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# *A Smart Control of Lean Blowout using Multistage Injection Systems in Gas Turbine Combustors*

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## *Abstract*

***Lean blowout is a critical issue in gas turbine combustors operating under lean fuel-air conditions to minimize NOx emissions. The effects of this phenomenon are widespread and can be severe, particularly in power plants (ground-based engines) and aerospace engines. Lean blowout occurs when the flame inside the combustion chamber suddenly extinguishes as the flame speed drops below the velocity of the unburned fuel mixture. This can lead to catastrophic consequences, including fatalities and significant financial losses. To address this issue, developing active and smart control strategies is essential for early prediction and prevention of lean blowout. In our previous research, we found that the blowout limit can be extended to leaner fuel-air mixtures by reducing the length or degree of fuel premixing. In this study, we apply this concept by examining two different premixing lengths to formulate an effective control strategy. We utilize two fuel entrances at varying heights: one with the maximum degree of premixing, designated as the primary fuel entrance, and the other with minimal premixing, referred to as the secondary fuel entrance. During our experiments, we inject fuel through the primary fuel entrance while keeping the air entrance constant. Using the color ratio technique outlined in our earlier work[2], we monitor the risk of blowout. Once the color sensor indicates that the system is nearing the blowout threshold, we introduce a small fraction of the total fuel flow into the secondary fuel entrance which has lower degree of premixing. By employing this strategy, we find that the blowout limit can be significantly extended towards leaner fuel-air***

***mixtures, effectively preventing occurrences of blowout that would not be feasible without this approach.***

*Keywords*: ***Lean Blowout, Gas turbine combustors, Smart control, Multi-port fuel injection, Degree of premixing***.

## 1. Introduction

The adoption of lean premixed technology increases the risk of blowout [1-5] and thermoacoustic instability in combustors [6, 7]. Blowout occurs when the local flow velocity of the reacting mixture exceeds the local flame speed of the species involved in the reaction. Under these conditions, the flame becomes unstable and is extinguished as it is swept away by the flow of unburned reactants. As the air-fuel ratio is adjusted to a lean mixture (i.e., a fuel-lean mixture), the flame speed gradually decreases from its value at stoichiometric conditions. This makes the flame more susceptible to blowout at lean conditions. Events where blowout occurs due to excessive leanness of the reacting mixture are commonly referred to as lean blowout (LBO) [8]. Lean blowout can be defined as a loss of static stability in flame dynamics within the combustor [9].

In land-based gas turbines, LBO is a significant concern, primarily stemming from the operation of combustors in a lean premixed mode to meet stringent emission regulations [10]. Moreover, the characteristics of gas turbines directly influence the stability of the power grid. When LBO occurs, it leads to a definitive shutdown of the combustion chamber, resulting in an abrupt decrease in turbine output. This sharp decline causes substantial variations in shaft speed and creates an immediate power imbalance at the generator. Such imbalances disrupt the system's frequency and can lead to serious stability issues within the power network [11]. A prolonged shutdown of power plants poses a direct threat to grid stability across extensive areas and results in considerable revenue losses. Therefore, it is imperative to implement proactive measures to effectively address these risks and ensure a reliable and efficient power supply [12].

In the absence of reliable detection systems, the industry often resorts to operating combustors with an excessively wide safety margin [13]. This is particularly evident in land-based gas turbines, where engines are run at air-fuel ratios significantly exceeding the lean blowout (LBO) limit, thereby contributing to heightened emissions. Yet, there is a better way. An optimal transient combustion process can effectively navigate an operating curve that not only reduces emissions but also adheres to safety standards. To achieve this ideal operating range and minimize emissions, it is crucial to control the undesirable disturbances within the combustor system, ultimately strengthening flame stability and promoting a cleaner environment.

Over the past two to three decades, numerous studies have been conducted to understand flame behavior near blowout limits [5, 8, 14]. Additionally, several flame stabilization techniques [15-17] have been explored to maintain flames under conditions that are prone to blowout. Researchers have effectively characterized blowout events in premixed flames by utilizing chemiluminescence signals [18-20]. This research is crucial for advancing our understanding and improving safety in various flame applications. Further insights were gained by examining the dynamic nature of flames near LBO limits [5, 21, 22]. These studies contributed to the development of numerous strategies and measures to predict the occurrence of LBO in both premixed and partially premixed flames [5, 20, 22]. As a result, a variety of statistical and dynamical measures have been introduced to identify the pathways of flame behavior transitions toward LBO. Notable methods include the use of flame color-based sensing techniques [20], the testing of Symbolic Time Series Analysis (STSA) [23], counting precursory events based on OH* and CH* chemiluminescence signals [18, 19], and the application of recurrence methods [5]—each representing significant advancements in this field of study.

Based on the prediction strategies over the last sixty years, extensive research on lean combustion has led to significant advancements in gas turbine combustor design. Key modifications have included the introduction of a bluff body [24] before the combustion chamber, variations in swirler vane angles [25], and the integration of pilot [26] and dump planes [27]. These component, whether used individually or in conjunction, greatly enhance flame stability during lean operation by creating low-velocity zones within the combustion chamber. One of the most effective stabilization techniques employed today involves the establishment of recirculation zones in the flow. On the other hand, a bluff body, characterized by its distinct cross-section and positioned perpendicular to the flow, serves to reduce the high flow velocity upstream of the flame. It is believed that the unburnt fuel mixture ignites within the shear layer as it mixes with hot gases from the recirculation zones formed behind the bluff body. This process facilitates the downstream flow of the reacting mixture along the shear layer, igniting adjacent mixture kernels in the process. When the reacting mixture reaches the wake, it is drawn into the recirculating zone, where it further interacts with the unburnt mixture, ultimately leading to ignition occurring in the shear layer. This sophisticated mechanism underscores the promising potential of these modifications in optimizing combustion performance. However, a further development is necessary as operating regimes evolve to meet the demand for eco-friendly and sustainable combustion at low fuel-air ratios [28, 29].

In this study, we seek to create an innovative control strategy that leverages flame color sensing techniques alongside a multi-port or staging fuel injection system. Our previous research [20] revealed significant changes in flame emissions through the use of a spectrometer, prompting us to focus specifically on the red and green color emissions. By building on our prior control strategy that utilized pilot operations [29], we plan to analyze the ratio of red to green color emissions to effectively monitor the flame's behavior as it nears blowout. This critical analysis will enable us to set a reliable threshold that informs our precautionary actions using the multi-stage injection system. We test this proposed strategy on a laboratory-scale gas turbine combustor model, yielding promising results that demonstrate its effectiveness and reliability.

The organization of the paper excluding the introduction section is as follows. The experimental facilities including the experimental setup of a model gas turbine combustor is described in Sec.2. We discuss the color sensing based strategy along with the adoption of staging injection system in Sec.3. We discuss the effectiveness of the strategy for preventing the blowout events and extension of blowout limits in Sec.4. Finally, we summarize the significant observations in Sec.5.

## 2. Experimental Facilities

We utilize a laboratory-scale model of gas turbine combustors, as illustrated in Fig. 1. This combustor serves as a representative system to examine the proposed control strategy for preventing lean blowout in gas turbine engines. The combustor consists of three main sections: a premixing chamber, a combustion chamber, and an exhaust chamber. The premixing chamber features both fuel and air inlets, allowing for varying degrees of premixing of the fuel-air mixture. The air inlets are positioned at the upstream end of the premixing chamber, while the fuel inlets are situated at different vertical heights to help achieve different levels of premixing. The fuel inlet closest to the air entry is referred to as the F1 fuel port, which provides the highest degree of premixing, as demonstrated in our previous literature [14]. Conversely, the degree of premixing decreases as we move to the next vertically positioned fuel inlets, namely the F3 and F5 fuel ports, as shown in Fig. 1.

Additionally, we design four inlets for each fuel and air entries to ensure symmetry in the flow configuration. A swirler with a vane angle of 60 degrees is positioned downstream of the F5 fuel port and upstream of the combustion chamber inlet to further enhance fuel-air mixing. The premixed fuel-air mixture, corresponding to a specific degree of mixing, is ignited in the combustion chamber. After combustion, the exhaust gases exit the combustion chamber through the exhaust chamber. The combustion chamber is constructed with a high-temperature resistant quartz tube, allowing for observation of the behavior of the turbulent flame. For a more comprehensive study of the combustor, readers are encouraged to refer to the work of De et al [5, 14, 20, 29].

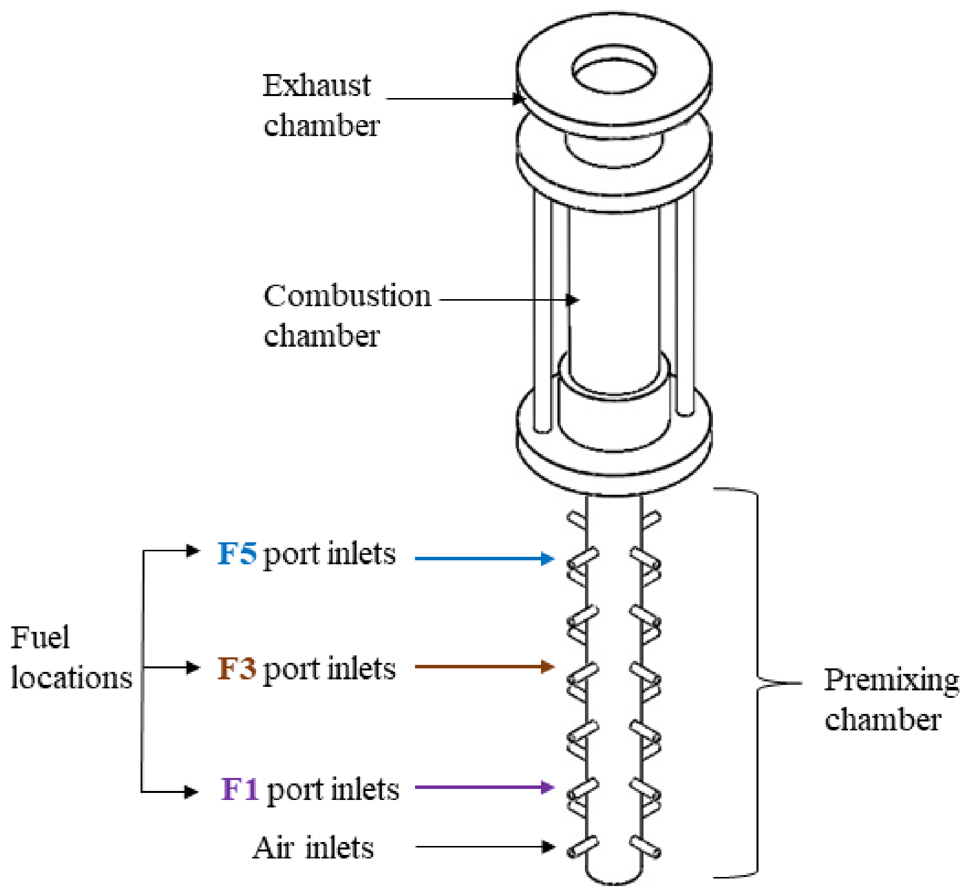


**Figure 1:** A laboratory scale setup of the premixed combustor having different degrees of fuel-air mixing is illustrated here. The fuel ports F1, F3 and F5 are shown here which indicate the various levels of mixing.

## 3. Methodology

In this work, we use a color emission sensing based strategy to stabilize the flame inside the combustor by shifting the blowout limits towards the leaner fuel-air mixture. This technique is described below.

### *3.1 RGB technique*

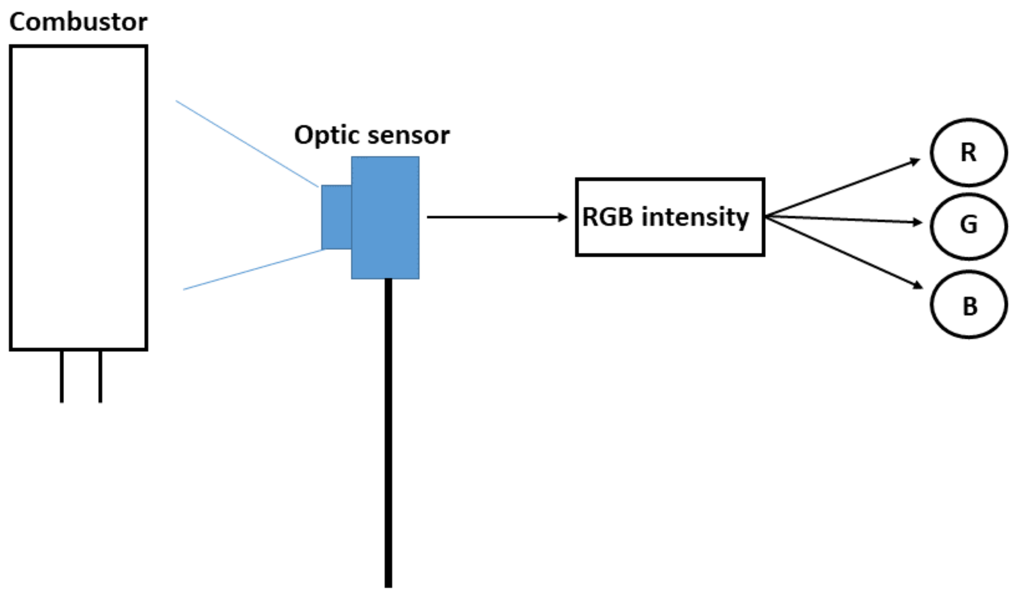


**Figure 2:** A schematic of RGB extraction from the flame emission is shown here. The emission from the combustor is captured by an optical sensor which can capture RGB intensities. A NI-LabVIEW platform is further opted to split the Red, Green and Blue intensities from the captured color flame image.

We employ a technique based on Red, Blue, and Green (RGB) colors to measure the intensities of these three primary colors emitted from the flame using an optical sensor, as shown in Fig. 2. The wavelengths for the Red, Blue, and Green spectra are approximately 717 nm, 430 nm, and 560 nm, respectively, as captured by the camera lens. To isolate the intensities of these colors, we utilize a National Instruments (NI) LabVIEW system paired with a digital input-output module. To ensure that the signal intensity is free from noise, we first capture the background noise before the experiment and subsequently subtract it from the intensity readings of the colors emitted by the flame.

### *3.2 Multi-Port injection system*

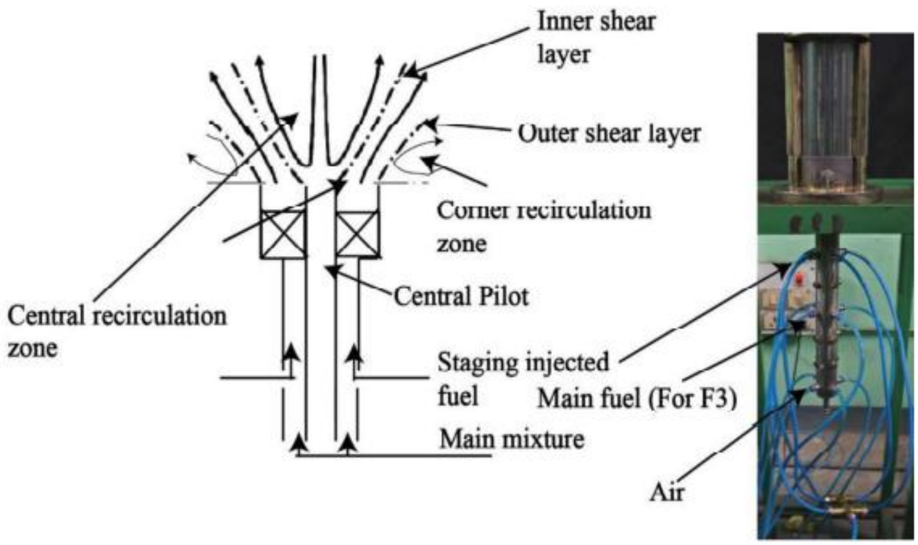


**Figure 3:** An illustration of the multi-port or staging fuel injection system is shown here, which is taken from De et al [30]. The multi-port injection or staging injection system indicates a primary and a secondary fuel injection. The primary injection indicates the main fuel while the secondary injection through the fuel port having relatively lower mixing degree is proposed in order to prevent the blowout. As a representative case, the main fuel is shown to enter through port F3.

Figure 3 illustrates a staging injection or multi-port fuel injection system. In this system, primary fuel flows through the fuel port at a specific premixing length, while additional fuel enters the combustion chamber through a second fuel port located at a lower premixing length. This concept is derived from our previous findings [14], which indicated that the blowout equivalence ratio decreases as the premixing length shortens. This reduction occurs due to the formation of local fuel-rich zones at the flame base, which helps sustain the flame for a longer duration [14]. In this approach, fuel port F5 is utilized for the staging action. Figure 3 also shows the flow field for the staging injection. The additional fuel injected from port F5 may enhance the outer or corner recirculation zone. This controlled flow system could serve as an alternative stabilization mechanism to pilot injection systems [29], helping to stabilize the combustor when the main flame is at risk of blowing out.

### *3.3 Proposal with steps*

Figure 4 provides a detailed explanation of the control strategy. Using the technique outlined in Section 3.1, the flame image is captured instantaneously by an optical sensor. The captured images are then processed through NI-MAX, which interfaces with the optical sensor, and sent to the NI-LabVIEW platform. Within LabVIEW, the background noise is subtracted from the captured images, and the intensities of the red, blue, and green colors are separated accordingly, as discussed in Section 3.1. An in-house code written in MATLAB is integrated into the LabVIEW command window. This code not only extracts the color intensities but also calculates the color ratios. In this study, we focus on the color ratio between red and green emissions to monitor flame behavior. We set a threshold value for this ratio, and if it falls below this threshold, an alarm is triggered to prompt the system to take precautionary action.

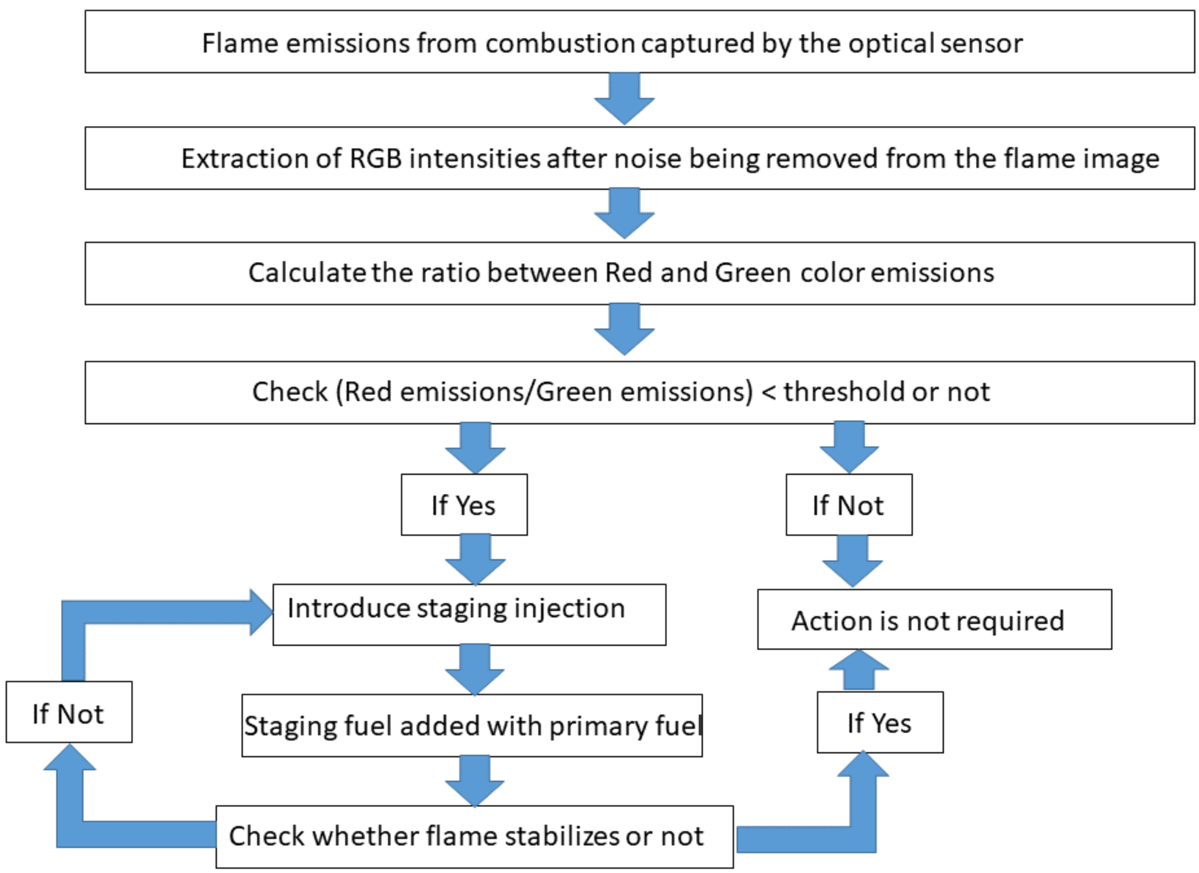


**Figure 4:** The strategy using a simple color technique with the addition of staging injection is illustrated here.

As a precautionary action, we introduce the staging fuel with the primary fuel which is small in percentage. We then check whether the flame stabilizes with this small amount of staging fuel. If it does not stabilize, we need to increase the percentage of staging fuel, as shown in Figure 4. However, in this present study, we adopt a constant amount of staging fuel that remains very small compared to the primary fuel flow rate, once the color ratio drops below the threshold. This amount of staging fuel is maintained until a final blowout occurs. We proceed to calculate the extension of blowout limits for this specific staging fuel injection. Let us check the efficacy of the constant fuel injection for staging operation in Sec. 4.

## 4. Results and discussion

The current work primarily focuses on employing a flame color-based sensing method that relies on the emissions of red and green colors from the flame, as mentioned before. This method utilizes an active control system to manage lean blowout (LBO) conditions. In contrast to previous studies [20, 29], which predominantly concentrated on flame color emissions corresponding to a wavelength of 430 nm when analyzing flame behavior, this research expands the scope. Additionally, the control system discussed incorporates a staged injection system or a configuration with multiple fuel ports. In this setup, the fuel flow rate is monitored while maintaining a constant air flow rate, as mentioned earlier. The main objective of this control study is to stabilize the flame in regions prone to LBO, allowing the engine to operate at lower loads. This approach not only reduces $NO_x$ emissions but also enhances engine efficiency. In the following sections, we first examine how the flame color ratio (FCR), $I_R/I_G$, changes in relation to variations in the equivalence ratio as it approaches the blowout point. Next, we evaluate the role of a multi-staging injection system once this threshold is crossed, focusing on its application in both premixed and partially premixed combustion. Finally, we discuss the effectiveness of this method in preventing blowout in non-premixed combustion.

### *4.1 Variation of Red/Green color emission ratio towards LBO*

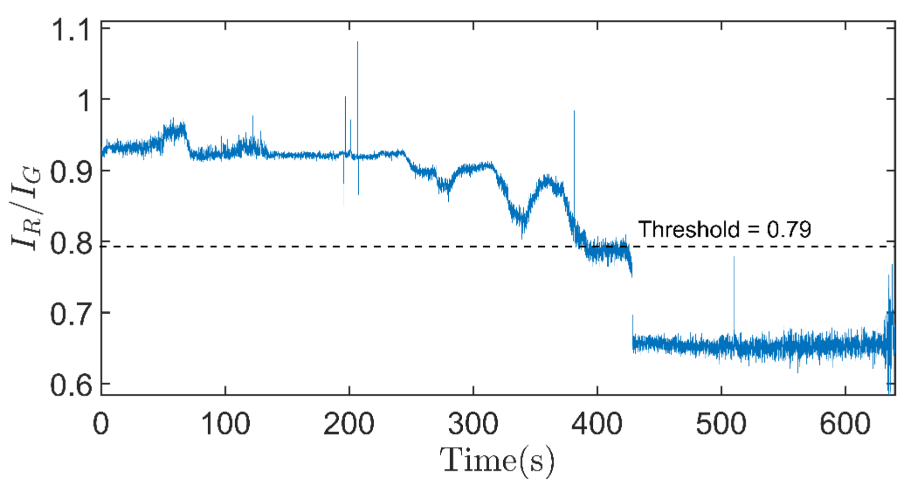


**Figure 5:** The ratio between red and green color emissions are shown here when the combustion process approaches lean blowout by reducing fuel flow rate. Note that the air flow rate is kept

fixed. The fuel flow rate is changed by 0.1 lpm after each 60 seconds. A threshold of 0.79 of the ratio is set for initiation of a smart feedback loop for preventing the blowout in the combustor.

Figure 5 illustrates the variation of the Flame Color Ratio (FCR) over time, with the fuel flow rate being reduced by 0.1 liters per minute (lpm) every 60 seconds, while the air flow rate remains constant at 80 lpm. It is important to note that flame ignition begins only after the fuel and air flow rates reach the stoichiometric equivalence ratio. Initially, the FCR shows a higher value at an equivalence ratio of 1.0. As the fuel flow rate is gradually decreased every 60 seconds, the FCR changes only slightly, indicating that combustion remains stable and is not significantly affected by the reduction in fuel flow until the 200 second mark, where the equivalence ratio is around 0.828. However, as the fuel flow rate continues to decrease, the FCR drops noticeably during the period around 300 seconds, corresponding to an equivalence ratio of 0.79. The FCR further decreases to a lower value when the flame inside the combustor transitions to an oscillatory state at 432 seconds, when the equivalence ratio reaches 0.67. Finally, FCR approaches a lower amplitude near the conditions of lean blowout. Thus, a similar variation of $I_R/I_G$ can be found near the blowout as the ratio between red and blue color emission flame was reported in our previous literature [29].

### *4.2 Implementation of the smart control strategy for the premixed combustion*

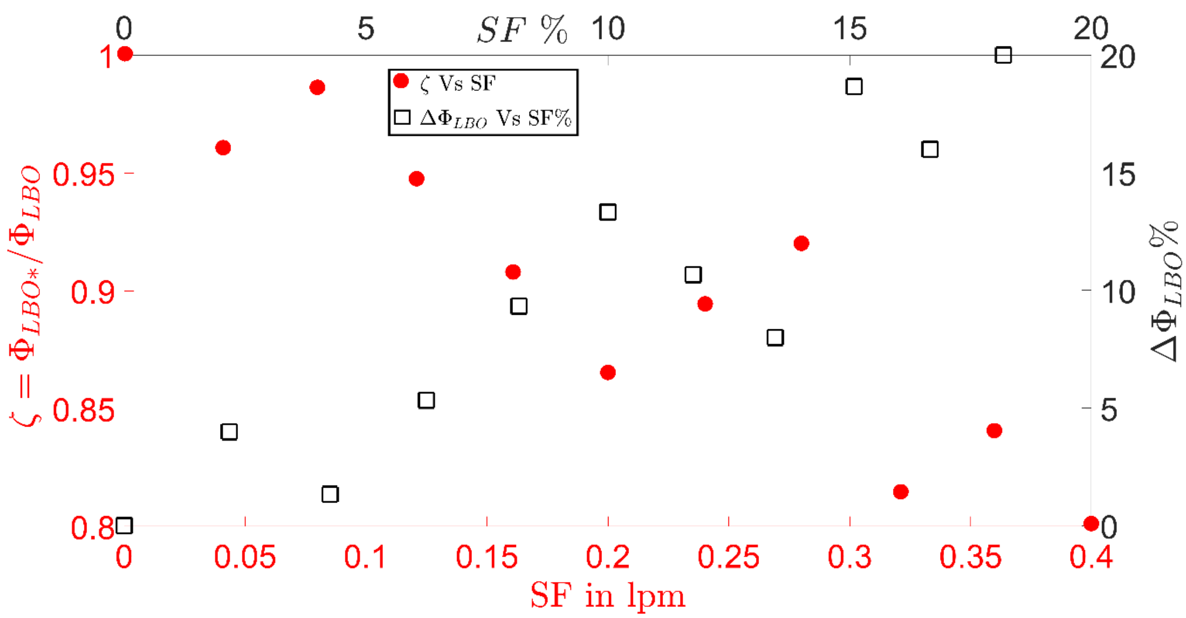


**Figure 6:** We test an online control method based on the threshold obtained from the ratio between red and green color emissions. The extension of the blowout limits are found for using staging fuel

injection at different values. We use a measuring index, $\zeta$, which can directly measures the extension of the blowout for using a particular mass flow rate value of staging fuel (SF). Note that this particular result is obtained when primary fuel is injected through F1 fuel port. A secondary, staging fuel is injected through F5 fuel port after the signal drops below the preset threshold.

Figure 6 illustrates the preview of the case studies used for staging injection through port F5, while the main fuel enters through port F1. Introduction of F1 signifies a greater degree of premixing, as quantified in our previous work [14]. In this context, combustion using the fuel port F1 demonstrates premixed combustion. The airflow rate remains constant throughout the transient process, and the primary fuel flow rate is decreased in steps over 60 seconds using the Flow Vision program. To simplify the strategy, it is proposed that continuous and constant staging injection will be maintained once the signal falls below a certain threshold. The threshold for current work is set at 0.79 of FCR, as illustrated in Figure 5. The combustion process begins near the stoichiometric condition and gradually transitions to the next condition as the fuel flow changes. There are two critical time instances to consider: the initial response (the time from ignition until control action is required) and the lead time (the duration from the start of control to the blowout of the modified flame). The initial response typically averages 432 seconds, with a tolerance of $\pm$ 20 seconds. Interestingly, as the percentage of staging fuel increases, the lead time is modified, suggesting a positive outcome for applying the algorithm in the staging injection configuration.

Figure 6 vividly illustrates a derived a measure, $\zeta = \Phi_{LBO*}/\Phi_{LBO}$ ($\Phi_{LBO*}$ indicates the global equivalence ratio when staging injection SF is on, $\Phi_{LBO}$ indicates the global equivalence ratio when SF is off) that directly evaluates the extension of the blowout limit. $\Phi_{LBO*}$ is calculated as:

$$\Phi_{LBO*} = \frac{(m_A/m_F)}{(m_A/m_F)_{st}} \tag{1}$$

Here, mass flow rate of fuel, $m_F = m_{PF} + \ m_{SF}$. $m_{SF}$ and $m_{PF}$ indicate the staging fuel flow rate and primary fuel flow rate, respectively. $(m_A/m_F)_{st}$ indicates the air-fuel mass flow rate ratio at stoichiometric or chemically correct condition. On the other hand, in the calculation of $\Phi_{LBO}$, $m_F = m_{PF}$ .

A value of $\zeta$ below 1.0 indicates an extension of the blowout limit, while a value of 1.0 or higher of this measure suggests that the control method is ineffective. During the staging operation, an observable trend emerges: this measure consistently declines below 1.0. Although there are occasional points in the staging injection process where the ratio experiences slight, temporary increases, the overall trend is a steady decrease as the quantity of staging fuel increases. Notably, the value of this measure remains below 1.0 when considering all amounts of staging fuel. The gradual decline implies a strong relationship between the quantity of staging fuel and $\zeta$. Additionally, the percentage change in the LBO ($\Delta\Phi_{LBO}$) is clearly presented on the right vertical axis of the figure, while it is plotted against the staging fractions (SF) displayed on the top X-axis, highlighting the importance of this strategy in understanding the efficiency of the staging process. This $\Delta\Phi_{LBO}\%\ Vs. SF\%$ analysis clearly shows the estimation of extension of blowout limits ($\Phi_{LBO} - \Phi_{LBO*}$) for different percentage of staging fuel injections. SF% or percentage of staging fuel injection is calculated as:

$$SF\% = \frac{m_{PF}}{m_{PF} + m_{SF}} * 100 \qquad (2)$$

***4.3 Implementation of the smart control strategy for the partially premixed combustion***

Figure 7 showcases a compelling preview of the case studies focused on staging fuel injection through port F5 while utilizing the main fuel entrance at F3. The incorporation of fuel via F3 highlights a significant variation in premixing levels relative to F1, underscoring the effectiveness of partially premixed combustion [14]. Notably, as the proportion of staging fuel rises, the lead time for deploying the main fuel through port F3 is greatly extended compared to F1. This pattern indicates that the staging action becomes increasingly vital much earlier for F3 than anticipated when using F1. Comparing with the findings from premixed combustion scenarios, the measured value $\zeta$ also declines sharply below 1.0 for all staging fuel injections in case of partially premixed flames. Consequently, the proposed method presents a robust solution for preventing lean blowout in partially premixed combustion, making it a valuable advancement in the field.

In a nutshell, we observe the substantial extension of blowout limits across all selected constant staging fuel flow rates in both premixed and partially premixed combustion. This finding also underscores the effectiveness of our approach and its potential for advancing combustion efficiency.

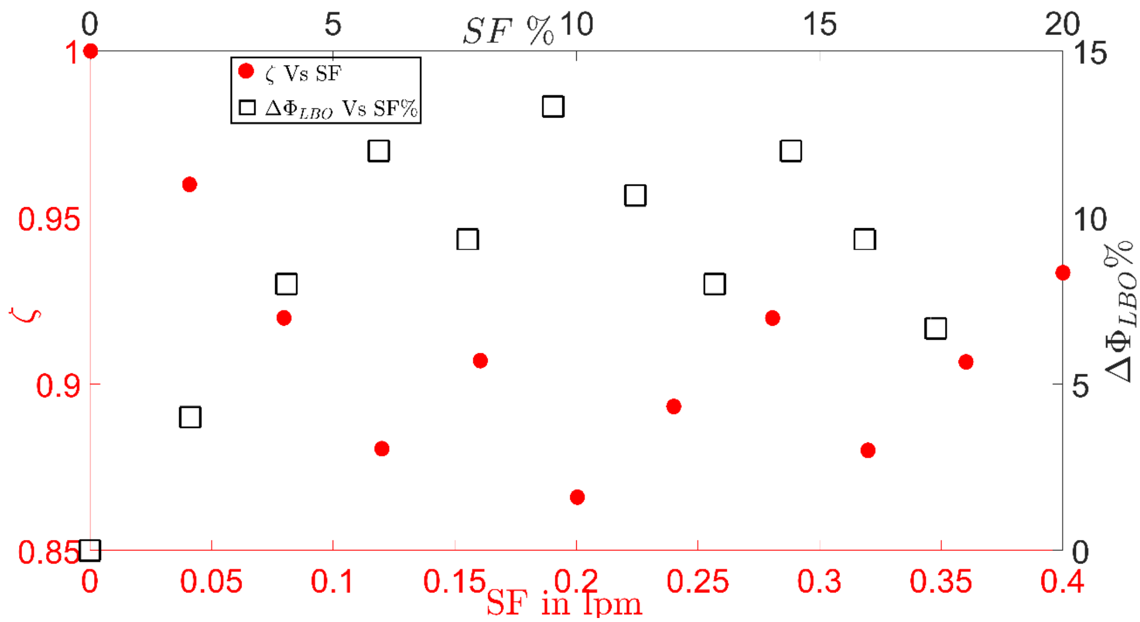


**Figure 7:** We test an online control method here when the F3 fuel port is used as the primary fuel injector and F5 fuel port is used as the staging fuel injection. For such scenario, the extension of the blowout limits are shown for using staging fuel injection at different values.

### *4.3 Discussion on the implementation of the strategy on the stabilization of non-premixed combustion*

By analyzing the declining trend of $\zeta$ with increase in SF for both F1 and F3 cases, the overall performance of the staging operation with F3 is not as high as that of F1. However, combining F3 with staging through F5 significantly improves flame stability. The slightly higher heterogeneity in the main fuel-air mixture, compared to F1, is likely due to a shorter premixing length. This increased heterogeneity may limit the further enhancement of the blowout limits compared to F1. Despite this limitation, the staging operation can produce a notable signature for coarse fuel-air mixtures, which is crucial for aero-engine and modern industrial applications where minimal heterogeneity is preferred for stable combustion. Additionally, this method can be very beneficial for controlling lean blowout (LBO) in higher premixed flames. While the effectiveness of this approach is somewhat reduced for partially premixed combustion, staging injection can still be effectively applied to highly premixed and moderately coarse premixed flames. However, there is a limit to this strategy, as it can only be implemented to a certain extent with lower levels of premixing.

## 5. Conclusion

In this work, we propose a smart control strategy to monitor the blowout limits in gas turbine combustion. This strategy is based on the sensitivity of RGB color response to changes in flame behavior as it approaches lean blowout, along with the idea that heterogeneity in the fuel–air mixture enhances flame stability. We extract the red and green emissions from the flame and calculate the ratio between these two colors. This color ratio serves as an index for monitoring flame behavior. According to our strategy, when the color ratio drops below a certain threshold, a secondary fuel will be introduced through a fuel port with a relatively lower degree of fuel–air mixing. Meanwhile, the primary fuel enters the premixing chamber through a fuel port that allows for a higher degree of mixing. Our findings indicate an extension of blowout limits of up to 20% for premixed combustion and 14% for partially premixed combustion towards lower equivalence ratios. We believe that the strategy proposed and discussed here has the potential to be useful in both aero- and land-based engines.

### *Author contribution*

**Somnath De** – Conceptualization (equal); Methodology (lead); Formal analysis(lead); Data curation (lead); Original draft writing (lead) Draft editing and reviewing (equal); Fund acquisition (equal); Project supervision (equal)

**Arijit Bhattacharya** – Draft editing and reviewing (equal)
**Achintya Mukhopadhyay** – Conceptualization (equal); Draft editing and reviewing (equal); Fund acquisition (equal); Project supervision (equal)
**Swarnendu Sen** – Conceptualization (equal); Draft editing and reviewing (equal); Fund acquisition (equal); Project supervision (equal)

### *Competing interests*

The authors declare no competing interests.

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### *Ethical approval*

Not applicable for our work.

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