that was used in the current study can be illustrated in Figure 2.

The experiments were carried out in the combustion lab of the Mechanical Engineering Department, College of Engineering, Al-Mustansiriyah University, Iraq, under atmospheric conditions, at 1 bar of pressure and 298 K of temperature. Iraqi liquefied petroleum gas (ILPG) was used as fuel, which was obtained from the Al-Doura gas plant in Baghdad, and its properties were measured in the Qadisiyah Branch Laboratory, Iraq. The proportions of its components and properties can be clarified as in Table 1. The swirl burner was supplied with ILPG from a gas cylinder and with air from an air blower through flexible hoses. The ILPG and air flow rates were controlled by a solenoid valve and a gate valve, respectively. To measure the flow rates, a flowmeter for ILPG and a hot air anemometer for air were used. Table 2 shows the specifications, resolution, and accuracy of the measuring instruments used.

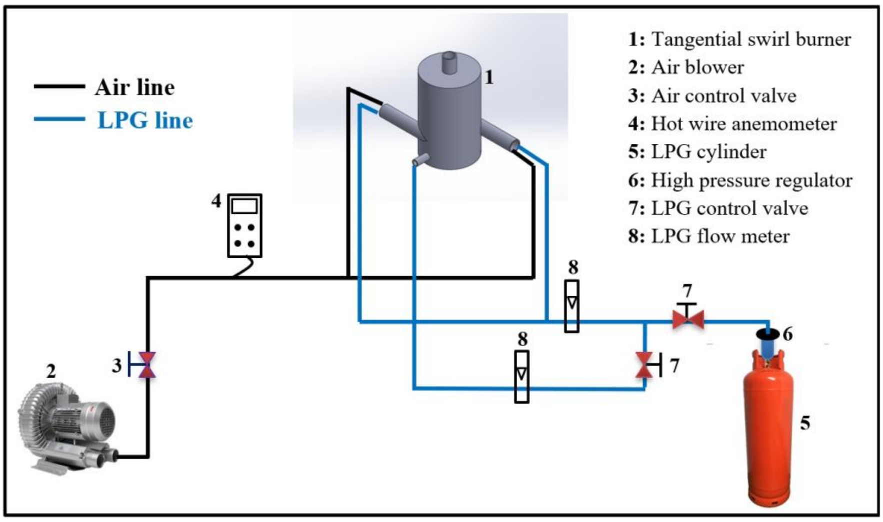

Figure 1. Schematic of experimental setup

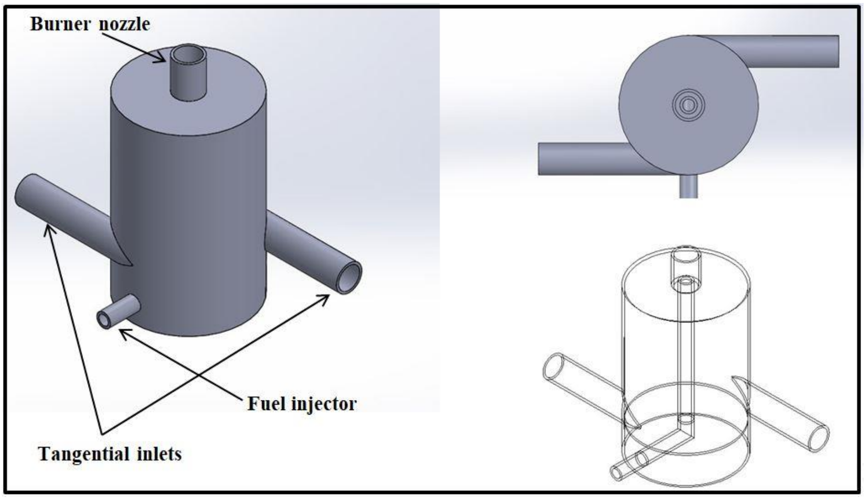

Figure 2. Tangential swirl burner used

Table 1. Specification of the Iraqi LPG used

Composition	Quantity by volume (%)	Chemical formula for ILPG mixture	Density (kg/m^3)	Lower calorific value (kJ/m^3)
C_2H_6	0.11	$C_{3.3286}H_{8.6574}$	1.976	90983
C_3H_8	67.00			
C_4H_{10}	32.86			
C_5H_{12}	0.04			

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

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

In the first part of this work, three burner nozzles of different diameters (D_N = 20, 25, and 30 mm) were used to obtain different swirl numbers. The swirl number is considered an important characteristic by which swirl flows can be described. The swirl number (S) is a dimensionless number that can be defined as the amount of rotation that is imparted to the axial flow[9][32][33]:

$$S = \frac{\text{Axial flux of angular momentum}}{\text{Axial flux of axial momentum x equivalence radius of nozzle}} = \frac{G_\theta}{G_x * R} \qquad (1)$$

However, due to the complexities that occur during swirling flows, it is difficult to calculate the S unless three-dimensional velocity measurements are obtained. Therefore, the geometric swirl number (S_g) can be used which entirely depends on the burner geometry [34][35], and considering that the pressure changes across the flow are few and can be neglected, so the S_g:

$$S_g = \frac{\pi\, r_e R_{eff}}{A_t}\left[\frac{tangential\ flow\ rate}{total\ flow\ rate}\right]^2 \qquad (2)$$

The rate of tangential flow in the case of using tangential swirl burners is considered the same quantity as the total flow rate, so equation (2) becomes:

$$S_g = \frac{\pi\, r_e R_{eff}}{A_t} \qquad (3)$$

Where,

r_e is the radius of the nozzle (m),

R_{eff} is the radius that the tangential inlets connect with respect to the burner's central axis (m),

A_t is the tangential inlet's total area (m^2).

In this study, tangential inlets and burner nozzles were relied upon to determine the S_g. Therefore, through equation (3), the S_g for this study was calculated for the three burner nozzles (D_N = 20, 25, and 30 mm) and was (S_g = 0.918, 1.148, and 1.377), respectively.

In the second part of this work, three central fuel injectors (as bluff-bodies) with different diameters (D_{inj} = 6, 8, and 12 mm) were used to obtain a variable annular passage area. The annular passage area (B) was determined, which is the ratio between the outer diameter of the bluff-body (D_{inj}) and the inner diameter of the burner nozzle (D_N), as indicated in Table 3. The central fuel injectors used and their position within the burner can be illustrated in Figure 3a and b, respectively.

Table 3. Values of the annular passage area

Central fuel injectors (D_{inj}) mm	Annular passage area (B)		
	$D_N = 20\ mm$	$D_N = 25\ mm$	$D_N = 30\ mm$
6	0.3	0.24	0.2
8	0.4	0.32	0.267
12	0.6	0.48	0.4

The inlet tangential velocity (W_{inlet}) of the current tangential swirl burner can be calculated as follows:

$$\dot{m}_{tot} = \dot{m}_a + \dot{m}_f$$

$$\rho_T\, Q_T = \rho_a\, Q_a + \rho_f Q_f$$

For two tangential inlets:

$$Q_T = W_{inlet} \times 2A_{inlet}$$

$$2A_{inlet} W_{inlet} \rho_T = \rho_a\, Q_a + \rho_f Q_f$$

$$W_{inlet} = \frac{\rho_a\, Q_a + \rho_f\, Q_f}{2A_{inlet}\rho_T} \qquad (4)$$

To start the combustion process using the premixed mode, a small quantity of LPG is injected through the central fuel injector until a flame is obtained; after that, the premixed mixture (LPG and air) is injected via the tangential inlets while gradually reducing the central fuel injector until it is closed. In this case, a stable premixed swirl flame is obtained. Flashback limits are determined when the LPG flow rate is increased while the air flow rate is kept constant, and as the LPG flow rate continues to increase, the flame spreads into the combustion chamber. At this moment, the values of the LPG and air flow rates are recorded. On the contrary, when the flow rate of LPG is decreased and the air is constant, the flame will rise from the mouth of the burner and a blowoff will occur. These steps are repeated for several readings to obtain different values for the flame flashback and blowoff. This procedure is repeated for the three nozzles and the three fuel injectors, and thus the flame stability map is determined through the limits of the flashback and blowoff equivalence ratios for each nozzle and injector.

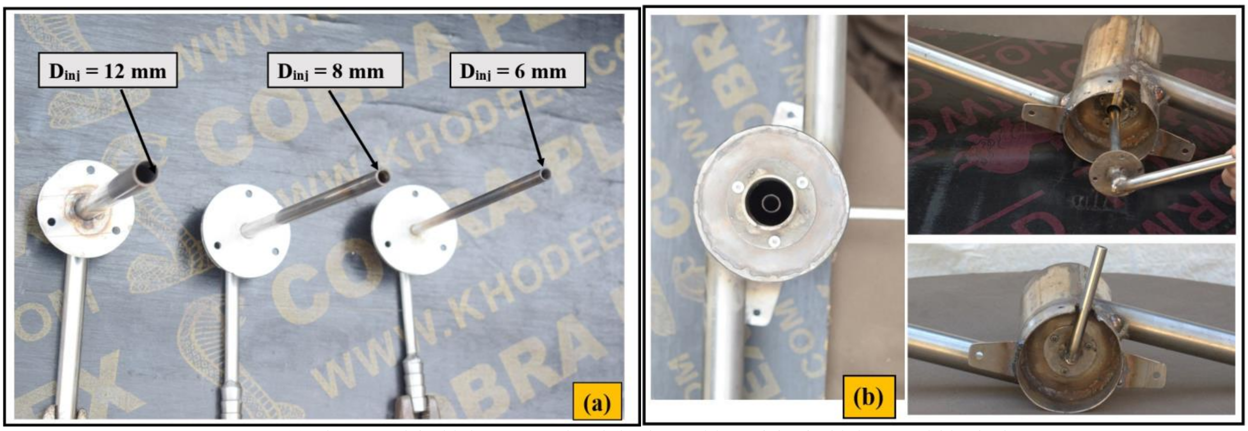

Figure 3. (a) The central fuel injectors used and (b) the position of the fuel injector within the burner

3. Results and Discussion

3.1. Effect of swirl number

As mentioned in the introduction, swirling flows are among the most widely used methods for flame stabilization; the main benefit of using them is to create CRZs that recirculate active chemical species to the flame root and enhance flame stability [11]. However, these swirling flows can be described by the swirl number (S). The S plays an important role during the combustion process, where it has a great influence on the creation, length, and intensity of the CRZs, as well as the turbulence level and the flame structure, and thus the stability limits of the flame. In this part, the swirl number impact on flashback and blowoff limits (stable operation map) has been studied for the current tangential swirl burner at three different swirl numbers (S = 0.918, 1.148, and 1.377) with the existing central fuel injector that acts as a bluff-body.

The limits of flame flashback (FB) and blowoff (BLO)at S = 0.918, 1.148, and 1.377 as a function of equivalence ratio versus inlet tangential velocity can be illustrated in Figures 4, 5, and 6 for three central fuel injectors (D_{inj}= 6, 8, and 12 mm), respectively. Using inlet tangential velocity for correlation makes the data more generic and can be compared with any combustor. Initially, during practical tests, it was noted that the type of flashback that occurred was boundary layer flashback (BLF), and this could be due to the presence of the bluff-body that prevented the occurrence of CIVB flashback[15]. For all fuel injectors used, it has been observed that as the swirl number increased, the flashback limits decreased (i.e., worsened) while the flame resistance to blowoff improved. The same behavior of flashback and blowoff limits has been observed in [15, 36].The reason for the decrease in the flashback limits can be due to several reasons: as the swirl number increases, the central recirculation zone expands and extends backwards over the bluff-body, which leads to flashback occurring. Also, the rapid mixing process by increasing the swirl number causes an increase in the turbulence intensity; excessive turbulence leads to an increase in the flame speed and hence causes flame flashback. As for the improvement of the blowoff limits, it can be attributed to the fact that when the swirl number is increased, the intensity of the CRZ increases, which recirculates the hot combustion products behind the bluff-body. These hot gases, in turn, give sufficient time to ignite the incoming reactants and thus improve the blowoff limits.

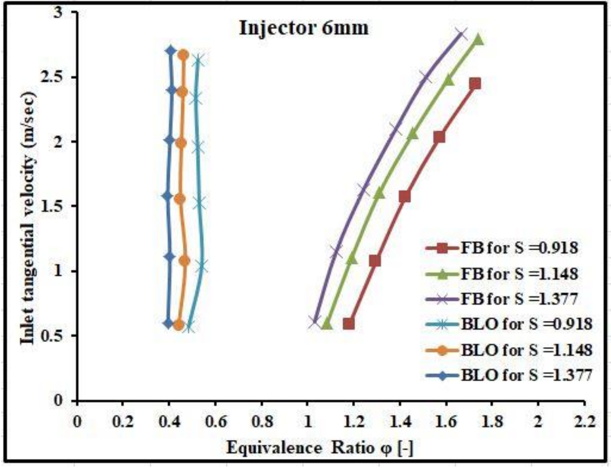

Figure 4. Flame flashback and blowoff for various swirl numbers using a fuel injector (6 mm)

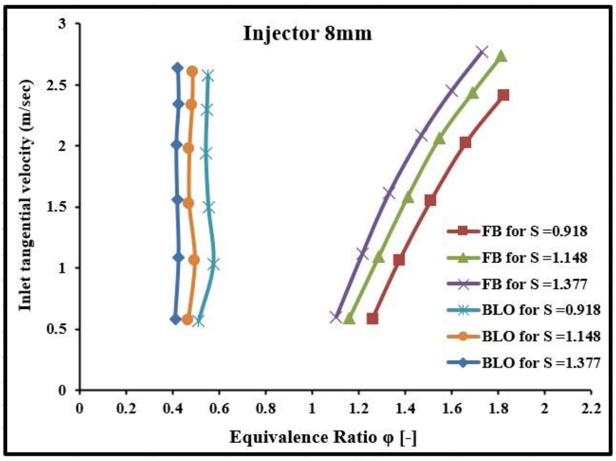

Figure 5. Flame flashback and blowoff for various swirl numbers using a fuel injector (8 mm)

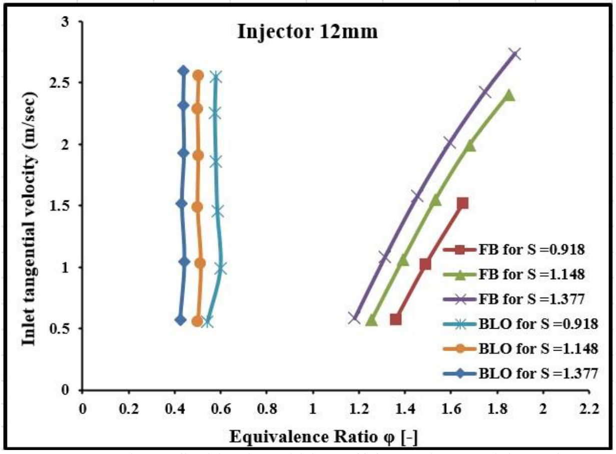

Figure 6. Flame flashback and blowoff for various swirl numbers using a fuel injector (12 mm)

The stable operation map lies between the flashback and blowoff limits (operation map $= \varphi_{FB} - \varphi_{BLO}$). In terms of the swirl number impact, from figures 4, 5, and 6, it was observed that there is a slight change in this stability map because both the limits of flashback and blowoff have changed with the swirl number. Consequently, as the swirl number increases, the stability map improves, and the mixing of the reactants is greatly enhanced. At the same time, the limits of the equivalence ratios move towards the lean, and this in turn greatly reduces the emissions of pollutants. This is what the designers of the swirl burners that work in premixed mode are looking for. Whereas, in terms of changing the diameters of the bluff-bodies (central fuel injectors), there was a clear change in the stability map, and this will be clarified in the next paragraph (3.2).

3.2. Effect of bluff-body diameter

The bluff-body's presence in the swirling flows raises the CRZs intensity as well as greatly improves reactant mixing and thus flame stability[25][26]. Also, there are other benefits of the bluff-body in that the hot gases recirculated behind it help to ignite the incoming mixture [27], and its presence can serve as a cause of turbulence in the flow field, etc.

In this part, the influence of altering the central fuel injector's (bluff-body) outer diameter on the flashback and blowoff limits (stability operating map) of a current tangential swirl burner for three different swirl numbers is studied. Changing the bluff-body's outer diameter results in a change in the annular passage area, so this area is represented by a dimensionless number (B), as indicated in Table 3.

Figure 7 shows the limits of FB and BLO for three different values of B (0.2, 0.267, and 0.4) as a function of equivalence ratio versus inlet tangential velocity (W_{inlet}) at a S of 1.377. The correlation between the tangential velocity and equivalence ratio at the flashback condition is fairly strong when the tangential velocity is used. Through the figure, it was observed that altering the bluff-body's size had a clear effect on the flashback limits while having a slight effect on the blowoff limits, and this is consistent with [37]. With the decrease of B, the limits of flashback equivalence ratios are observed to decrease and move towards the lean regions at the range of W_{inlet} from 0.58 to 2.83 m/s.

The lowering of B (reducing the fuel injector diameter) leads to an increase in the annular passage area. Consequently, the adverse pressure gradient across the combustion region because of a sudden rise in density across the front of the flame, thus, the boundary layer separates from the injector's wall due to the static pressure created at the tip of the flame, causing flashback propagation upstream. Also, increasing the annular passage area leads to a decrease in the flow velocity of the fresh mixture, which is one of the reasons for the increase in the flashback propensity. On the other hand, for all inlet tangential velocities, it was noted that with the small diameter of the injector, the CRZ surrounds the center fuel injector and extends towards the base plate of the burner, causing a significant increase in the temperature around the injector and thus increasing the levels of pollutants and reducing the injector life [38].

Whereas with increasing B (increasing fuel injector diameter), the annular passage area decreases and thus affects the position of the CRZ. However, reducing the annular passage area increases the momentum of the incoming mixture and stabilizes the CRZ more upstream, near the burner outlet. Therefore, increasing B led to an increase in the flow velocity of the unburned mixture, which led to shifting the stagnation point of the flow downstream and thus better resistance to flashback, and this behavior is consistent with [38].

As for the blowoff limits, it was observed that with reducing B, the BLO very slightly decreased towards lean regions, which means an improvement in the BLO limits. This decrease in the BLO limits can be due to the fact that with the small fuel injector, the CRZ surrounds the fuel injector, and then the flame moves downstream towards the region of low velocity by lowering φ to the global limits in order to keep the kinematic equilibrium between the flame speed and fresh mixture velocity.

For S =1.377, it was observed that at small values of B (0.2) the flame stability map (φ_{FB} = 1.03 - φ_{BLO} = 0.39) was the smallest, and this meets the low emission requirements. With the increase of B, the operation map of the burner increases, the operation map for case B = 0.267 was (φ_{FB} = 1.10 - φ_{BLO} = 0.41), while with B = 0.4 it gave the best performance and a larger operating range (φ_{FB} = 1.18 - φ_{BLO} = 0.42). It is considered that obtaining a larger operating map is interesting in high-power operations as mentioned in [7]. Figures 8a, b, and c show the operating window of the tangential swirl burner at S = 1.377 and for B = 0.2, 0.267, and 0.4, respectively.

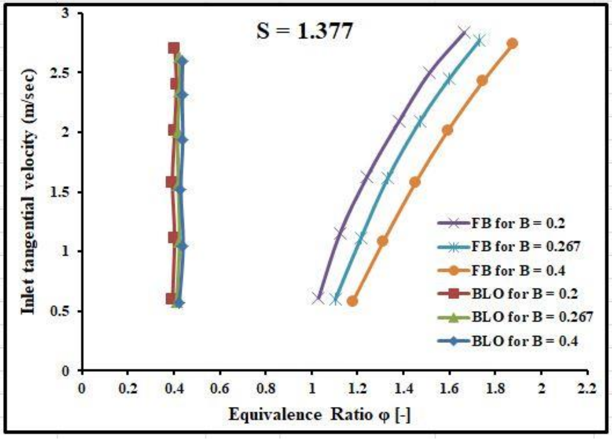

Figure 7. Stability map for different annular passage areas (B) at swirl number 1.377

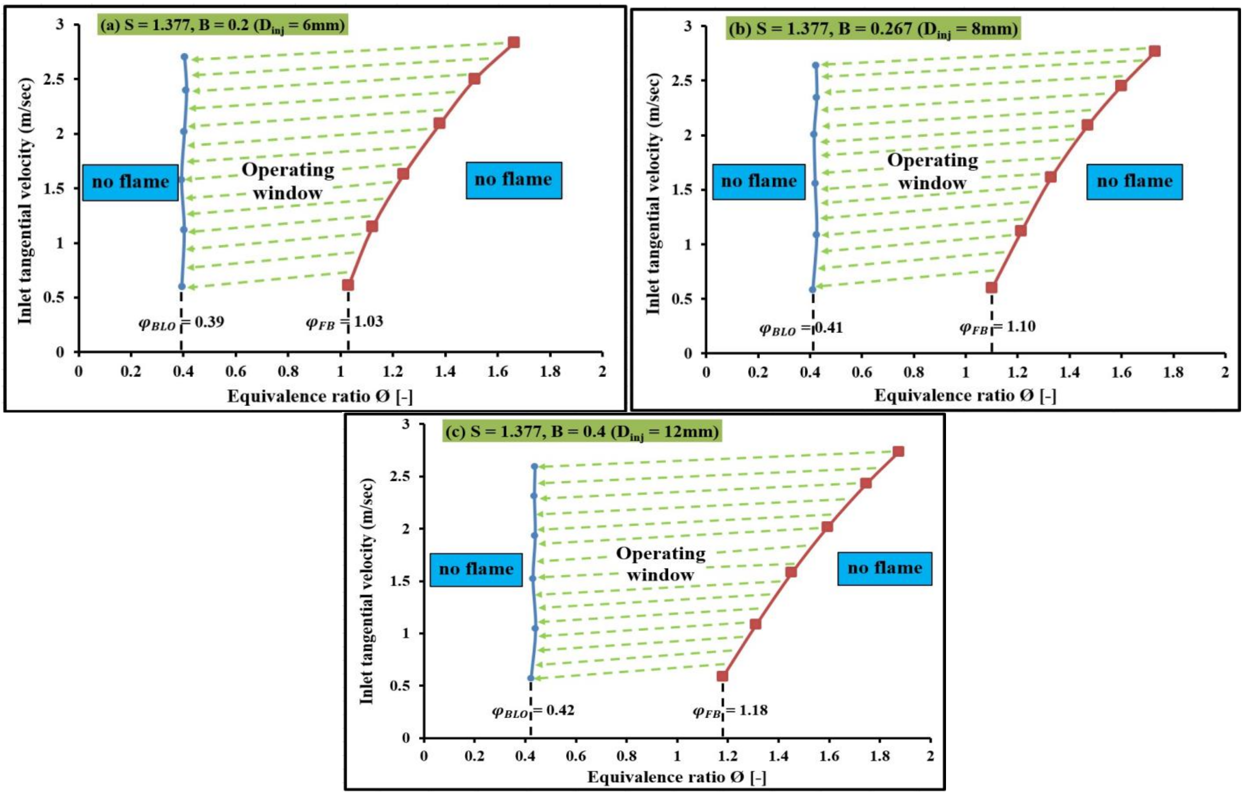

Figure 8. The operating window of the burner used at S = 1.377 for (a) B = 0.2, (b) B = 0.267, and (c) B = 0.4

When the S was reduced to 1.148 and 0.918, the flame flashback behavior was similar to that of the S of 1.377 and for the same sizes of fuel injectors used, as shown in Figures 9 and 10. Compared to the S of 1.377, a slight increase in the stability map was observed when the S was reduced, i.e., moving the flashback limits towards the rich side, which is undesirable because it increases pollutant emissions.

The flame stability map for S = 1.377 in the range of the inlet tangential velocity was ($W_{inlet} = 0.58$ to 2.84 m/s), for S = 1.148 was ($W_{inlet} = 0.55$ to 2.78 m/s). Whereas, for S = 0.918 the range of the W_{inlet} was 0.58 to 2.45 m/s for the fuel injectors of 6 and 8 mm, except in the case of B = 0.6 (central fuel injector with a diameter of 12 mm), it was observed that when the $W_{inlet} > 1.5$ m/sec, no flashback occurred. This is due to the significant increase in the momentum of the unburned mixture, which provided the required match with the flame speed and thus gave a more stable flame.

Figure 11 shows a set of photos taken with a Nikon D5300 camera during practical tests with the bluff-body present. The figure shows the state of a stable flame, BLF, and before the blowoff occurred.

Figure 12 shows the flame stability map of the current swirl burner obtained at S = 1.148 and $D_{inj} = 8$ mm and its comparison with the stability map results of Syred et al. [13] (2014) and Hatem [39] (2017). As for [13], use coke oven gas (COG) (4% N_2 + 6% CO + 25% CH_4 + 65% H_2) as fuel in a generic swirl burner with radial inlets at S = 1.04 and $D_{inj} = 12.8$ mm. Whereas [39] uses natural gas (NG) as fuel in a tangential swirl burner at S = 1.12 and $D_{inj} = 23$ mm. From Figure 12, it can be seen that the stability map of the current swirl burner was wider compared to that of [13] and [39]. This could be due to the higher hydrogen (H_2) content present in the fuels used by [13] and [39], which led to an increased flashback propensity as a result of the higher flame speeds of H_2 and thus a narrower stability map.

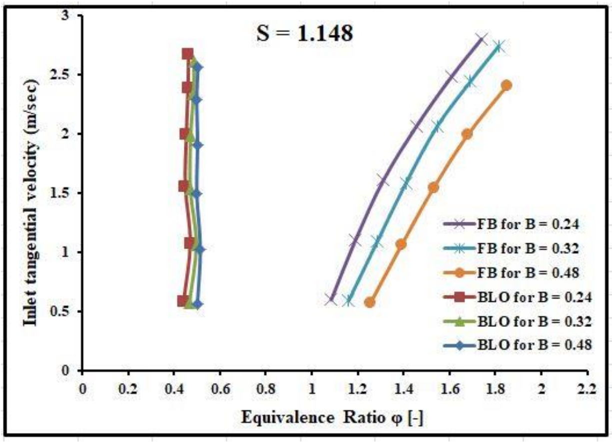

Figure 9. Flame stability map at different annular passage areas (B) at swirl number 1.148

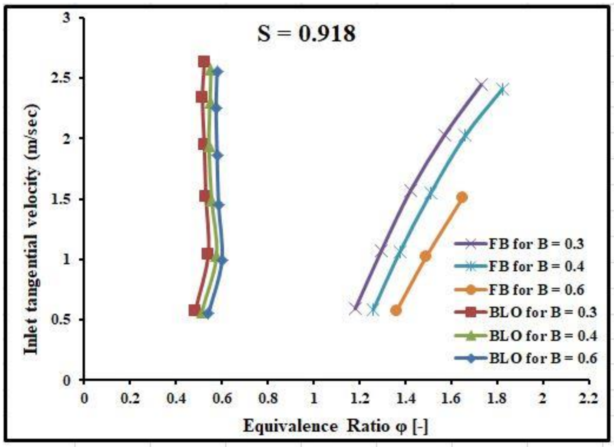

Figure 10. Flame stability map at different annular passage areas (B) at swirl number 0.918

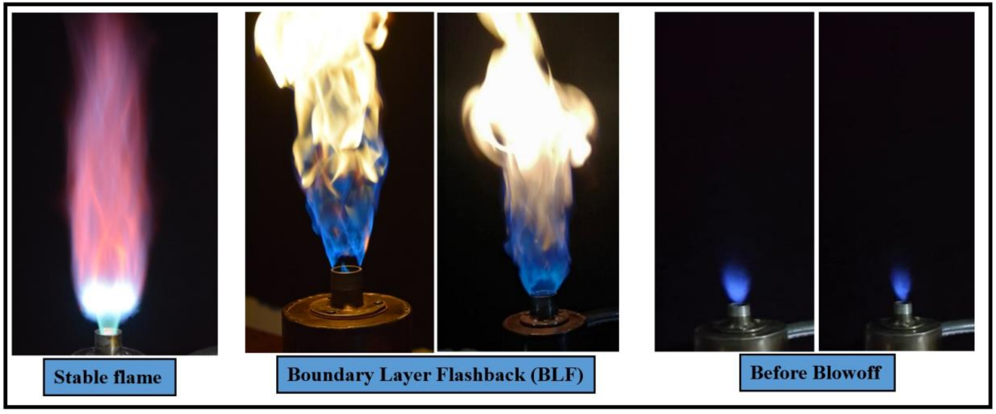

Figure 11. Practical images for flame stabilization, boundary layer flashback, and before blowoff occurred with the bluff-body present

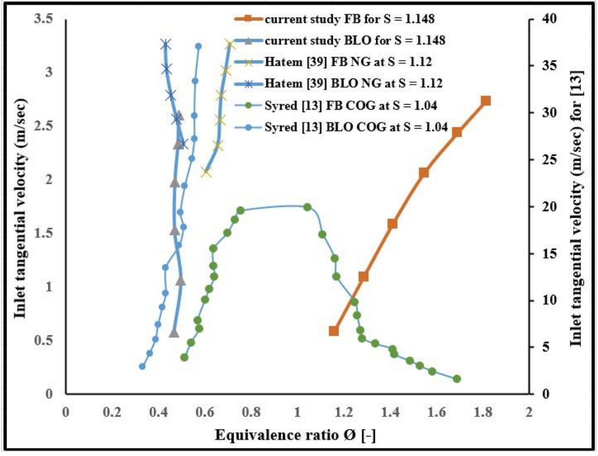

Figure 12. Comparison of the flame stability map of the current swirl burner with the previous studies

3.3. Without central fuel injector

Further experiments were conducted on the current swirl burner, but without using the bluff-body (central fuel injector). The flame flashback during these experiments was of the CIVB.

Figure 13 shows the FB and BLO limits for the burner used without using the bluff-body at S = 0.918, 1.148, and 1.377. In terms of the swirl number effect, as mentioned in paragraph 3.1, as the S increased, the flashback limits decreased and moved towards the lean region while the flame resistance to blowoff improved. This is due to when the swirl number increases, the CRZ improves and expands.

On the other hand, the removal of the bluff-body had a clear impact on the flow field as well as the location and size of the CRZ. It has been observed that when the flame is stable, it is attached to the nozzle inlet and concentrated on the recirculation zone. When the fuel-air flow rate increases (equivalence ratio, ∅), the flame begins to shift and attack the mixing zone, and with the continued increase in ∅, the flame propagates completely into the mixing chamber accompanied by a loud sound, and this is the explanation for the CIVB flashback. Figure 14 shows some images taken that show the CIVB flashback mechanism for the burner used without the bluff-body.

However, the operating map of the current tangential swirl burner without the central fuel injector was narrower compared to that of the burner that used fuel injectors. Figure 15 shows a comparison of the flame stability map for the swirl burner used with a central fuel injector of 6 mm diameter and without a central fuel injector. Although the central fuel injector with a diameter of 6 mm was used in comparison, where it gave a lower operating map compared to the fuel injectors of 8 and 12 mm (see Figures 4, 5, and 6), but it gave a wider operating map than those without fuel injectors. This is due to the fact that the addition of the bluff-body to the swirling flows significantly improves the mixing properties, increases the length and intensity of the CRZ, thus enhances the stability of the flame [25][26].

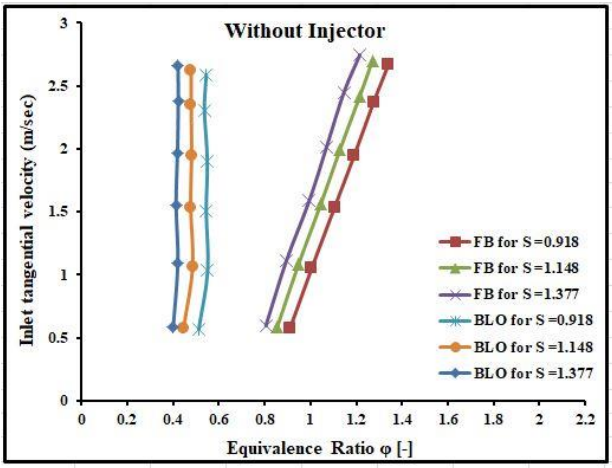

Figure 13. Flashback and blowoff limits for the burner used without using a central fuel injector

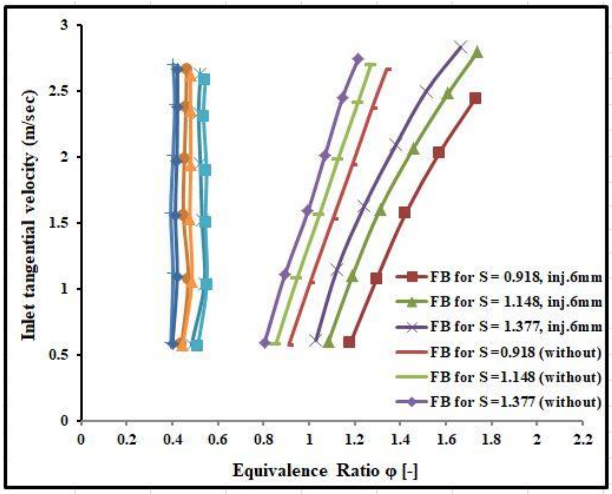

Figure 15. Comparison of stability limits for the burner used in cases with and without a central fuel injector

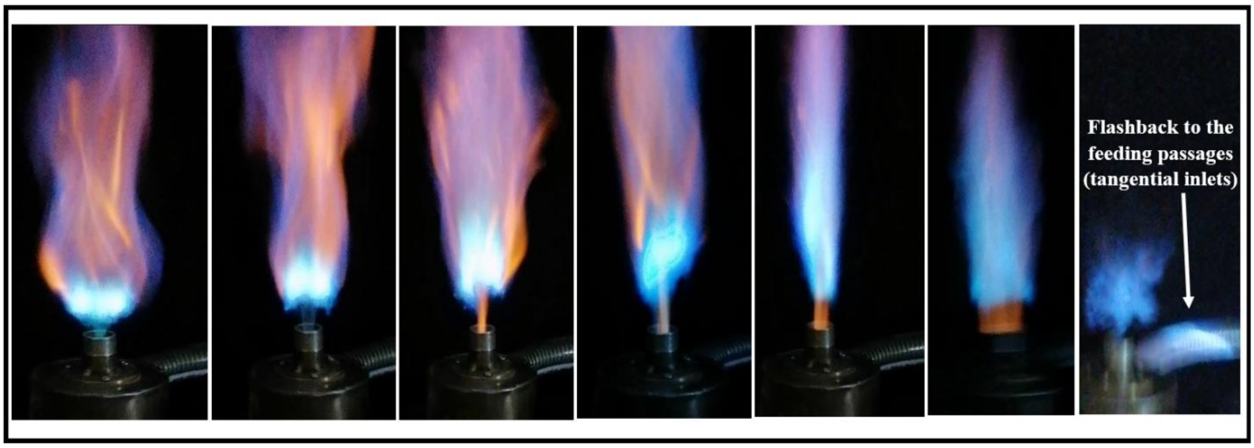

Figure 14. Photos of the CIVB flashback mechanism for the burner used without a bluff-body

4. Conclusion

In this study, experimental tests were conducted to study the effect of swirl number (S) and annular passage area (B) on the stability map of the premixed LPG-air flames in a 20-kW tangential swirl burner. Three nozzles with different diameters (D_N = 20, 25, and 30 mm) for the burner were used to obtain a variable swirl number, and three central fuel injectors (as a bluff-body) with different diameters (D_{inj} = 6, 8, and 12 mm) were also used to obtain different annular passage areas. The conclusions of this study can be summarized as follows:

- It was noted that two types of flashback occurred in the current tangential swirl burner: BLF with the presence of the bluff-body and CIVB with the absence of the bluff-body.
- In the first part of the study, it was observed that the swirl number has a clear impact on the limits of flame flashback and blowoff. With an increase in S, the flashback limits decreased while the blowoff limits improved.
- With the increase of S, a better flame stability map was obtained because the equivalence ratio limits of the flashback and blowoff moved towards the lean regions, which meet the low emission requirements.
- In the second part of the study, altering the central fuel injector's (bluff-body) outer diameter resulted a change in the annular passage area (B), and it had a major effect on the flashback limits while having a very slight effect on the blowoff limits.
- When an increase of B (increasing fuel injector diameter), the annular passage area decreases, which increases the momentum of the unburned mixture and thus improves flashback resistance. Whereas, with a decrease in B (reducing fuel injector diameter), the limits of the flashback equivalence ratios decrease and move towards the lean regions.
- With the increase of B, the operation map of the burner increases, at S = 1.377, it was found the operation map for B = 0.2 was the smallest (φ_{FB} = 1.03 - φ_{BLO} = 0.39), while with B = 0.4 it gave the best performance and a larger operating range (φ_{FB} = 1.18 - φ_{BLO} = 0.42) at the inlet tangential velocity range (W_{inlet}= 0.58 to 2.84 m/s).
- When the bluff-body was removed, there was a significant effect on the flow field, the shape and location of the recirculation zone, and thus the combustion stability.
- A swirl burner without the bluff-body gave a narrower stability map compared to that of the burner that used the bluff-body.
- Consequently, adding bluff-bodies to swirling flows improves the mixing properties, increases the intensity of the CRZ, and thus enhances the stable operation map. In addition, the bluff-body's presence greatly helps in eliminating CIVB flashback.

References

[1] G. Ahmed, A. Abdelkader, A. Bounif, I. Gökalp, "Reduced Chemical Kinetic Mechanisms: Simulation of Turbulent Non-Premixed CH 4-Air Flame". Jordan Journal of Mechanical and Industrial Engineering, Vol. 8, No. 2, 2014, 66 - 74.

[2] R.H. Khalil, A. Sakhrieh, M. Hamdan, & J. Asfar, "Effect of Pressure and Inlet Velocity on the Adiabatic Flame Temperature of a Methane-Air Flame". Jordan Journal of Mechanical and Industrial Engineering, Vol. 4, No. 1, 2010, 21-28.

[3] I. Mabrouki, M.A. Merghini, Z. Driss, and M.S. Abid, "The Effects of a Magnetic Gradient on Lifted Diffusion Flames". Jordan Journal of Mechanical and Industrial Engineering, Vol. 9, No. 4, 2015, 263 - 268.

[4] R. Ali, S.H. Raheemah, and N.N. Al-Mayyahi, "Numerical Analysis of Combustion Characteristics and Emission of Dual and Tri-Fuel Diesel Engine under Two Engine Speeds". Jordan Journal of Mechanical and Industrial Engineering, Vol. 14, No. 2, 2020, 205 - 213.

[5] F. Sk, and D.V. Kumar, "Optimization of Performance and Exhaust Emissions of a PFI SI Engine Operated with Iso-stoichiometric GEM Blends Using Response Surface Methodology. Jordan Journal of Mechanical and Industrial Engineering, Vol. 15, No. 2, 2021, 199 - 207.

[6] F. Hatem, M. Al-Fahham, A.S. Alsaegh, Z.M. Al-dulaimi, & A. Valera Medina, "Experimental Investigation on effects of bluff-body size and axial air injection on blowoff limits in swirl burners". Journal of Engineering Science and Technology, Vol. 16, No. 3, 2021, 2202-2214.

[7] M. Abdulsada, N. Syred, P. Bowen, T. O'Doherty, A. Griffiths, R. Marsh, and A. Crayford, "Effect of exhaust confinement and fuel type upon the blowoff limits and fuel switching ability of swirl combustors". Applied Thermal Engineering, Vol. 48, 2012, 426-435.

[8] Y. Huang, and V. Yang, "Effect of swirl on combustion dynamics in a lean-premixed swirl-stabilized combustor". Proceedings of the combustion institute, Vol. 30, No. 2, 2005, 1775-1782.

[9] Gupta, A.K., Lilley, D.G. and Syred, N. Swirl flows. Tunbridge Wells; 1984.

[10] T.K. Sahoo, and P. Ghose, "Effect of Inlet Swirl on Combustion Performance and Soot Formation of a Turbulent Methane-Air Non-Premixed Flame". Jordan Journal of Mechanical and Industrial Engineering, Vol. 16, No. 2, 2022, 309-318.

[11] N. Syred, "A review of oscillation mechanisms and the role of the precessing vortex core (PVC) in swirl combustion systems". Progress in Energy and Combustion Science, Vol. 32, No. 2, 2006, 93-161.

[12] M. Abdulsada, N. Syred, A. Griffiths, P. Bowen, and S. Morris, S., "Effect of swirl number and fuel type upon the combustion limits in swirl combustors". In Turbo Expo: Power for Land, Sea, and Air, Vol. 54624, 2011, 531-539.

[13] N. Syred, A. Giles, J. Lewis, M. Abdulsada, A.V. Medina, R. Marsh, P.J. Bowen, and A.J. Griffiths, "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, Vol. 116, 2014, 288-296.

[14] A. Kalantari, and V. McDonell, "Boundary layer flashback of non-swirling premixed flames: Mechanisms, fundamental research, and recent advances". Progress in Energy and Combustion Science, Vol. 61, 2017, 249-292.

[15] F.A. Hatem, A.S. Alsaegh, M. Al-Faham, A. Valera-Medina, C.T. Chong, and S.M. Hassoni, "Enhancing flame flashback resistance against Combustion Induced Vortex Breakdown and Boundary Layer Flashback in swirl burners". Applied energy, Vol. 230, 2018, 946-959.

[16] H. Yilmaz, O. Cam, and I. Yilmaz, "Experimental investigation of flame instability in a premixed combustor". Fuel, Vol. 262, 2020, 116594.

[17] A.M. Jawarneh, "Heat transfer enhancement in a narrow concentric annulus in decaying swirl flow". Heat transfer research, Vol. 42, No. 3, 2011, 199-216.

[18] E. Gorelikov, I. Litvinov, and S. Shtork, "Aerodynamics and characteristics of the premixed swirl flame". International Conference on the Methods of Aerophysical Research-AIP Publishing, Vol. 2351, No. 1, 2021, 030082-1–030082-7.

[19] R. A. Zubrilin, I.A. Zubrilin, S.S. Matveev, and S.G. Matveev, "Gaseous fuel flame stabilization in a modular swirled burner". Proceedings of ASME Turbo Expo: Turbomachinery Technical Conference and Exposition, Seoul, South Korea, 2016.

[20] K. Yellugari, R. Villalva Gomez, and E.J. Gutmark, "Effects of Swirl Number and Central Rod on Flow in Lean Premixed Swirl Combustor". In AIAA Scitech Forum, Orlando, FL, 2020.

[21] W. Jerzak, and M. Kuźnia, "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, Vol. 29, 2016, 46-54.

[22] M. Kroner, J. Fritz, and T. Sattelmayer, "Flashback limits for combustion induced vortex breakdown in a swirl burner". Journal of Engineering for Gas Turbines and Power, Vol. 125, No. 3, 2003, 693-700.

[23] J. Fritz, M. Kroner, and T. Sattelmayer, "Flashback in a swirl burner with cylindrical premixing zone". Journal of Engineering for Gas Turbines and Power, Vol. 126, No. 2, 2004, 276-283.

[24] M. Konle, F. Kiesewetter, and T. Sattelmayer, "Simultaneous high repetition rate PIV–LIF-measurements of CIVB driven flashback". Experiments in Fluids, Vol. 44, 2008, 529-538.

[25] C. Jiménez, D. Michaels, and A.F. Ghoniem, "Stabilization of ultra-lean hydrogen enriched inverted flames behind a bluff–body and the phenomenon of anomalous blow–off". Combustion and Flame, Vol. 191, 2018, 86-98.

[26] B.R. Chowdhury, and B.M. Cetegen, "Effects of free stream flow turbulence on blowoff characteristics of bluff-body stabilized premixed flames". Combustion and Flame, Vol. 190, 2018, 302-316.

[27] Y. Chen, Y. Fan, Q. Han, X. Shan, Y. Bi, and Y. Deng, "The influence of cooling air jets on the premixed flame structure and stability of air-cooled bluff-body flame holder". Fuel, Vol. 310, Part A, 2022, 122239.

[28] S.L. Plee, and A.M. Mellor, "Characteristic time correlation for lean blowoff of bluff-body-stabilized flames". Combustion and Flame, Vol. 35, 1979, 61-80.

[29] A. Rowhani, Z.W. Sun, A. Chinnici, P.R. Medwell, G.J. Nathan, and B.B. Dally, "Effect of bluff-body diameter on the flow field and residence time of turbulent ethylene/nitrogen flames". In 12th Asia-Pacific Conference on Combustion, Fukuoka, Japan, 2019.

[30] Y. Tong, X. Liu, S. Chen, Z. Li, and J. Klingmann, "Effects of the position of a bluff-body on the diffusion flames: A combined experimental and numerical study". Applied Thermal Engineering, Vol. 131, 2018, 507-521.

[31] Y. Gao, X. Zhang, W. Han, J. Li, and L. Yang, "Effects of swirl number and bluff body on swirling flow dynamics". AIP Advances, Vol. 13, No. 2, 2023, 025246-1-025246-12.

[32] A.M. Jawarneh, G.H. Vatistas, and A. Ababneh, "Analytical approximate solution for decaying laminar swirling flows within a narrow annulus". Jordan Journal of Mechanical and Industrial Engineering, Vol. 2, No. 2, 2008, 101-109.

[33] A.M. Jawarneh, H. Tlilan, A. Al-Shyyab, and A. Ababneh, "Strongly swirling flows in a cylindrical separator". Minerals Engineering, Vol. 21, No. 5, 2008, 366-372.

[34] Alsaegh, A. Fundamental characterisation of coherent structures for swirl combustors. Doctoral dissertation, Cardiff University; 2022.

[35] Abdulsada, M.Flashback and blowoff characteristics of gas turbine swirl combustor. Doctoral dissertation, Cardiff University; 2011.

[36] K.S. Hasan, H.H.S. Khwayyir, and W.A. Abd Al-wahid, "Experimental Investigation of the Flame Stability Map (operating Window) by Using a Tangential Swirl Burner for the Confinement and Unconfinement Space". 2nd International Scientific Conference of Al-Ayen University, Thi Qar, Iraq, 2020.

[37] M. Behzadi, S.H. Siyadat, F. Ommi, and Z. Saboohi, "Study of the effect of bluff body size on stability limits of a premixed natural gas swirl burner". Journal of Thermal Analysis and Calorimetry, Vol. 147, 2022, 1583–1596.

[38] F.A. Hatem, A. Valera-Medina, N. Syred, R. Marsh, and P.J. Bowen, "Experimental investigation of the effects of central fuel injectors on premixed swirling flames". In 53rd AIAA Aerospace Sciences Meeting, Kissimmee, Florida, 2015.

[39] Hatem, F.Flashback analysis and avoidance in swirl burners. Doctoral dissertation, Cardiff University; 2017.