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# FLAME STABILITY IN SWIRLING AND BLUFF-BODY BURNERS: A REVIEW

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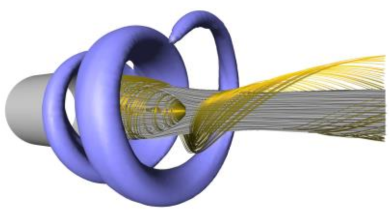
**Graphical abstract**



**Abstract**

Flame stability is one of the main challenges facing the different combustion applications. A lot of undesirable phenomena such as blow-off and flashback may occur according to the instability of the flame causing damage to the overall combustion system. Therefore, it is necessary to develop methods which help improve the combustion process and obtain wider flame stable regions. Among these methods, swirling flows and bluff-bodies are the most commonly used in flame stabilization. These may create central recirculation zones (CRZ's) that, in turn, recirculate the heat and active chemical species to the root of flame, improving the reactants mixing and as a result, flame stability. Hence, the current article presents an overview of flame stability mechanisms and the operation map using swirling flows and bluff-bodies. The effect of the swirl number (S) and burner's geometry, as well as the influence of the bluff-body shape, size and position on the flame stabilization mechanisms are discussed.

*Keywords*: Flame stability map, swirling flows, bluff-body, blowoff, flashback



## 1.0 INTRODUCTION

The combustion process plays a vital role in human life, as it is considered the main part in the operation of many applications that use combustors such as the industrial furnaces, gas turbines and steam generators [1, 2]. Unfortunately, the combustion process emits many emissions such as carbon dioxide ($CO_2$), nitrogen oxides ($NO_X$), soot, etc., which affect the climate and human health [2, 3]. In general, the ratio of fuel-air mixture, burner geometry, and turbulence level are considered major factors affecting the combustion process represented by the stability and efficiency of combustion as well as the emissions level [4]. Therefore, it is necessary to focus on these factors during the design process to get a combustion device that works with good performance and lower emissions.

Among these factors, the flame stability is an important issue that must be focused on in the combustors. Through the flame stability, the flashback and blow-off limits of flame can be known. Thus, the operating conditions of the combustors can be determined between these limits [5-8]. The use of swirling flows and bluff-bodies greatly helps to stabilize the flame in most combustion devices [9-11]. The swirl flow leads to creating a central recirculation zone (CRZ), where it works to recirculate the heat and active chemical species to the root of flame, hence stabilizing the flames in zones of relatively low velocity [12, 13]. As for the bluff-body, it is also an effective method for stabilizing the flame, as it helps to create a region of hot gas recirculate, which in turn improves the mixing process [14, 15]. However, the recirculation zones created by the bluff-body and swirl flow, are not only improved from the mixing process but also return the products of hot combustion to ignite the incoming mixture, thus it leads to stabilization the flame, in addition to reducing the emission levels of carbon monoxide

(CO) and nitrogen oxides ($NO_X$) [16, 17]. Although most of the previous studies proved that the swirl flows act as an effective method of flame stabilization, it can also be more prone for flashback to occur [18]. Whereas in case of existence the bluff-body in the combustors it significantly helps to reduce the occurrence of flashback [19].

Several previous studies have investigated the effect of swirling flows and bluff-bodies on flow characteristics and flame stability. Gao *et al*. [1] (2023) investigated numerically the effect of swirl number and bluff-body on flow characteristics. They discovered that the presence of the bluff-body in the swirling flows helps in the formation of the inner recirculation zone (IRZ) as well as acts as a source of flow turbulence, leading to the formation of large-scale vortex structures, which is appropriate. Yellugari *et al*. [20] (2020) observed that the presence of the bluff-body helped in the formation of central recirculation zones (CRZ) even at low swirl numbers (S = 0.52), and as the swirl number increased, the CRZ moved upstream and caused flashback. An experimental study on the effect of swirl number on the stability of a $CH_4$-air/$O_2$ swirling flame was performed by Chakchak *et al*. [21] (2023). They found that the flame stability map improved and a better attached flame was obtained with an increase in the swirl number. Behzadi *et al*. [9] (2022) studied the effect of the bluff-body size on the flashback and blowoff limits of a premixed natural gas flame in a swirl burner. They reported that the blowoff limits were slightly affected, while the flashback limits were greatly affected by the change in the bluff-body size.

Therefore, focus should be placed on the flow field because any change in the swirl number, burner geometry, size, and position of the bluff-body will lead to a change in the flow structure and thus combustion instability (flashback or blowoff). These phenomena (flame flashback and blowoff) are considered dangerous and undesirable problems during the combustion process because they can lead to damage and corrosion of the combustion device. Thus, there must be a comprehensive and detailed understanding of these two phenomena to obtain a more stable flame.

## 2.0 SWIRL FLOW

### 2.1 Swirl Flow Characterization

Swirl flows are used in several combustors likes boilers [22], furnaces [23], gasifiers [24] and gas turbines [25]. The benefit of using swirl flows is their ability to form a central recirculation zone which helps to improve the reactants mixing and reducing emissions, this means controlling the combustion process and stabilizing the flame [26, 27]. Swirl flow can be obtained either by using tangential inlets for air and fuel entry [28], or by using swirl with vane guide [29] as shown in Figure 1 (a and b). The tangential inlets are positioned perpendicular to the burner's center axis to create a swirling flow, where the oxidizer is introduced through the tangential inlets resulting in a flow circulating around the axial injector. As for the fuel, it can be mixed in advance with air and entered from the tangential inlets, or it can be entered axially through an injector. In the case of axial inlets, vane guides tilted at an angle are placed in the flow field of air or fuel-air mixture to obtain a vortex.

For both of the above methods through which swirl flows are generated, in the case of using tangential inlets, the performance of the burner in forming a vortex in the inner wall core is better if compared with those using vane guides [30]. Despite the better performance of the tangential inlets system, but it has defects in the higher degree of asymmetry in addition to the effects associated with the vortices formed the burner inner wall [19].

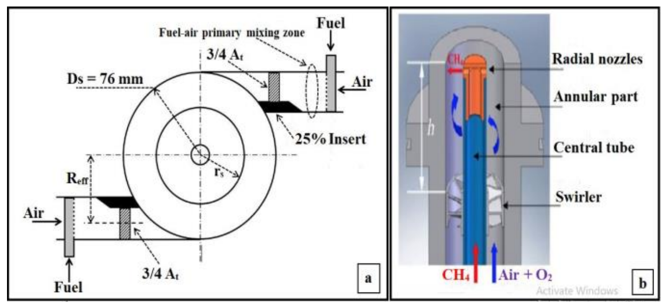



**Figure 1** Swirl by (a) tangential inlets [28] and (b) vane guide [29]

When air or mixture is introduced in both tangential and axial states, a swirl flow is obtained, and this, in turn, leads to create a region of low pressure in the flow core accompanied by opposite pressure gradients, and hence a central recirculation zone (CRZ) is created [28]. Swirl flow can be described by many parameters such as swirl number, geometrical swirl number, strouhal number and Reynolds number [31, 32]. Swirl number (S) is chosen to determine the swirl force; this is because the swirl number greatly affects the combustion intensity, flame stability and flame length [33]. Swirl number (S) is defined as the ratio between the axial flow of angular momentum and the axial flow of axial momentum multiplied by the radius of equivalent nozzle [13], and swirl number is a dimensionless number.

$$S = \frac{G_\theta}{G_x * r_e} \quad (1)$$

$$G_\theta = 2\pi\rho \int_0^R (uw) r^2 \, dr \quad (2)$$

$$G_x = 2\pi\rho \int_0^R u^2 \, r \, dr + 2\pi \int_0^R p \, r \, dr \quad (3)$$

Where, u and w represents the axial and tangential velocities, while p represents the flow pressure.

There are three types that can be identified of stream swirl, when the swirl number (S<0.6) it's called the weak swirl, (S=0.6) is called the critical swirl and (S>0.6) is called the strong swirl [34, 35].

### 2.2 Vortex Breakdown (VB)

Vortex breakdown is a phenomenon occurs in swirl combustors. This is because the swirl flows greatly help to create a central recirculation zones (CRZ), which in turn is considered a form of vortex breakdown [36]. The phenomenon of vortex breakdown refers to a sudden expansion in the flow field when the swirl number (S) is higher than the critical value (which is believed to be S = 0.6) [36, 37], characterized by deceleration in the flow field, which leads to the development of a stagnation point, after which is followed by a separation region with disturbances behind [37]. Increasing swirl number leads to the development of strong coupling between the components of tangential and axial velocity. When this coupling reaches a point where the kinetic energy for the flow cannot overcome the adverse pressure gradient, a recirculation zone is developed, and hence the vortex breakdown [37].

Some cases for the vortex breakdown phenomenon have been described as turbulent and laminar flows [38]. A variety of research studies are conducted to observe the vortex breakdown. [36–39] they found seven different types of vortex breakdown. In swirling flows, three forms were considered to be the more distinguished: bubble, spiral, and double helix types [36-40].

### 2.3 Swirling Flow Structure

Structures of coherent flow will form downstream of the swirler when vortex breakdown occurs. The most distinctive structures in the flow field are the central recirculation zone (CRZ) formed by vortex breakdown, the shear layers (SL) at the outer edge, and the precessing vortex core (PVC) that surrounds the CRZ [41, 42]. These structures formed downstream of a gas turbine swirl burner which can be illustrated in Figure 2. The presence of these structures in the flows has a significant desirable and undesirable effect on the flame stability.

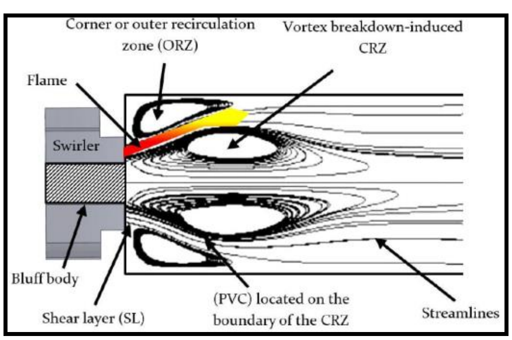



**Figure 2** Structures of coherent flow formed downstream of the swirl burner, reproduced by [43]

The structures that occur during swirling flows have been widely described and studied by several previous studies [44 - 47]. It has been proven that the presence of structures in the form of a CRZ, increases flame stability [48], whereas the existence of structures in the form of PVC leads to instability.

Moreover, when the vortex breakdown is strong, it can lead to create an inner recirculation zone (IRZ) along the axis of the burner [49]. In the IRZ, the products of combustion recirculate and help to burn the incoming mixture continuously. This zone also works as an aerodynamic blockage in flame stabilization [26, 50]. Additionally, during swirling flows a sudden expansion from the dump plane or nozzle to the surrounding environment occurs. This sudden expansion leads to the creation of outer recirculation zones with low pressure (ORZ) which greatly helps in flame stabilization. As well as, shear layers (SL) can occur in swirling flows due to the bluff-bodies, and this leads to increase the turbulence level and improves the mixing process [49, 50]. These shear layers are the inner shear layer (ISL) and the outer shear layer (OSL). The flow structures for a confined swirl flame can be illustrated as in Figure 3 [51]. Therefore, in the regions with high rates of stretch, swirl flows give a more stable flame [52], and allow extending the blowoff limits of the flame [53].

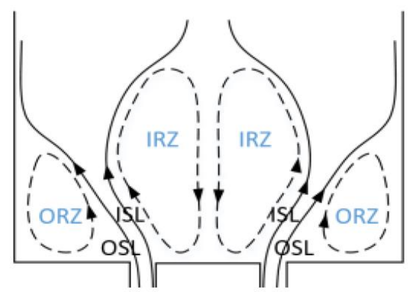



**Figure 3** Flow structures for a confined swirl flame [51]

### 2.4 Flame Stabilization by Swirling Flow

During the combustion processes, flame stability is considered an important issue that must be focused on, since instability can cause some undesirable phenomena such as blow-off and flashback, which leads to damaging the combustion systems [5, 20, 54]. Blowoff occurs when the flow velocity of the incoming mixture exceeds the flame speed and then causes the flame to leave the burner edge and it separates from the source. Blowoff can be influenced by the fuel type, burner geometry and mixing ratio [54, 55]. Whereas flashback occurs, when the flame speed is greater than the speed of the incoming mixture and this leads to the penetration the flame into the fuel mixing region [54, 56-59]. There are four flashback mechanisms: boundary layer flashback, combustion instabilities flashback, turbulent core flashback and combustion induced vortex breakdown [60, 61]. Therefore, the flashback is more complex if compared to the blowoff.

Therefore, it is necessary to search for ways to help in improving the combustion process and the stability of flame, and to get rid of these undesirable phenomena. There are several ways in which stable flames can be obtained such as swirling flows, bluff-body, opposed jets and sudden expansion etc. [62]. In this paper, the focus will be on swirling flows and bluff-bodies.

Swirling flows are used in various industrial combustors, and their primary advantage is to create a CRZ that greatly helps in flame stabilization [48]. The formed CRZ causes to effectively recirculate the active chemical species and mix them with the incoming reactants, consequently, enhance the flame stability [12, 13, 63, 64]. Also, the recirculation of reactants leads to increase the flame speed, due to an increase of the turbulence level [65]. Moreover, swirling flows are characterized by their high rates of the air-fuel mixture entrainment, most of which are near the boundaries of CRZ wall, which in turn helps to decrease the combustion lengths [66]. Therefore, the use of swirling flow technique gives robust to the flame, as well as to maintain the flame's attachment with the burner nozzle, and improves the stability process [67-70]. The use of swirling flow to obtain a stable flame has been the subject of several previous studies [13, 21].

### *2.4.1 Effect of Swirl Number*

In swirl combustors, there are several factors that influence or help to stabilize the flame, among these factors is the swirl number and the method of swirl generation [28]. Saediamiri *et al*. [71] (2014) studied experimentally the impact of the swirl strength on a non-premixed biogas flame stability limits. They found that swirl plays an important role, which can significantly affect the flame stabilization limits. An experiment to investigate the swirl number impacts the premixed flame behavior for a various mixtures in swirl combustor that has been implemented by Yilmaz *et al*. [72] (2020). From the results, they noticed that the swirl intensity is one of the main factors by which the behavior of the flame can be determined. They found that a change in the swirl number had a slightly impact on the stability of the flame.

The influence of swirl on a biogas flame's stability was verified experimentally by Rowhani and Tabejamaat [73] (2015), where the swirl was generated using swirler blades in the air flow at different angles of 30°, 45° and 60° to obtain a variable swirl number. Compared to the non-swirling air flow, they found that the swirling air flow improved the stability limits of flame approximately four or five times. It was also observed that the flame is attached to the burner edge in case of the low swirl (30° swirler blades), while it lifts off and stabilizes at the downstream of a burner with increasing swirl number (45° and 60° swirler blades).

Syred *et al*. [74] (2014) carried out an experimental study to evaluate the impact of changing the swirler vanes angle on the blowoff limits of a premixed flame using natural gas (NG). They found that the blowoff limits were poor in case of the low swirler vanes, whereas in the high swirler vanes the blowoff limits improved, as shown in Figure 4 (a). Also, an experimental and numerical analyses to evaluate the impact of swirler vanes angle on the lean blowoff limits (lean BLO) of a premixed methane-air flame in a swirl burner have been conducted by Zubrilin *et al*. [75] (2016). They reported that the lean blowoff limits improve with the increasing angle of swirler vanes. The results indicated that the findings of the numerical simulation and the experimental data are in a satisfactory agreement, as shown in the Figure 4 (b).

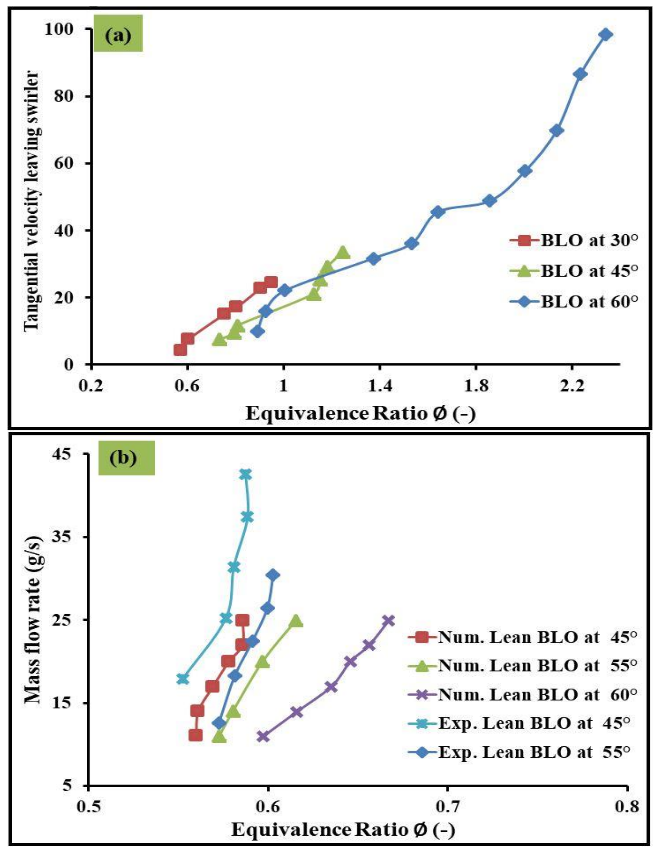



**Figure 4** (a) Blowoff limits of premixed natural gas flame and (b) Numerical and Experimental lean blowoff limits for methane flame (Produced from data in [74, 75])

Gorelikov *et al*. [76] (2021) investigated the effect of swirl number (S = 0, 0.3 and 0.75) on the premixed butane-propane/air flame structure at constant equivalence ratio using a swirler with radial vane at the burner exit. They reported that the flame shape and length could be controlled with increasing of the swirl number. They also noticed that the CRZ is formed when the S>0.6, which in turn improves the mixing process between the products of hot combustion and the incoming mixture; hence it changes the flame shape.

Dam *et al*. [77] (2011) performed an experiments to examine the influence of swirl number on the premixed flame flashback from different fuel blends of $H_2$-CO and syngas fuel. They noted that when the swirl is high, the formed recirculation zone is more intense. This in turn gives more stability in the flow field and thus reduces the tendency of flame flashback. So, they found that increasing swirl number, the flame flashback tendency decreases with respect to a given flow rate of air as shown in Figure 5.

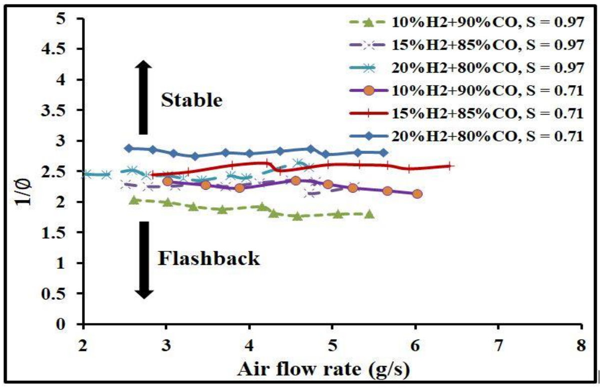
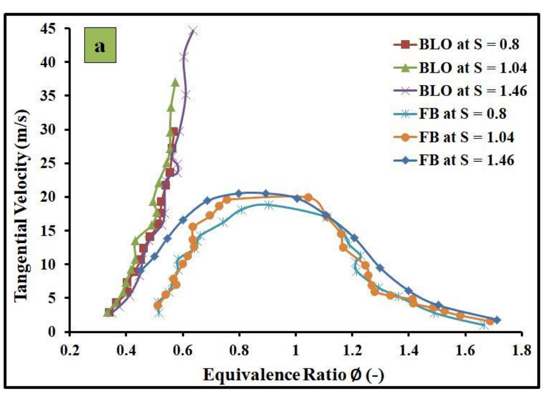



**Figure 5** shows limits of flashback at various blends of a premixed $H_2$-CO at S = 0.97 and 0.71 (Produced from data in [77])

The influence of swirl number on the premixed flame flashback and blowoff of a coke oven gas (COG) (65% $H_2$ / 25%$CH_4$) and methane in a swirl burner has been studied by Syred *et al*. [74] (2014). They reported that when the CRZ was extensive and developed, a flame blowoff was observed to occur. Whereas two types of flashback have been found, flashback occurred first at low swirl numbers and again through the outer boundary layer. They found that there was an improvement in the flashback, but the blowoff is slightly worsened with the increased of swirl number from 0.8 to 1.5. The blowoff and flashback data for COG at (S = 0.8, 1.04 and 1.46), and CH4 at (S = 0.8, 1.04, 1.2 and 1.5) can be illustrated in Figure 6 (a and b), respectively.



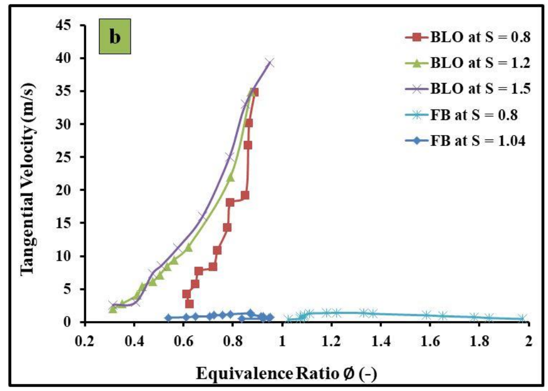
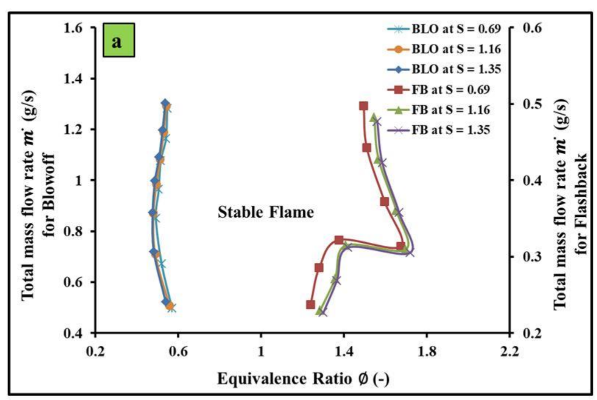




**Figure 6** Blowoff and Flashback limits at various swirl number (a) for COG and (b) for CH4 (Produced from data in [74])

Jerzak and Kuźnia [78] (2016) performed experiments to determine the swirl number effect on the flame blowoff and flashback limits in a tangential swirl burner, using premixed natural gas (NG) with three different oxidizers (air, air enriched with 25% $O_2$, and air enriched with 25% $O_2$ and an addition of 15% $CO_2$) at swirl numbers of (S = 0.69, 1.16 and 1.35). The results indicated that for all mixtures used, the limits of the stability map (represented by the flame blowoff and flashback) improved as the swirl number increased, as shown in Figure 7 (a, b and c).

Also, the flashback and blowoff limits (operation map) of a premixed methane flame at two swirl numbers (S = 1.2 and 1.5) has been studied by Abdulsada [79] (2019). A significant improvement was observed in the mixing process of the reactants at the swirl number more than 1. Therefore, there was no significant difference in the operation map when the swirl number was changed from 1.2 to 1.5, as shown in Figure 7 d.



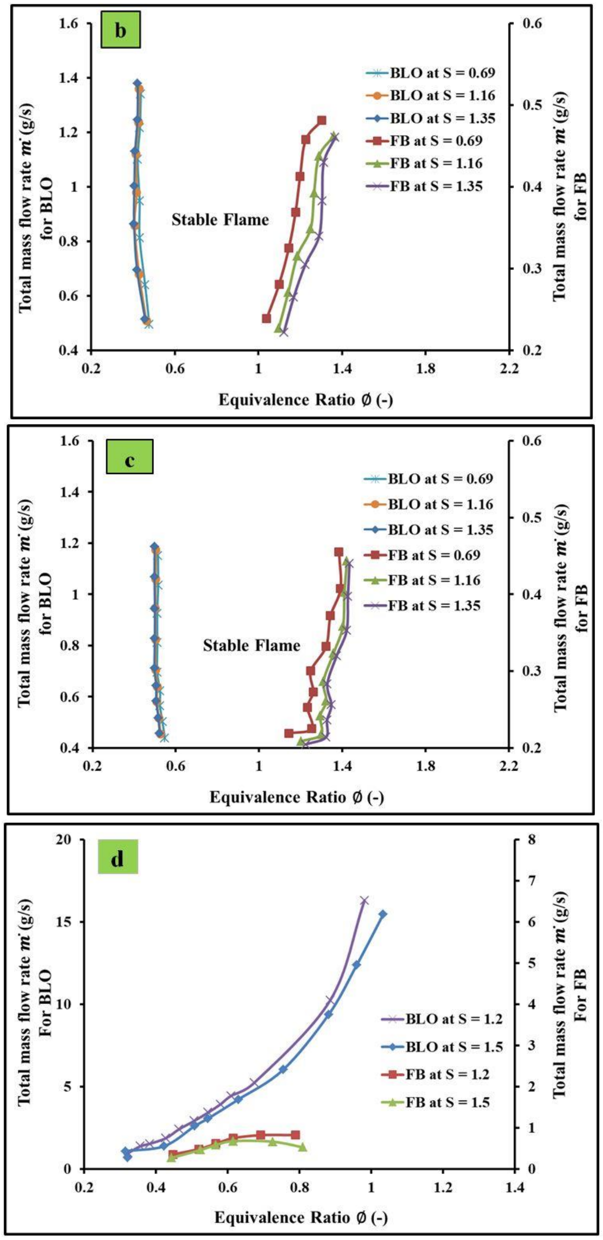



**Figure 7** Blowoff and Flashback limits at various swirl number (a) NG–21%$O_2$+79%$N_2$, (b) NG–25%$O_2$+75%$N_2$, (c) NG–25%$O_2$+15%$CO_2$+60%$N_2$ and (d) $CH_4$ – air (Produced from data in [78], [79])

It can be noticed that the swirl number (S) is an important factor that can affect the flow field and the flame characteristics in a swirl combustors through Figures (4 – 7) which are produced from the data in the previous studies. Increasing the swirl number decreases the flashback tendency, but the blowoff worsens slightly, while the flame stability map improves. This can be explained that the swirling flows nature creates a central recirculation zone (CRZ) which is believed to be at the swirl number ≥ 0.6 [80]. However, with the swirl number increases more than this value (0.6) and will increase the shape and size of the CRZ as well as the turbulence level, which in turn results in improved mixing process between fresh reactants and hot products and enhances and increases the flame stability map significantly.

It was also noted that there are very different directions for flashback and blowoff, although some researchers have used similar or somewhat close swirl numbers. This can be attributed to the different operating conditions as well as the difference in the type of fuel used, which is considered a major reason. In addition, it was noted that in the case of comparison between swirl numbers that are greater than 1 and the difference between them is little, there was no significant difference in the tendency of flashback and blowoff. This is due to the fact that when the swirl number is greater than 1, it gives a good mixing process for the reactants [79].

### 2.4.2 Effect of Swirl Burner Geometry

The change in burner geometry is considered as one of the factors that can significantly impact the field of swirling flow and the flame stability map. A large number of research work has been conducted by changing or adding some parts to the burner for preventing or eliminating flashback and blowoff of the flame (i.e enhancing flame stability).

In addition to the swirl number's impact, Abdulsada [79] (2019) conducted another experimental study, which is the effect of adding cylindrical and conical confinement to the burner nozzle on the stability map of a premixed methane flame in a swirl burner as shown in Figure 8, at swirl number (S = 1.2). It was found that the addition of both cylindrical and conical confinement increased the operating map compared to the open flame, as shown in Figure 9 a.

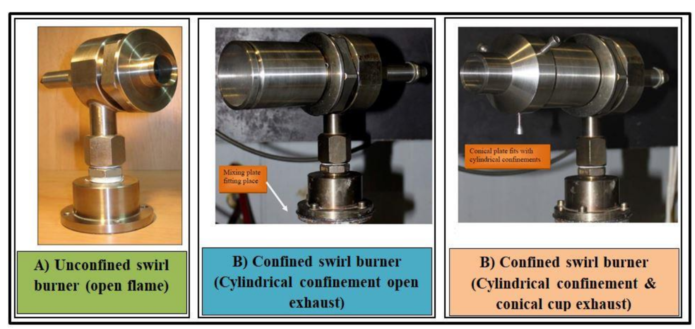



**Figure 8** The tangential swirl burner with different nozzle configurations [79, 81]

An experimental study to examine the impact of exhaust confinement on the stability limits of premixed methane ($CH_4$) and blends of 30%$H_2$ - 70%$CH_4$ flames with the same burner shown in Figure 8 but at S = 0.8 was implemented by Abdulsada *et al*. [81] (2012). They reported that the better blowoff limits were with blends of 30% $H_2$ - 70% $CH_4$ compared to 100% $CH_4$ as shown in Figure 9 b. This may be due to the hydrogen existent in the blends, which in turn cause the turbulent burning velocity to increase. On the other hand, they found that the blowoff limits are greatly improved with the use of confinement (cylindrical and conical cup) compared to the case of without confinement, where the best results were found in the case of confinement with conical cup. Consequently, the use of exhaust confinement leads a wider operating map compared to open flames.

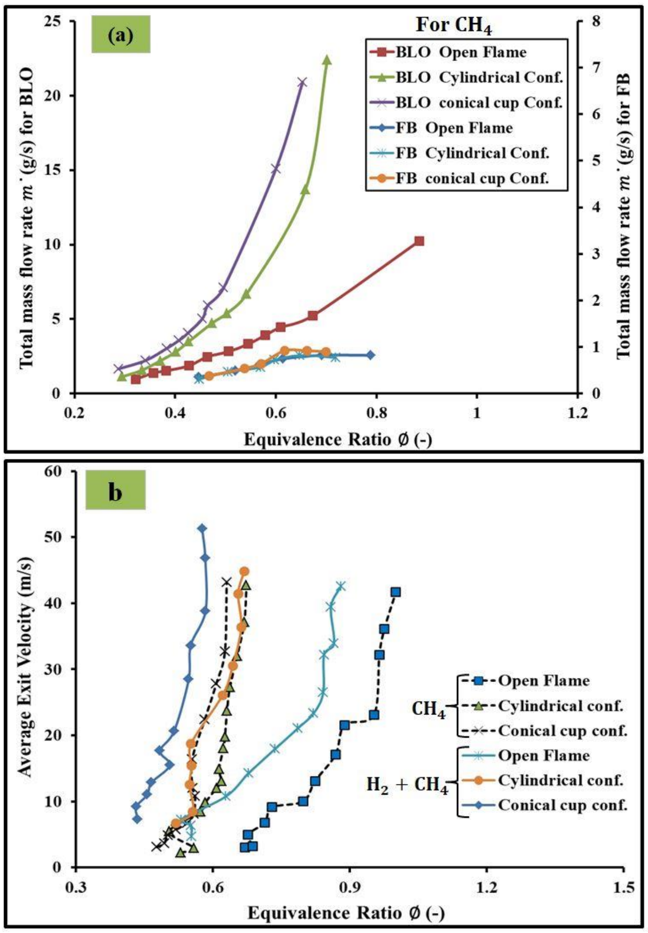



**Figure 9** (a) Operation map of pure methane and (b) Blowoff limits of pure methane and blends of 30%$H_2$+70%$CH_4$ (Produced from data in [79], [81])

Liu *et al*. [82] (2020) conducted an experimental investigation to assess the impact of the injection nozzle geometry on the flame blowoff limit. They used four different shapes of the injection nozzle (circle, cross, rectangular, and triangle), as shown in Figure 10. They reported that as the fuel jet's velocity decreased, the blowoff limit of the flame was slightly affected by the nozzle geometry, whereas it was significantly impacted by the increase in fuel jet velocity. In the case of high velocity in the fuel jet, they found that the triangular nozzle gave the maximum blowoff speed, while the minimum blowoff speed was for the rectangular nozzle.


**Figure 10** The geometry of the injection nozzles used [82]

Al-Fahham *et al*. [83] (2017) studied the impact of adding the microsurfaces grid as an inner lining to the nozzle on flame flashback in a tangential swirl burner experimentally and numerically, as shown in Figure 11. They noticed good agreement between both numerical and experimental results. The results revealed that the use of these microsurfaces has slightly enhanced the flame flashback, which gave a wider stability map compared to those without using the microsurface, as illustrated in Figure 12 a. They also found that the flame diameter with the microsurfaces was 5% lower than those without the microsurfaces.

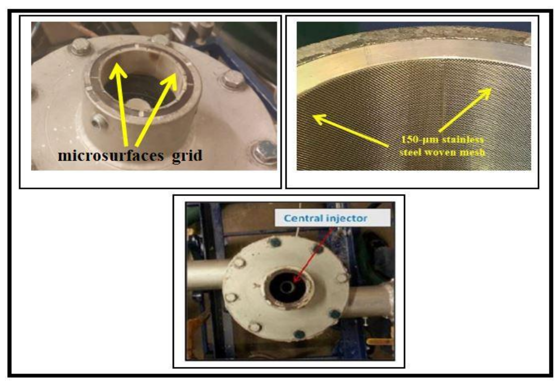



**Figure 11** The tangential vortex burner with the microsurfaces grid used [83]

The influence of the swirl burner rim length ratio to its diameter on the LPG flame stability map has been verified by Al-Naffakh *et al*. [84] (2019). They tested three different burner neck lengths (L = 5, 10, and 15 cm) with a diameter of 5 cm, as illustrated in Figure 13. They found that with increasing burner neck length, blowoff limits were improved, while flashback occurring was accelerated as shown in Figure 12 b. They also reported that as the burner neck's length increased, the swirl strength decreased.

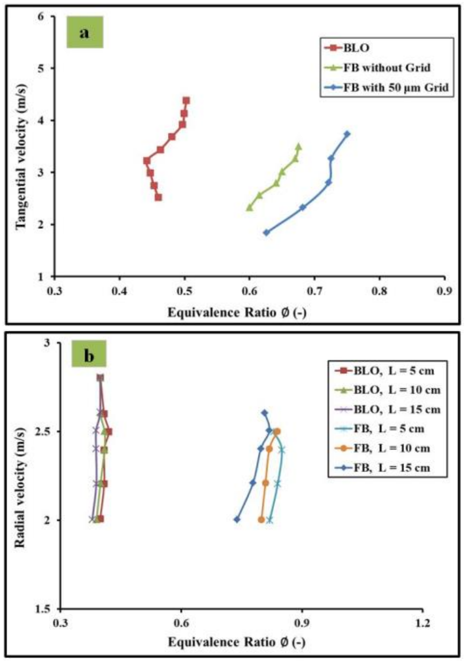



**Figure 12** (a) Flashback limits for with and without using microsurfaces and (b) Operation map for three different lengths of burner neck L = 5, 10 and 15 cm (Produced from data in [83], [84])

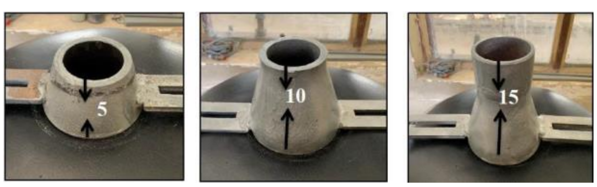



**Figure 13** The swirl burner with different burner neck lengths [84]

Therefore, through previous studies, it was noted that any change or addition to the burner geometry can affect the blowoff and flashback limits (operational map). This can be explained as in swirl combustors that the characteristics of the flow field can be greatly changed because of the interaction between swirling flows and the geometries of the burner. Consequently, this change can affect the central recirculation zones (CRZ) that are formed as a result of the swirling flows and the stability of the flame.

It can be seen that the presence of confinement in the burner nozzle greatly improves the operating map, and the reason for this improvement is that the presence of confinement maintains the CRZ staying for a longer distance, and helps to stabilization the flame [79]. Additionally, properties of the burner nozzle inner wall can have a significant impact on the flame propagation [83]. This occurs when the parallel flow of the mixture interacts with the inner surface of the nozzle wall, which leads to enhancing the velocity gradient due to the adverse pressure gradient which is produced from the viscous drag generated during the interaction. Therefore, the wall roughness degree has a clear effect on the flame characteristics, where it leads to enhancing the heat transfer process, and increasing or decreasing the shear wall stress [85]. As for the geometry of the injection nozzle, it had a great impact on blowoff limit when the velocity of fuel jet increased. This is due to the moment of inertia, which is considered as a major parameter in material mechanics [82].

## 3.0 BLUFF-BODY

Flame stability is a topic of great interest in a wide variety of combustion applications including gas turbines, furnaces, steam generators for heat recovery, afterburners, etc. [1, 14, 65]. Therefore, the bluff-body (or so-called flame holder) is considered as a practical method that has been widely used, where it has the ability to stabilization the flame and to control the combustion process [14, 86-88]. For many years, the use of bluff-bodies as flame stabilization means has been verified by the several researchers [89-92]. The benefit of using the bluff-body is creating a recirculation zone for the hot gas behind it which helps to re-ignite the mixtures, hence stabilization the flame [14]. On the other hand, the bluff-body can negatively influence the stabilization of flame as well as the flow field, which is considered as an unstable vortex, and can lead to blowoff of flames [93].

In general, the main problems that face the bluff-body especially in the gas turbine combustors is the high temperatures and convection of its surface, which affects the lifetime of the combustion system [94]. There are different shapes of bluff-bodies that have been used in many studies; the most commonly used are discs, cylindrical rods, cones [95].

### 3.1 Flame Structure in a Bluff-Body Burner

The flame structures stabilized by the bluff-body are considered of great interest because they are closely related to the characteristics of flame stabilization. Typical flow field structures of a stable flame with the presence of a bluff-body are illustrated in Figure 14 [96], where these structures have been studied by many previous studies, most notably [96–98]. The figure shows that the recirculation zone contains two types of vortices: the outer vortex caused via the air flow and the inner vortex caused via the fuel jet [98, 99]. For the shear layers, there are three layers: the first is located between the zones of outer vortex and air flow that called the outer air shear layer, the second is positioned between the zones of inner vortex and the jet of central fuel and called the inner air shear layer, and the third is located between the zones of inner and outer vortex that is called the fuel shear layer (or intermediate layer) [97, 98], where there are significant velocity fluctuations because of strong velocity gradients. Near the stagnation point and downstream of the recirculation zone the neck region is located, it also contains big fluctuations because of the interaction between the annular air flow and the fuel jet [100]. Flow structures can be split by the ratio of fuel-air flow velocity that is considered as an important parameter, where they can be four or three modes [96, 97]. Also, the stagnation point position is related to the ratio of fuel-air velocity [101]. The shear layer can control its position and shape by changing the position and geometry of the bluff-body as well [102].

Flow fields can change with bluff-body size, and the flame structure [103]. Three stable modes of flame structures were observed with bluff-body: the flame of the recirculation zone, the jet-like flame, and the central jet-dominated flame. Additionally, they identified the split flames, split flashing flames and lift-off flames that appeared under specific operational situations [99]. Also through another study, different flame patterns with bluff-body were identified which are turbulent flame, unstable flame, jet flame, upraised flame and bubble flame by [104].

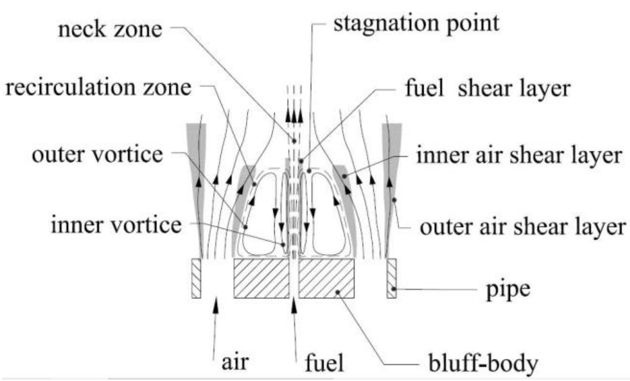



**Figure 14** schematic of the flow fields with the presence of a bluff-body and central fuel jet [96]

### 3.2 Flame Stabilization by a Bluff-Body

Flame stability is an important issue and considered as a major factor for obtaining good performance in various combustors such as gas turbines, industrial furnaces, heat recovery, afterburner, and steam generators [1, 14, 65]. To achieve good flame stability in the combustors, it is necessary to focus on the flow field which is considered as a critical factor. In addition, some operational parameters must be taken into account like: mixing quality, fuel distribution uniformity, temperature distribution, flame length, attachment and dynamics of flame [105, 106].

Therefore, the bluff-body is one of the methods widely used to stabilize the flame in many industrial applications [9, 10, 14]. The main benefit of using bluff-bodies is the creation of recirculation zones which in turn help to improve mixing of the reactants, and the combustion process [65, 88, 107]. In addition to improving the mixing process, the recirculation zones circulate the hot gases behind the bluff-body, which helps to re-ignite the incoming mixture continuously and hence enhances the stability of the flame [16, 108]. In the diffusion combustion process, a bluff-body with a central jet is often utilized to stabilization the flame, whereas a solid cone or solid plate with various geometry shapes are used as a bluff-body to stabilization the flame in the premixing mode [88]. Due to the different combustion systems, this prompted researchers in this field to take some parameters into consideration. Among these parameters are the effect of bluff-body geometry represented by the position of the bluff-body [109], shape of the bluff- body [110, 111] and the blockage or confinement ratio [10, 111]. There are also other parameters such as turbulence intensity, flow speed, temperature of the flame holder and stoichiometry, in case of changing these parameters leads to flame blowoff [112]. In addition, the contact between the hot gases, the incoming mixture and the bluff-body play a major role in the process of heat exchange between the bluff-body itself and the flame, and this affects the pressure distribution, coherent structure characteristics, blockage ratio, and density ratio [105, 113, 114]. In order to control the blowoff limits using bluff-bodies, this can be done chemically by heat transfer with the reactants mixture and physically by altering the flow field. Therefore, a numerous of previous studies have been done to understanding the blowoff mechanism and the flame stability using bluff-bodies [14-16, 112, 115, 116].

The influence of blockage ratio using bluff-bodies with different blockage ratios of 0.4, 0.5, 0.6, and 0.7 was verified by Wan and Zhao [117] (2020). They found that with the increase in the blockage ratio, the length of the recirculation zone increased. Rowhani *et al*. [118] (2019) reported that the recirculation zone length plays an important role in the distribution of residence time and mechanism of flame stabilizing.

A numerical study of the combustion characteristics of a premixed hydrogen-air flame using bluff-bodies of various shapes (circle, semi-circular, triangle, ellipse, half-ellipse, crescent, diamond, wall-blade and arrowhead) has been implemented by Bagheri *et al*. [110] (2014). They found that the highest temperature of flame was in the case of using the wall-blade as a bluff-body at low speed (10 m/s) and equivalence ratio (0.5).

Tong *et al*. [88] (2017) conducted experimental investigation to examine the impact of central air injection on the surface temperature of the conical-shape bluff-body and blowoff of premixed methane-air flames. The results indicated that the heat load to the bluff-body surface decreased significantly with the central air jet. They also found that the central air jet led to altered in the flame structures and made the flames blowoff easier.

The influence of a bluff-body position on the stability limits and structures of the methane-air diffusion flame was studied experimentally and numerically by Tong *et al*. [109] (2018). With the changing of the bluff-body position, it was observed that the strength and size of the recirculation zones have been changed downstream of the bluff-body. They found that the flame was more stable when placed (10 mm) over the annular channel outlet. They also observed different patterns of flame, the flames of recirculation zone, the stable diffusion, the split and the lifted until the flame blowoff.

Tong *et al*. [98] (2018) carried out an experimental and numerical study to examine the impact of changing the bluff-body diameter ($d_b$=14 and 20 mm) on the flame structure. There was good agreement for the simulation results and experimental data. They found that the bluff-body size could influence the position of the outer recirculation zone. The results revealed that the air driven recirculation zone was placed further upstream close to a burner outlet, and also the flame was more stable when the bluff-body diameter was largest.

The flame behavior on a flame holder with triangle-shape using propane, methane and ethylene-air blends as a fuel was studied by Roy and Cetegen [119] (2021). The changes in flame dynamics were observed under highly combustion and near blowoff conditions. They reported that the structures of symmetrical flame moved slightly to the asymmetric structures through decreasing equivalence ratio until it reached to blowoff.

Rowhani *et al*. [120] (2022) implemented a numerical and experimental study to determine the impact of the bluff-body diameter ($D_{BB}$ = 38, 50 and 64 mm) on the flow field and distribution of the residence time. They noticed that the length of the recirculation zone increased with the increase in the bluff-body diameter. They also observed that increasing the bluff-body diameter from 38 to 64 mm, the volume and length of the flame decreased by 9% and 20%, and the residence time of the reactants increased three times within the recirculation zone.

An experimental investigation to examine the impact of various shapes of bluff-body (disc, V-gutter, cone, horizontal and vertical cylinders) with blockage ratios (B.R. from 0.25 to 0.55 with a step of 0.1) on the stability limits of a premixed LPG flames has been performed by Ibrahim *et al*. [121] (2022). For all forms of bluff-bodies, they found that when the blockage ratio increases, flame temperature increases, flame length decreases, and its diameter increase. It was also observed that when the blockage ratio increases, the region of stable flame increases, where they found that the cone-shape bluff-body had more stability region, whereas the horizontal cylinder had the smallest stability region if compared with other shapes of bluff-bodies as shown in Figure 15 (a and b).

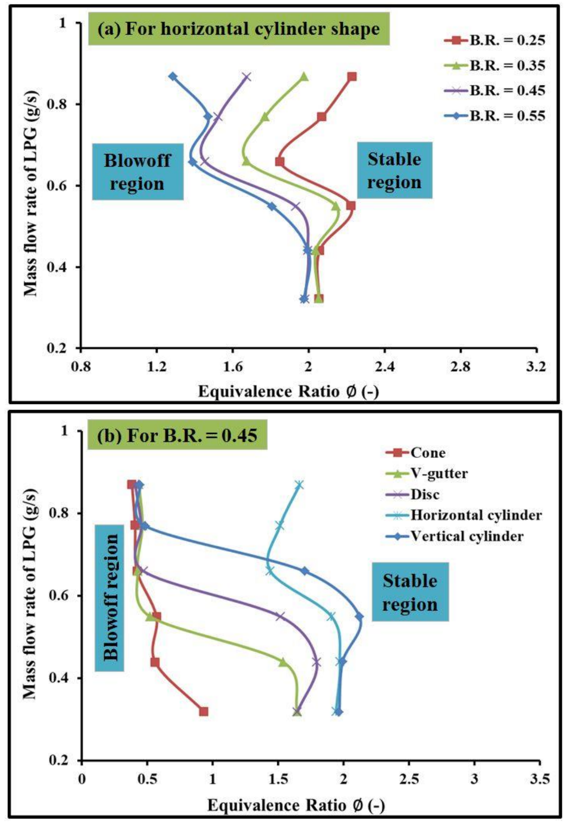



**Figure 15** the flame blowoff limits for (a) for horizontal cylinder shape bluff body at various blockage ratio (b) for various shapes of bluff-body at B.R. = 0.45 (Produced from data in [121])

Hatem *et al*. [122] (2021) carried out an experimental investigation on the influence the bluff-body diameter (D) on the limits of flame blowoff in a tangential swirl burner. They reported that the blowoff limits change dramatically with the external diameter of the bluff-body changes. The results showed that the blowoff limits moved towards leaner region with the small diameter of the bluff-body, which gave a narrower stability map. However, the blowoff limits occurred with a wider range for bluff-body with large diameter, and this gave the optimum stability map as illustrated in Figure 16 (a).

In addition to the effect of the bluff-body diameter, Hatem *et al*. [122] (2021) conducted another experimental study, which is the effect of using axial air injection at different positions (Lo = 0, 29, 75, 110 and 150 mm) inside the burner on the flame blowoff limits. Compared with the bluff-body, the results indicated that the operation map was wider with the use of axial air injection. They reported that the air-jet opening position can significantly impacted the blowoff limits, where they found that the wider range of the tangential velocity of inlet at which the blowoff occurs was in the case of the position Lo = 0 mm (baseline) and Lo = 150 mm. The narrower ranges were for the tangential velocity of inlet to the other three positions, as shown in Figure 16 (b).

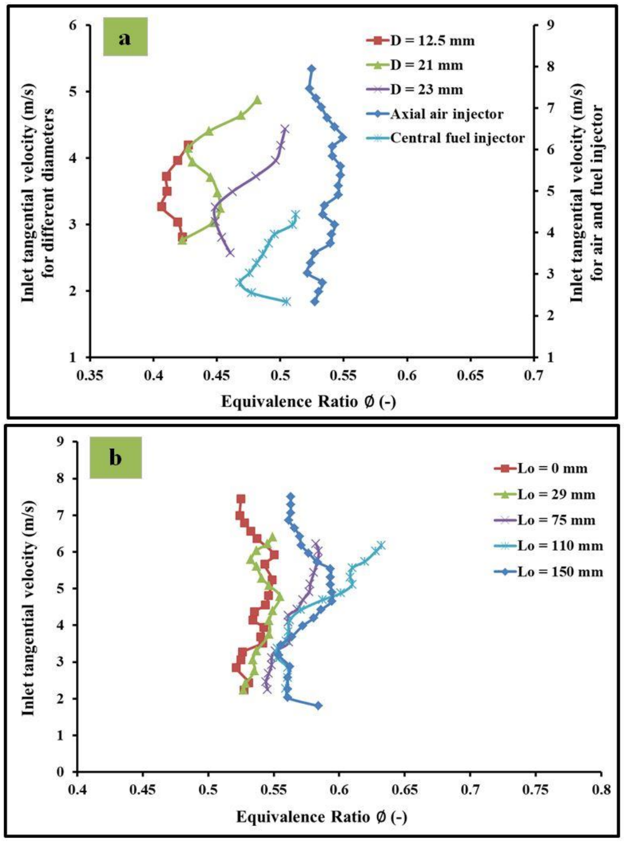



**Figure 16** the flame blowoff limits for (a) for various bluff-body diameters (D), axial air injection and central fuel injection (b) for various positions of air injection (Lo) (Produced from data in [122])

Therefore, it can be noted that the use of the bluff-body in combustors is considered as a good technology and contribute significantly to stabilization the flame. This could be due to the good mixing of the reactants as a result of the recirculation zones that were created because of existence of the bluff-body [65, 88, 107].

Despite the benefit of using bluff-bodies in flame stability, some associated problems can affect the stability map. For example the shape, size and position of the bluff-body are important issues that should be considered because of their effect on the recirculation zones and hence the flame stability. There are some shapes used as bluff-bodies that can have negative effects on the stability of the flame leading to an accelerated blow-off occurrence and a smaller operation map [121]. The diameter of the bluff-body is another important factor. It is clear that when the diameter of bluff-body increases, the recirculation zone length increases, and this in turn increases the residence time of the reactants within the recirculation zone, and can enhance the stability of the flame [120]. The position of the bluff-body also plays a major role in stabilizing the flame, where the strength and size of the recirculation zones alter as a result of changes in the bluff-body position.

## 4.0 CONCLUSION

This article presents an overview of the flame stability and the operation map represented by the limits of flashback and blowoff in combustors. Flame stabilization mechanisms using swirling flows and bluff-bodies methods are discussed. The use of these two methods greatly helps to stabilize the flame, where they can create central recirculation zones (CRZ's) that in turn recirculates the heat and active chemical species to the root of flame, and enhances the stability of the flame.

The review demonstrated that in the case of swirling flows, the swirl number (S) is considered an important factor that can influence the flow field and flame characteristics, whereby an increase in the swirl number improves the flame stability map. In addition to the swirl number, any change or addition to the burner geometry had a clear effect on the swirling flow field, the blowoff, and flashback limits (operational map). It was noted that the existence of confinement in the burner nozzle significantly improved the operating map, and the inner wall of the burner nozzle also had a clear effect on the propagation of flame during flashback.

As for the use of bluff-bodies, its shape, size and position had an important role in stabilizing the flame and controlling the combustion process because it affects the recirculation zones. It has been observed that some bluff-bodies shapes can lead to an accelerated of the blowoff occurrence and a smaller operating map. Increasing the diameter of the bluff-body increased the length of the recirculation zone, as well as, changing the bluff-body position led to change the strength and size of the recirculation zones.

## Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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