Abstract. Next generation modern aircraft gas turbine engines (GTE) should provide ultra-low emissions, higher operating efficiencies and cost-effective production and use of energy with decreased emissions at local and global levels. However, the combustors particularly developed for ultra-low NOx emission combustors being developed for aircraft gas turbine engines are more susceptible to combustion instabilities. Premixed combustion systems have the capability to meet future regulations on NOx emissions. However, premixed systems always involve the risk of flame flashback into the premixing section. From a gas turbine manufacturer’s point of view, it is required to enlarge the safe operating range, in particular with respect to flame flashback. The significance of these flashback phenomena is a strong function of fuel composition and operating conditions. In the literature, flashback along the wall boundary layer shows the most critical failure mechanism for many burner configurations using hydrogen-rich fuels. Therefore, in the past few years, Government, academia and several industries conducting extensive research in this area for the introduction of green technologies as lean fuel combustion and premixed burners in aero-engines. Therefore, this review paper focus on flashback propensity mechanisms in more detail and the conclusions are drawn as to mitigation technologies.

1. Introduction
The impact of aircraft pollutant emissions on human-induced climate change has gotten to be a serious concern in the last few decades. The limiting of pollutant emissions, such as CO2 and NOx, becomes one of the major obstructions in the manufacturing of a gas turbine engine. One of the best methodologies to scale down these emissions is to design and the advancement of innovative propulsion systems. Besides that, the usage of alternative fuels, such as hydrogen and biofuels, are too impressive choices to take over current fossil fuels [1, 2]. The execution of new combustion techniques (e.g. Lean premixed prevaporized (LPP), Flameless combustion) probably improves the performance of GTE and reduces the emissions and excludes CO2 and NOx emissions. In any case, this method includes the plunge of flame flashback, particularly for fuels having high burning velocity such as hydrogen rich fuels. The Premixed combustion of hydrogen-rich gases remains a without a doubt challenging issue. [3]. Compared to hydrocarbon fuels, the reactivity of hydrogen is much higher because of its different physical and thermal properties such as smaller quenching distances, wider flammability limits, higher diffusivity, and greater flame speed [4]. Thus, the chances of a flame flashback into regions upstream of the desired flame position is essentially more prominent than in hydrocarbon applications. This applies to the regions where the flow velocity is low, for example, wake regions or in wall boundary layers. Flame flashback in an industrial application can start to combustion instabilities and harms the
equipment due to overabundance heating of machine components that are not outlined for excess temperatures, also it causes premature component wear that could lead to costly shutdown or engine failure. Subsequently, a comprehensive understanding of flashback mechanisms is significant for the security and unwavering quality of lean premixed combustion systems. From the resulting of vast literature research on flashback mechanisms, four reasons have been identified and they are explained below: [5]

(a) **Core Flow Flashback**: When the local flame speed surpasses the bulk flow velocity, this action drives to the flashback in the core flow. In turbulent flows, velocity fluctuations can raise this situation.

(b) **Flashback due to Combustion Instabilities**: The interaction of acoustic modes, flow variation and changes in heat release fluctuations can cause periodically flashback propensities.

(c) **Flashback due to Combustion Induced Vortex Breakdown (CIVB)**: In swirl-stabilized burners, a recirculation zone is made on the burner axis at the cross-sectional jump from the burner duct into the combustion chamber, which stabilizes the flame during standard operation. Under certain conditions, the interaction of heat release in the combustion chamber with vertical and turbulent structures in the burner duct can lead to the upstream propagation of the recirculation zone and the flame, provokes flashback.

(d) **Boundary Layer Flashback (BLF)**: Due to the non-slip condition flow speed diminishes constantly towards solid walls. If the flame speed at a certain distance from the wall exceeds the local flow velocity, the flame starts to propagate upstream along the boundary wall layer [6].

As this work mainly focuses on boundary layer flashback (BLF), the other flashback mechanisms will not be discussed. This paper summarizes the early and more recent findings concerning boundary layer flashback (BLF) mechanisms and suitable mitigation strategies.

2. **Boundary layer flashback**

Boundary layer flashback (BLF) mechanisms in laminar tube burner flames were already examined by Lewis and von Elbe in 1943 [8], they presented widely accepted critical gradient velocity concept. The below figure 1 described their perceptions. At enough high velocity, a steady laminar flame occurs at the burner exit (1). Near to the burner exit the reaction is suppressed due to large amount of heat losses to the wall and the flame root is bent outwards. If the velocity is further decreased, this outward bending is expanded up to some other parts in the flame front becomes perpendicular to the approaching stream.

![Figure 1. Boundary layer flashback of a laminar tube burner flame.](image)

(1): Stable flame, (2): flame at flashback conditions, (3): upstream propagating flame [8].

If this criteria continue beyond the wall distance of laminar flashback yFB, the l, the flashback limit is reached (2). Further reduction in the extension of the flow velocity leads to upstream flame propagation adjacent to the burner wall at yFB,l (3).

Numerous recent investigations and early flashback avoidance studies since decades proclaimed in the literature about the effect of confinement flame, tip temperature [9, 11] fuel composition and pressure [9]. It was identified that confinement flame considerably increases the plunge of boundary layer flashback. Also, flashback mechanisms depend on various parameters such as heating values, reaction rate and so on, which makes quite difficult to use of possible alternative fuels. Some of the
researchers have experimented with CO2 and N2 diluents to determine flame propagation for these fuels. Another important parameter in flashback propensity propagation is the geometry. If the small happened in the geometrical structure of the premixing tube such as diverging sections, steps, surface discontinuities, or fuel injecting method’s such as counter flow injection, diffusive penetration, etc., can allow serious changes in flashback performance [12].

2. 1 Parameters influencing boundary layer flashback (BLF)

There are several parameters which can trigger flashback propensity, some of them are explained above; as a result, isolating the effect of a specific variable is difficult. Therefore, overall parameters can be divided into the following groups:

- Flame configuration and boundary layer heating.
- Flow and combustion characteristics.

2.1.1 Flame configuration and boundary layer heating

Most of the researchers declared that confined flames are more bound to suffer from flashback propensity, besides that flame-wall interaction for confined flames acknowledged huge attention in the last few years in both numerical modeling and experimental studies. While the flame originates upstream in the confined configuration, the flame leading edge becomes bulged and impending towards the reactants, which increasing the flame stretch effect and the flame flow begins to slow down.

Burner heads designed for different alloys exhibit an unstable flashback propensity, the effect of thermal coupling between the flame and the burner head on flashback mechanism determined to be an influencing parameter. The dependency has been observed between flashback and the variables involved in the operation of the burners and construction. The product species and flame temperature also differ with fuel composition, and then impact the heat changes between the flame front and burner rim. The stable flame front schematic diagram is shown in Fig.2 (a), and also when the BLF limit is shown up, the flame propagates upstream into pre-mixed reactants can be seen in Fig. 2(b).

![Figure 2(a)](image1)

**Figure 2(a).** Flame configuration: (a) unconfined flame stabilized downstream of the pre-mixer tube [13]

![Figure 2(b)](image2)

**Figure 2(b).** Confined flame stabilized in a tube [13].

This causes burner tip temperature to alter based on the fuel compositions for a given equivalence ratio. The heat is conducted upstream together with the burner, generating the excess amount of heat from the wall to the incoming reactants. The boundary layer heating leads to a point of variation in the velocity profile, which can create the stream partition. Subsequently, flashback propensity is more apparent for uncooled burners. Unsteady changeover in working conditions for example, sudden drops in the reactant flow rate can also create BLF [13].

2.1.2 Flow and combustion characteristics
The bulk flow velocity directly impacts the BLF by altering the streamwise momentum near to the wall region. As the mean flow velocity increases, the local flame speed also increases in order to proliferate the upstream. Hence, flashback propensity occurs at fuel/air ratios close to those related to the maximum flame speed as the bulk flow velocity increases. Additionally, the velocity profile of the incoming flow, where the flame stabilizes, disrupts the flashback limits. For instance, it was observed experimentally that when the incoming flow is not fully advanced, the flashback propensity decreases because of the higher wall shear stress, which is an action of entrance length.

The BLF limit is very diverse under laminar and turbulent boundary conditions. The flame-wall interaction is indeed more complicated beneath turbulent conditions. Depending on the turbulent Reynolds number, the turbulent combustion regime manages the flame structure and characterize how the small-scale eddies relate with the flame. Thus, the turbulent flame speed is also dependent on turbulence intensity. Therefore, higher turbulence intensity consequence to higher flashback propensity. Combustion characteristics of premixed flames also rely on the fuel composition. The burning velocity mixture shows a crucial role in activating the flashback and is mainly a function of chemical kinetic mechanisms. Besides that, the thermal and radical quenching by the wall differs with different fuel compositions which leads to different flashback limits. The high flashback propensity of hydrogen mixtures is an outcome of small quenching distance and high rise in burning velocity [13].

3. Mitigation strategies to avoid boundary layer flashback (BLF)

Improving gas turbine engine flexibility to use distinct potential candidate fuels is a big challenge for both the manufacturers and designers when working with present operation stability issues. Flashback propensity is quite challenging for developing low NOx premixed combustion of high hydrogen content fuels. In this section, some of the control parameters and mitigation strategies which can resist boundary layer flash back (BLF) are summarized from the latest available literature.

The well-known critical gradient concept of Lewis and von Elbe used these assumptions, such as laminar burning velocity, burner diameter (d) and the wall distance of flashback, but they didn’t consider the vital significance of flame stretch on the burning velocity explained by Hoferichter et al., 2018. For that reason, they developed modified prediction models for confined and unconfined flames. However, they claimed that the outcome of flame stretch is an important parameter to identify BLF limits exclusively for highly reactive fuels, such as hydrogen. The additional parameter which is used in the modified predictive model is that “susceptibility of a given fuel-oxidizer mixture to flame stretch is included via its Markstein length”.

![Figure 3(a). Flashback limits of laminar hydrogen-air flames calculated with the modified prediction model and compared with the critical gradient concept for different burner diameters [14].](image1)

![Figure 3(b). Flashback limits of laminar methane-air flames calculated with the modified prediction model and compared with the critical gradient concept for different burner diameters [14].](image2)
To confirm the developed prediction model, the authors compared the computed flashback limits of both the model and are correlated with experimental data for hydrogen-air and methane-air mixtures can be seen in the above fig. 3 (a) and fig. 3(b). The effect of including flame stretch, Markstein length and the main parameters used in the prediction model for laminar flows leads to good propagation of experimentally determined flashback limits of hydrogen-air as well as methane-air jet flames. [14] Although plenty of research studies in the literature focused on BLF, limited experiments have concentrated on flashback propensity at high pressures. Flashback propensity accelerates at high pressures due to small quenching distances and maximum turbulent burning velocity. Therefore, tools to anticipate BLF at actual gas turbine engine working conditions (high pressure and temperature) is of high interest. The author’s kalantari et al., 2018 performed an experiment for a boundary layer flashback. The boundary layer flashback of an injector from a commercial 65 kW microturbine generator (i.e., a Capstone C-65 MTG) operated on hydrogen is studied at pressures and preheat temperatures between 2-7 atm and 390-610 K.

In this process, they were utilized two injectors used (a) original injector and (b) retrofittable flashback resistance injector. In both the cases, the fuel is injected in the axial direction in a series of air jets introduced via radial passages. The main target of this orientation is intended to advance rapid mixing of a fuel. The original injector was being basically planned to create a uniform fuel/air mixture at the exit plane to reduce outward emissions. However, the main objective of the modified injector is to avoid flashback by limiting fuel near the outer wall [15].

![Figure 4](image-url)

**Figure 4.** (a) Original injector and (b) flashback resistant injector [15]

The equivalence ratio at flashback for the original injector managed on pure hydrogen as a function of pressure for various preheat temperatures (420-620K). The bulk flow velocity at the injector is 50 m/s for all the cases. They noticed that for a given preheat temperature, an increase of pressure decreases the equivalence ratio at which flashback pops up. This is due to the lower quenching distance and maximum turbulent burning velocity at higher pressures. The authors found that, simply increasing the bulk flow velocity of the original injector for a given equivalence ratio is not enough to avoid flashback propensity. Altering the bulk flow velocity has only a less effect on reducing BLF propensity. Another good technique is to lean out the fuel/air mixture near the wall, which had been demonstrated to be competent in an idealized premixing tube in [16]. The tests were conducted for the flashback resistant injector at various operating conditions. Flashback was not recognised even for extreme case ($P_u = 7$ atm, $T_u = 600 \text{ K}, \phi = 0.7$) [15].

In the below figure, CFD computed hydrogen/air mass ratio at the exit plane of the injectors can be seen. The hydrogen/air mass proportion is nearly same across the initial injector, showing a decent mixing level. But, the original or initial injector prone to flashback at actual working condition due to the presence of high hydrogen concentration in the near-wall region. In a contrary, the flashback resistant injector, produced a non-uniform hydrogen/air concentration at the exit plane. The concentration is more
at the center line, while it drops suddenly in the vicinity of the wall. This confirms that the flame, no longer exhibits upstream in the near-wall region, although the relative flow velocity is somewhat low in that area and avoids flashback propensity.

Figure 5. Contour of hydrogen/air mass ratio of the exit plane: (a) original injector and (b) flashback resistant injector [15].

As discussed in the previous section, burner geometries play a crucial role in the stable combustion operation. The interaction of the geometries with the swirling flows can essentially alter the flow field characteristics. Flashback propensity mechanisms in swirl combustors are complex and it’s difficult to achieve acceptable flame flashback resistance, change in geometry changes should be able to reduce the effects forced by different flashback mechanisms.

Mohammed Al-Fahham et al 2017 proposed a new technique called Biomimetic Engineering has been developed to use microsurfaces to achieve this aim. The advantage of these biologically designed shapes can be seen in the below fig.6 and fig.7 for the outstanding flow stabilization allows improved control of the boundary layer flashback.

Figure 6. Steel wire micromesh underlying nozzle inner wall [17]

Figure 7. The Structure of wire micromesh (up) lotus ribblet structure (down) [17]

The advantage of ribblet microstructures is that, decreases skin friction drag by regulating the naturally acquiring turbulent velocities which tend to decrease shear stress and momentum transfer. The
capability of ribblets on drag reduction is directly related to their shape. In their research they were introduced three configurations and are as follows: Configuration a) the swirl burner with no central air injection and no micromesh; Configuration b) the swirl burner with no central air injection and the micro surface located at the nozzle; Configuration c) the swirl burner with central air injection and the micro surface at the nozzle and this concept was examined both numerically and experimentally in a 150 kW tangential swirl burner. As can be seen from the Figure 8, when the grid is not used, stability region lies in between the range $\Phi=0.45-0.65$, then boundary layer flashback occurs at higher tangential velocities, due to the absence of a damping mechanism against BLF, flashback occurs earlier.

![Figure 8](image)

**Figure 8.** Comparison between with and without micro surface (grid) [17]

The Figures 9a and 9b show the alter in the flame flashback tendency when the nozzle inside surface is covered by the microsurface. The outcome shows the improved flame flashback avoidance, with tangential velocities of $W_t= 2.8$. Thereafter condition no flame flashback is seen over the ranges when tested the microsurface [17].

![Figure 9(a)](image)

**Figure 9(a).** Flashback trend using different configurations; a) central air injection without grid.[17]

![Figure 9(b)](image)

**Figure 9(b).** Flashback trend using different configurations; b) combined central air injection and grid.[17]

4. Conclusions

Designing the gas turbine engine in a sustainable and eco-efficient manner is a challenging task for manufacturers due to thermo-acoustic instabilities. The Boundary layer flashback is one of the drawbacks to introduce green technologies as lean fuel combustion and premixed burners in aero-engines. This review paper focused on the effects of different parameters like preheat temperatures, burner materials, change in geometry structures, operating pressures and how they influenced boundary layer flashback mechanism. The main goal of this paper is to identify some of the best possible mitigation strategies to avoid BLF from the available literature. This helps to understand the instability behavior of lean flame and enlarge the stability region of lean gas turbines.
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Acknowledgments
The Ministry of education and science of the Russian Federation in the framework for implementation of the Program for increasing the competitiveness of Samara University among the world leading scientific and educational centres for 2013-2020 years supported this work.