Turbulent Flame Speed as an Indicator for Flashback Propensity of Hydrogen-Rich Fuel Gases

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The turbulent flame speed (S_T) is proposed to be an indicator of the flashback propensity for hydrogen-rich fuel gases at gas turbine relevant conditions. Flashback is an inevitable issue to be concerned about when introducing fuel gases containing high hydrogen content to gas turbine engines, which are conventionally fueled with natural gas. These hydrogen-containing fuel gases are present in the process of the integrated gasification combined cycle (IGCC), with and without precombustion carbon capture, and both syngas (H_2+CO) and hydrogen with various degrees of inert dilution fall in this category. Thus, a greater understanding of the flashback phenomenon for these mixtures is necessary in order to evolve the IGCC concept (either with or without carbon capture) into a promising candidate for clean power generation. Compared to syngas, the hydrogen-rich fuel mixtures exhibit an even narrower operational envelope between the occurrence of lean blow out and flashback. When flashback occurs, the flame propagation is found to occur exclusively in the boundary layer of the pipe supplying the premixed fuel/air mixture to the combustor. This finding is based on the experimental investigation of turbulent lean-premixed nonswirled confined jet flames for three fuel mixtures with $H_2>70$ vol. %. Measurements were performed up to 10 bar at a fixed bulk velocity at the combustor inlet ($u_0=40$ m/s) and preheat temperature ($T_0=623$ K). Flame front characteristics were retrieved via planar laser-induced fluorescence of the hydroxyl radical (OH-PLIF) diagnostics and the turbulent flame speed (S_T) was derived, accordingly, from the perspective of a global consumption rate. Concerning the flashback limit, the operational range of the hydrogen-rich mixtures is found to be well represented by the velocity gradients prescribed by the flame (g_c) and the flow (g_f), respectively. The former (g_c) is determined as $S_T/(Le\times\delta_{L0})$, where Le is the Lewis number and δ_{L0} is the calculated thermal thickness of the one-dimensional laminar flame. The latter (g_f) is predicted by the Blasius correlation for fully developed turbulent pipe flow and it indicates the capability with which the flow can counteract the opposed flame propagation. Our results show that the equivalence ratios at which the two velocity gradients reach similar levels correspond well to the flashback limits observed at various pressures. The methodology is also found to be capable of predicting the aforementioned difference in the operational range between syngas and hydrogen-rich mixtures. [DOI: 10.1115/1.4025068]

Introduction

To mitigate the CO_2 emissions from the power generation sector, process configurations combined with various technologies of carbon capture and sequestration have been proposed. One of the alternatives is the concept of integrated gasification combined cycle (IGCC), which is essentially based upon the combustion of fuel mixtures derived from the gasification of solid fuels. These mixtures mainly consist of H_2 and CO (syngas) with various degrees of inert dilution (N_2 and CO_2). Depending on the feedstock and the gasification process, the volume compositions (e.g., the H_2-to-CO ratio) vary. If precombustion carbon capture is additionally implemented, the H_2 content may reach almost 100 vol. % in the fuel gas. Challenges arise when burning these so-called "H_2-rich" fuel gases (with the hydrogen content typically over 70 vol. %) instead of natural gas in the lean-premixed gas turbine combustor and one of the operability issues is the higher propensity of flashback [1]. Accordingly, in order to materialize the IGCC concept with or without carbon capture, more understanding on the combustion characteristics and flashback phenomena of the H_2-rich fuel gases is essential.

The term "flashback" is generally defined as the phenomena that the flame propagates upstream of the location where it is supposed to anchor and enters the premixing passage [1]. In the review paper by Lieuwen et al. [1], four mechanisms of flashback relevant to steady flowing combustors are categorized and discussed. While *the turbulent flame propagation in the core flow*, *the flashback due to combustion instabilities*, and *the flashback in the boundary layer* may occur in both nonswirling and swirling flows, *the flashback in the core flow due to alteration of vortex breakdown dynamics* is exclusively observed in the swirling condition. Specifically for the flashback that advances in the boundary layer, it is indicated in Ref. [1] that adding a small amount of air along the burner wall (the "effusion" technique), which effectively suppresses the flashback of natural gas, may be insufficient when dealing with the H_2-rich fuel gases.

This effusion technique is actually linked to the general concept of the "critical velocity gradient," which was first proposed by Lewis and von Elbe [2] for the laminar pipe flow. The study on the laminar flames was carried out with a tube burner and it is stated that the tube wall not only reduces the gas velocity by friction, but also reduces the burning velocity by its quenching effect on the explosive reaction. For a fixed composition of the combustible mixture, a certain level of gas velocity has to be kept in order to prevent flashback. With the presence of an established flame, flashback occurs if the burning velocity exceeds the gas velocity somewhere in the stream and the critical condition can be

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predicted by the velocity gradient at the wall of the burner tube. By gradually reducing the gas velocity, the critical value upon which the flashback occurs is reached. This critical gas velocity is then used to evaluate the "critical velocity gradient" according to the characteristics of laminar tube flow. The gradient principle was further extended by Putnam and Jensen [3], in which the Peclet number was implemented to correlate the flashback data. Note that although modifications on the gradient principle might be necessary to better describe the turbulent boundary layer flashback, the aforementioned effusion technique is essentially based upon the same concept. The burning velocity (or even the flammability) of the combustible mixture close to the wall is decreased by the dilution, so that the critical value of the velocity gradient shall never be exceeded. Similarly, the flashback propensity in the boundary layer can be mitigated by adding momentum to the flow in the near wall region, such as the plasma actuation control introduced by Versailles et al. [4].

It is suggested that more investigations are required to verify whether the concept of the critical velocity gradient is still valid for the flashback within the turbulent boundary layer [1]. If so, then it turns to the issue of which velocity and length scales are capable of providing an appropriate and representative velocity gradient. The critical velocity gradient is generally considered to be proportional to the burning velocity divided by the "penetration" distance [5], which stands for the height from the wall where the velocities of the flame and the flow match. Compared to the laminar case, it is found that the turbulent flashback takes place at a considerably higher average velocity than that prescribed by the gradient principle [5]. In other words, the critical velocity gradients at flashback are significantly increased when the flow conditions are changed from laminar to turbulent [6–10]. Accordingly, the increase in the critical velocity gradient may be attributed to the decreased penetration distance, the increased burning velocity, or the combined effect of both. If the burning velocity is still assumed to be the laminar flame speed [7–9], the penetration distance will become less than the thickness of the laminar sublayer [11]. The turbulent burner flame near flashback is then considered to be stabilized under laminar conditions. On the contrary, the possibility of an increase in burning velocity is also addressed in Refs. [5,6,12]. In this case, the turbulent flashback is not necessarily caused by conditions in the laminar sublayer and the turbulent flame speed is proposed to be a candidate for characterizing the increased burning velocity [12].

Specifically for the hydrogen-containing or hydrogen-rich mixtures, the issue of boundary layer flashback has been investigated in some recent studies [10,13–15]. From the perspective of fuel compositions, it is found that the flashback behavior is dominated by the hydrogen content [10,16,17]. This is attributed to the fact that for the combustible mixtures containing hydrogen, the mass and thermal diffusivities strongly differ among the components. Under lean conditions, these mixtures can be characterized by the less-than-unity Lewis number ($Le < 1$), which is defined as the thermal diffusivity of the mixture divided by the mass diffusivity of the deficient species. The flame propagation is facilitated since the flame front is enriched with the limiting component (hydrogen) and the critical velocity gradient for flashback is found to be increased with decreasing Lewis number [5,18,19]. On the other hand, concerning the validity of the gradient principle, it is proposed that the outer regions of the boundary layer should also be taken into account to better predict the flashback propensity in turbulent boundary layers [14,15]. A confinement of the stable flame is found to modify the pressure boundary conditions and the flashback limits are shifted accordingly. In summary, there is still a lot to be explored about the flashback phenomena in the turbulent boundary layer for the H_2-rich fuel gases. As indicated in Ref. [12], more reliable turbulent flame speed data are needed to justify the rationale that the increased critical velocity gradients at flashback are mainly attributed to the increased burning velocity. A robust methodology of evaluating the turbulent flame speed for the hydrogen (-rich) fuel gases shall facilitate the understanding on this issue.

The turbulent flame speed itself remains a topic of interest within the combustion community [20–23]. The recent work by Kobayashi et al. [20] focuses on the turbulent premixed flame characteristics of several model syngas relevant to the gasification of coal. The effects of the turbulent Reynolds number on the turbulent flame speed are emphasized. Based on the measurements performed with the implosion technique, correlations of turbulent burning velocities at elevated pressure for various fuel gases are proposed by Bradley et al. [21]. The Karlovitz stretch factor is implemented to correlate the normalized burning velocities and the effects of various strain rate Markstein numbers are found to be well represented via this approach. On the other hand, scaling laws of the turbulent consumption speed for various syngas mixtures are presented in Refs. [22,23], which are derived from the perspective of the leading point concept. The maximum stretched laminar flame speed is claimed to be a more appropriate normalizing factor and the pressure sensitivities are found to be better correlated by the ratio of chemical to flow time scales. Nonetheless, it is worth noticing that relatively few investigations dedicated to the evaluation of the turbulent flame speed for H_2-rich fuel gases at gas turbine relevant conditions (preheated and high pressure) are available in the literature [24–26].

In our earlier investigation [26] on the turbulent lean-premixed nonswirled confined jet flames of H_2-rich fuel gases, the operational range of these mixtures were compared with that of syngas [27]. For the syngas (H_2-CO 50%-50%), while the limits for lean blow out are found to be roughly constant over a wide range of pressures, the flashback limits are significantly shifted to leaner conditions at higher pressure. Although the flashback limits for the H_2-rich mixtures were not specifically determined due to safety concerns, it was found that the length of the flame may correlate well with the flashback propensity. The length of the flame becomes shorter when the equivalence ratio becomes richer. Flashback is observed if the fuel flow is further increased after the flame becomes shorter than twice the diameter of the combustor inlet (d). At higher pressure levels, the flames approach a similarly short length at much leaner conditions. The corresponding equivalence ratios are considered to be the approximate flashback limits and these limits are found to be much leaner than those of the syngas (H_2-CO 50%–50%). It should be noted that under the specific burner configuration and boundary conditions, the flame propagation at flashback was found to occur exclusively within the boundary layer [27], as evidenced in Fig. 1.

Figures 1(*a*) and 1(*b*) show the instantaneous false-colored images based on the planar laser-induced fluorescence of the hydroxyl radical (OH-PLIF) for a stable and an "anchored" H_2-rich flame, respectively. Under this specific condition (10 bar, equivalence ratio $\Phi \sim 0.3$), a stable flame is slightly detached, as shown in Fig. 1(*a*). This is in contrast to the anchoring of the flame in Fig. 1(*b*), which is considered as a prelude to flashback. The flame front seems to be attached to the wall of the premixing pipe somewhere upstream of the combustor inlet and this observation is consistent with the characteristic of the boundary layer flashback. The absence of the OH-PLIF signal in the core region of the flow also rules out the possibility of turbulent flame propagation in the core flow. Accordingly, the concept of the critical velocity gradient is chosen as the starting point for the discussions in the present paper. An attempt is made to inspect the observed operability issue and flashback phenomena of the H_2-rich fuel gases [26] from the perspective of turbulent flame speed. The same approach will also be implemented to revisit the syngas data in [27,28], in which the flashback limits were specifically determined.

Experimental Setup

The experimental investigation was carried out in an axial-dump combustor that is installed within a high pressure vessel

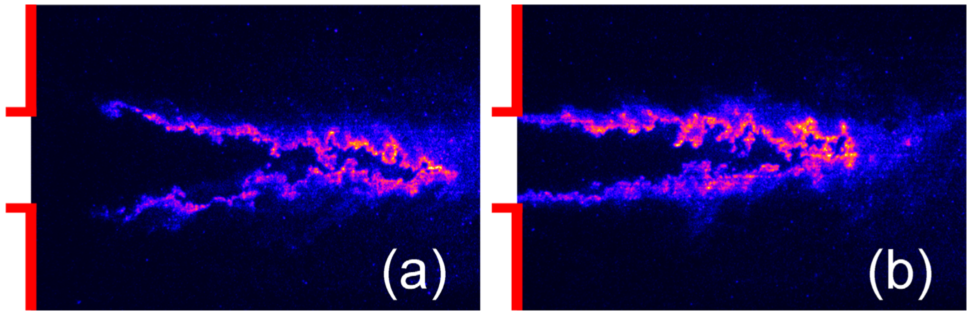

Fig. 1 (*a*) Stable, and (*b*) "anchored" flames. The red bars indicate the boundaries and inlet of the combustor.

(see Fig. 2). The rig can be operated up to 20 bar, with the maximum air mass flow rate of 750 m_N^3/h (0.3 kg/s) and the maximum preheat of 823 K. The corresponding maximum thermal power is 400 kW. The optical access for laser diagnostics is provided by the cylindrical liner consisting of two coaxial quartz glass tubes, which are convectively cooled by air. The diameter of the inner quartz glass tube (D) is 75 mm and the diameter of the combustor inlet (d) is 25 mm. The fuel is injected 400 mm upstream of the combustor inlet and mixed with the preheated stream of air. The premixed combustible mixtures are issued from a circular pipe ("premixing pipe") that forms part of the axial-dump combustor. Good mixing is achieved by the long premixing passage, which is evidenced by the analysis on the NO_x emissions [26,29].

At the beginning of the operation, the combustible mixtures are ignited by a hydrogen torch flame. The torch is switched off after successful ignition and the flame is stabilized by the recirculation of hot flue gas. Three H_2-rich fuel gases (H_2-N_2 70-30, H_2-N_2 85-15, and pure H_2; numbers are in vol. %) were investigated. Measurements were performed up to 10 bar at fixed bulk velocity at the combustor inlet ($u_0 = 40$ m/s) and preheat temperature ($T_0 = 623$ K). Concerning the investigated conditions, the Reynolds number based on u_0 and d ranges from 15,000 to 160000, which indicates the highly-turbulent nature of the flow. To investigate the characteristics of the flame front, planar laser-induced fluorescence of the hydroxyl radical (OH-PLIF) is utilized. For more details about the setup of the laser diagnostics, the interested reader is referred to Refs. [24,30].

During the whole operation, the aforementioned "effusion" technique has been implemented as a passive measure to avoid the occurrence of flashback. To dilute the combustible mixture adjacent to the wall of the premixing pipe, nitrogen is injected from an annular slot located 15 mm upstream of the combustor inlet [27]. The amount of nitrogen injected was always kept below 1% of the preheated air stream and it has been verified that the flame geometry is not appreciably influenced [28]. At the surface of the section between the annular slot and the combustor inlet, the oil-lampblack technique was applied to inspect the mean shear stress distribution in the boundary layer. The mixture for the surface streak visualization was similar to that implemented by Hale et al. [31]. Preliminary results show that the injected nitrogen does not alter the patterns of the surface streak in a discernible way either. Nonetheless, while the effusion technique was considered effective in reducing the flashback propensity for syngas [27], the operational range of the H_2-rich fuel gases did not seem to benefit significantly from this measure.

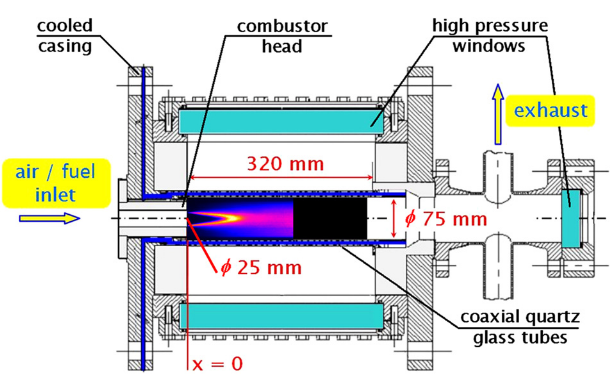

Fig. 2 Schematic of the high-pressure combustor

Flashback Criterion Based on Critical Velocity Gradients at Wall

In order to understand the observed flashback phenomena in the present rig configuration and boundary conditions, the concept of the critical velocity gradient is selected as the starting point for the following discussion. Upon the occurrence of the turbulent boundary layer flashback, the velocity gradient represented by the flame front characteristics exceeds that of the near-wall flow within the premixing pipe and the flame is able to penetrate upstream in a thin layer close to the wall. To compose a velocity gradient, both a characteristic velocity scale and a length (thickness) scale are both required. In the present work, the turbulent flame speed (S_T) and the unstretched laminar flame thickness (δ_{L0}) are proposed to be the characteristic velocity and length scales, respectively.

Characteristic Velocity Scale: Turbulent Flame Speed (S_T). In this work, the turbulent flame speed (S_T) is derived from the perspective of a global consumption rate. For each of the test conditions (namely, various pressure levels and equivalence ratios), 400 planar instantaneous contours of OH-PLIF were acquired to ensure good statistics. The instantaneous flame fronts were retrieved via a specific routine that incorporated the concept of a geometrically nonuniform threshold [32]. By summing up the instantaneous flame fronts, the location and distribution of the combustion wave can be deduced. The progress variable (c) approach was implemented as a measure for normalization and the iso-contour of $c = 0.05$ was defined as the representative flame front ($c = 0$ and 1 corresponded to the unburned and burned side, respectively). The choice on the progress variable $c = 0.05$ was specifically defined to be compatible with that of the laminar flame speed, which always refers to the unburned mixture. Based upon the assumption of an axial-symmetric flame, the surface area of the flame was evaluated by rotating the representative flame front with respect to the combustor centerline (x-axis). Accordingly, the S_T was derived by solving the continuity equation that correlates the mass flow at the combustor inlet and the mass flow at the flame front surface. For convenience, the "flame length" ($F_L^{\langle c=0.05 \rangle}$) was defined as the distance between the combustor inlet and the axial location at which the representative flame front crosses with the combustor centerline.

It has been pointed out earlier that the flame length may provide a good indication for the occurrence of flashback. But is the length

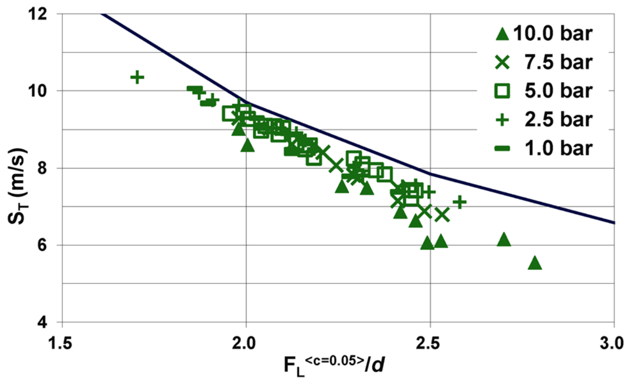

Fig. 3 S_T versus the normalized flame length for the fuel mixture H_2-N_2 85-15

itself relevant to other characteristics of the flame? For the H_2-rich mixtures, the representative flame front in the geometric configuration used (dump combustor) generally approaches the profile of a perfect cone [26]. This is evidenced in Fig. 3, in which the S_T is plotted against the normalized flame length ($F_L^{\langle c=0.05\rangle}/d$) for the fuel mixture H_2-N_2 85-15 (85 vol. % H_2 and 15 vol. % N_2). The curve in blue represents the S_T if the flame front exhibits a perfectly conic profile. Similar phenomena were also observed for syngas flames [24], but the representative flame front deviates more strongly from the conic condition as the flame becomes longer (e.g., $F_L^{\langle c=0.05\rangle}/d>2.5$). Accordingly, the S_T can be well-correlated with the flame length for both the H_2-rich and syngas flames that are relatively short.

As previously reported, flashback occurs when the flame becomes shorter than twice the diameter of the combustor inlet ($F_L/d<2$). From Fig. 3, the maximum S_T before flashback is on the order of 10 m/s and this value is found to be very close to the velocity evaluated at the boundary of the viscous sublayer within the premixing pipe. This observation serves as a link among the flame length, the S_T, and the flashback propensity. At the critical condition ($F_L/d\sim 2$), the flame propagation within the boundary layer is facilitated by the high S_T, which is approaching the velocity at the boundary of the viscous sublayer. Accordingly, it is proposed here that the S_T can be implemented as a representative velocity scale in the concept of the critical velocity gradient. Note that the S_T is much less than the bulk velocity at the combustor inlet ($u_0=40$ m/s). This is again in support of the statement that the flashback does not occur in the core flow under the investigated conditions.

Characteristic Length Scale: Laminar Flame Thickness (δ_{L0}). Besides the velocity scale, a representative length scale is also required to composite a velocity gradient. Various length scales of the flame front with the presence of cool walls as boundaries, which are relevant to the flashback phenomena, were addressed by Wohl [5]. It was found that the penetration and the quenching distances for hydrogen and for hydrocarbon fuels are roughly on the same order of magnitude as the flame front thickness. In the present study, no specific effort was devoted to the determination of the penetration distance. Instead, the thermal thickness of the unstretched one-dimensional laminar flame (δ_{L0}) is used as a reference. This is defined as the temperature rise from the preheat (T_0) to the adiabatic flame temperature (T_{ad}) divided by the maximum temperature gradient normal to the flame front. In order to derive the δ_{L0}, chemical-kinetic calculations for the freely-propagating one-dimensional adiabatic unstretched laminar premixed flames were performed with the open-source software tool CANTERA [33]. The reaction mechanism developed by Li et al. [34] was implemented to derive the relevant combustion properties, such as the aforementioned unstretched laminar flame thickness (δ_{L0}) and the unstretched laminar flame speed (S_{L0}). The reaction scheme was specifically selected to provide a more reliable estimation of the properties of interest for the H_2-rich fuel mixtures [35]. It can be shown that similar results were obtained via adopting the more recent kinetic model by Burke et al. [36].

Velocity Gradient of the Flame: g_c. By incorporating both the characteristic velocity (S_T) and length scales (δ_{L0}), the velocity gradient g_c relevant to the flame propagation can be evaluated by the following definition

$$g_c = S_T/(\mathrm{Le} \times \delta_{L0}) \tag{1}$$

where Le is the Lewis number and is defined as the thermal diffusivity of the mixture divided by the mass diffusivity of the deficient species (hydrogen). The latter is estimated as the ordinary multicomponent diffusion coefficient for the H_2-N_2 (bath gas) pair. The Lewis number is incorporated in the denominator to reveal the observed trend that the critical velocity gradient is increased when the Lewis number is decreased [5,18,19]. Note that the evaluation of the Lewis number was performed, respectively, at each of the conditions (preheat temperature, pressure, and compositions of the combustible mixtures) covered in the experiment via an online tool [37].

Velocity Gradient of the Flow: g_f. While the previously defined velocity gradient g_c can be seen as the capability of the flame front to propagate upstream during the boundary layer flashback, another gradient determined by the flow is equally important concerning the critical condition. For our case, the latter is evaluated based on the flow characteristics at the wall of the premixing pipe. In the present study, the velocity gradient of the flow (g_f) is estimated according to the Blasius correlation for fully-developed turbulent pipe flow [38]

$$g_f = 0.03955 \times u_0^{7/4} \times \nu^{-3/4} \times d^{-1/4} \tag{2}$$

In Eq. (2), g_f, u_0, ν, and d are the velocity gradient of the flow, the bulk velocity at the combustor inlet, the kinematic viscosity of the combustible mixture, and the diameter of the combustor inlet, respectively. The kinematic viscosity was also evaluated via the same tool as that for the Lewis number [37]. It should be mentioned that due to the geometrical limitations of the rig, the flow was not fully-developed in the experiment. The distance between the fuel injector and the combustor inlet is about half of the entrance length at 10 bar. Nonetheless, the Blasius correlation is expected to provide a reasonably good estimation of the velocity gradient, as suggested in Ref. [15].

In contrast to g_c, g_f indicates the capability with which the flow can counteract the opposed propagation of the flame front. Accordingly, there are corresponding velocity gradients g_c and g_f for each of the conditions, and the boundary layer flashback occurs when g_c exceeds g_f. The concept can also be pictured as that the higher the g_c, the more resistant the flame front to the strain rate induced by the flow. With higher g_c, the flame can more easily survive within a thin flow sheet at high shear stress without being extinguished and, hence, the flashback propensity is higher.

Results and Discussion

Figure 4 demonstrates the two velocity gradients g_f and g_c, plotted against the equivalence ratio (Φ) for the fuel mixture H_2-N_2 85-15. It can be shown that similar trends are revealed for the two other H_2-rich fuel gases (H_2-N_2 70-30 and H_2). At each pressure level, the values for the velocity gradient of the flow (g_f) can be calculated from Eq. (2) for all Φ. Contrarily, the g_c values depend on the experimentally-derived S_T and are limited by the operational range observed. The g_f exhibits a relatively "flat" behavior, with its value slightly decreasing with Φ due to variations of the

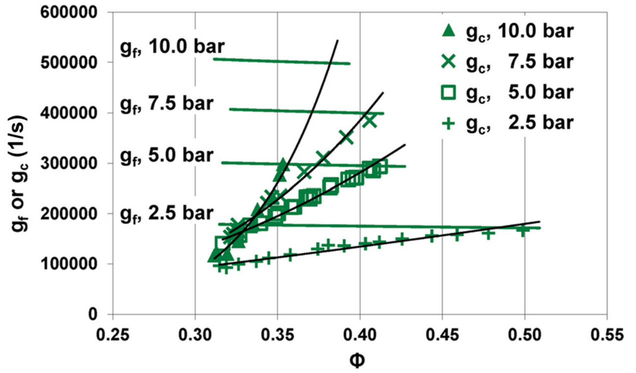

Fig. 4 The velocity gradients g_f and g_c (symbols) plotted against Φ for the fuel mixture H_2-N_2 85-15 ($T_0 = 623$ K). The nearly horizontal curves indicate the g_f at various pressure levels. The black regression curves of g_c are added to illustrate the "critical" conditions when g_c reaches g_f.

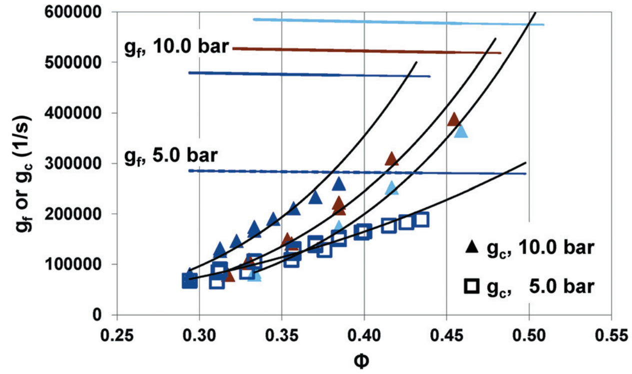

Fig. 5 The velocity gradients g_f and g_c (symbols) plotted against Φ for the syngas mixture (H_2-CO 50-50). The color coding corresponds to the respective preheat temperature. Dark blue: $T_0 = 673$ K; brown: $T_0 = 623$ K; and light blue: $T_0 = 573$ K. The symbol of g_c indicates the respective pressure level. Filled triangle: 10 bar; empty square: 5 bar.

kinematic viscosity of the combustible mixtures. For the velocity gradient of the flame (g_c), both the data points and the regression curves (the curves shown in black) from the power regression are plotted. It can be seen that the richer the mixture, the closer g_c approaches g_f from the flashback-safe condition ($g_c < g_f$).

From Fig. 4, the crossover point (between the velocity gradients g_f and g_c) at 2.5 bar is reached at around $\Phi = 0.5$. This condition is close to the flashback limit for the H_2-rich fuel gases, as reported in Ref. [26]. Another observation is that the g_c is approaching g_f with a faster rate at higher pressure by increasing the equivalence ratio. Since the proportion between the Lewis number and Φ is consistent over the investigated pressure levels, the phenomena are mainly attributed to the combined effects of S_T and δ_{L0} with respect to Φ. While the slopes of the increase in the turbulent flame speed with the equivalence ratio are consistent among the data at 2.5–7.5 bar, the S_T is found to be increased with Φ at a much higher rate at 10 bar. In contrast, by comparing the decrease in δ_{L0} within the two pressure elevations, i.e., from 1 to 5 bar and from 5 to 10 bar, it is observed that the former is much more significant. More investigations would be required to clarify whether the pressure effect on the velocity gradient g_c is dominated by the pressure response of S_T or δ_{L0}.

According to Fig. 4, while the experimentally derived g_c data at 2.5-7.5 bar closely approach the respective critical g_f, those at 10 bar could not be experimentally achieved towards flashback. This is essentially attributed to an operational issue. A larger safety margin (in terms of Φ) is usually kept at higher pressure since the consequence of flashback is much more severe. The experiments at 10 bar were thus performed with less intention to push the limit. Nonetheless, it can be found in Fig. 3 that the turbulent flame speed at 10 bar is already reaching the aforementioned maximum before flashback ($S_T \sim 10$ m/s). Based upon the trend revealed in Fig. 4, there is already very little margin left ($\Delta\Phi \sim 0.03$) before g_c reaches the level of g_f. Accordingly, the methodology is considered valid at high pressure, even though further proof is needed. It can also be seen in Fig. 4 that the equivalence ratio (Φ) at which the two velocity gradients match is shifted to leaner conditions as the pressure is increased. This is consistent with our previous finding [26] that the operational envelope (mainly dominated by the flashback limits) is strongly reduced at elevated pressure.

Besides the selected definition of $S_T/(\mathrm{Le} \times \delta_{L0})$, alternative formulations for the velocity gradient g_c were also evaluated. Velocity scales such as S_{L0}, length scales such as the viscosity-based flame thickness $\delta_{L\nu}$ (defined as the kinematic viscosity ν divided by S_{L0}, such as that used in Ref. [21]), and the "quenching distance" d_q implemented in Refs. [12,39], have all been taken into consideration. Nonetheless, none of the formulations was able to deliver the quantitative match between g_f and g_c as that demonstrated by the present approach. For comparison and further validation, the same methodology for deriving the velocity gradients g_f and g_c was also implemented for the syngas mixture (H_2-CO 50-50; the numbers are in vol. %) investigated in Refs. [27,28]. To be compatible with the procedure for the H_2-rich mixtures, the properties of the syngas flames were evaluated based on the same reaction scheme [34]. Note that since the flashback behavior was considered to be still dominated by the hydrogen content [10,16,17], the Lewis number was again evaluated by dividing the mixture thermal diffusivity with the ordinary multicomponent diffusion coefficient for the H_2-N_2 pair.

The velocity gradients g_f and g_c of the syngas mixture were evaluated at various pressure levels and additionally at various preheat temperature. Accordingly, the effects of both pressure and preheat temperature on the flashback propensity can be investigated. Figure 5 demonstrates the velocity gradients g_f and g_c at two pressure levels (5 bar and 10 bar) and three preheat temperatures ($T_0 = 573$ K, 623 K, and 673 K). Note that at 5 bar, only the g_f and g_c at $T_0 = 673$ K are plotted. It can be shown that a similar trend is exhibited for the velocity gradients at $T_0 = 573$ K and 623 K. Compared to the H_2-rich flames (see Fig. 4), the same shift on the equivalence ratio Φ at which the two velocity gradients match is observed when increasing the operating pressure for the syngas flames (see Fig. 5). Nonetheless, while the g_c is increased with Φ at a slightly higher rate at 10 bar compared to that at 5 bar for the syngas flames, the change in rate is more significant for the H_2-rich flames. The distinct response to pressure can also be evidenced by the increase in the exponent of the regression curves for g_c ($g_c \sim \Phi^x$). For the syngas mixture ($T_0 = 623$ K), the exponent (x) is increased from 3.3 to 4.4 as the pressure is elevated from 5 to 10 bar, but the increment is from 2.7 to 7.4 for the H_2-N_2 85-15 mixture. In contrast, the effects of the preheat temperature are also revealed in Fig. 5. By decreasing T_0, the velocity gradient of the flow g_f is increased due to the decrease in the kinematic viscosity. Since the trend of increasing g_c with Φ does not significantly differ among various T_0, the equivalence ratio at which the two velocity gradients match is shifted to richer conditions at lower T_0. In other words, the flashback limits are pushed to the richer side if the preheat is decreased. This is, again, consistent with the finding in Ref. [27], in which decreasing the preheat temperature has been shown to be an effective measure for reducing the flashback propensity. Similar conclusions have also been drawn for a radial-inflow micromixing cup injector [12] and for the lean prevaporized premixed combustion in the stagnation flow [40].

By implementing the presented methodology, it is possible to predict the flashback limits for both H_2-rich and syngas mixtures. At the respective pressure level, the predicted flashback limit

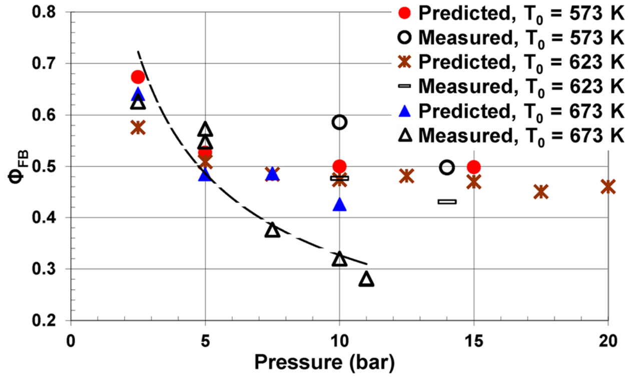

Fig. 6 The predicted and measured Φ_{FB} plotted against the pressure for the syngas mixture (H_2-CO 50-50; $T_0 = 573$ K, 623 K, and 673 K)

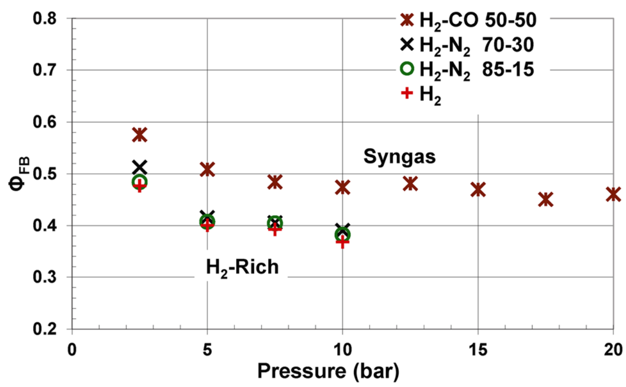

Fig. 7 The predicted Φ_{FB} plotted against the pressure for the syngas and H_2-rich mixtures ($T_0 = 623$ K)

(Φ_{FB}) is determined by the crossover point at which the two regression curves (for g_f and g_c) intersect. The outcome from this approach for the syngas flames investigated in Refs. [27,28] is plotted against the pressure in Fig. 6. The flashback limits (Φ_{FB}) experimentally determined in Ref. [27] are included for comparison and a dashed curve derived from the power regression for the Φ_{FB} at $T_0 = 673$ K is plotted. It can be seen that the current approach provides reasonable predictions of the flashback limits for the syngas mixture. Deviations do exist at various pressure levels, which can be partly justified by the slightly different bulk velocity at the combustor inlet ($u_0 = 45$ m/s) during the flashback test. The increase in the bulk velocity at the combustor inlet scales the S_T up to a certain extent [32], thus the regression curves for g_c are expected to be correspondingly adjusted. By correcting the deviation in u_0, the predicted flashback limit is shifted to the rich side by $\Delta\Phi_{FB} \sim 0.015$ at 5 bar, which is even closer to the experimentally determined value.

Nonetheless, judging from the limited flashback data available at high pressure, the proposed methodology serves as a good estimation on the flashback propensity for the syngas mixture. From Fig. 6, the phenomenon of a reduced operational envelope at higher pressure is well captured. In addition, the extension of the operational range (in terms of the flashback limit) by reducing the preheat temperature is also correctly reproduced. For the cases with lower preheat ($T_0 = 573$ K and 623 K), the flashback limits are shifted to leaner conditions at higher pressure with a relatively slower rate compared to the trend for $T_0 = 673$ K. This could be an indication that reducing T_0 as a measure to avoid flashback functions more effectively at higher pressure, even though the benefit seems marginal by decreasing T_0 further below 623 K for the syngas mixture.

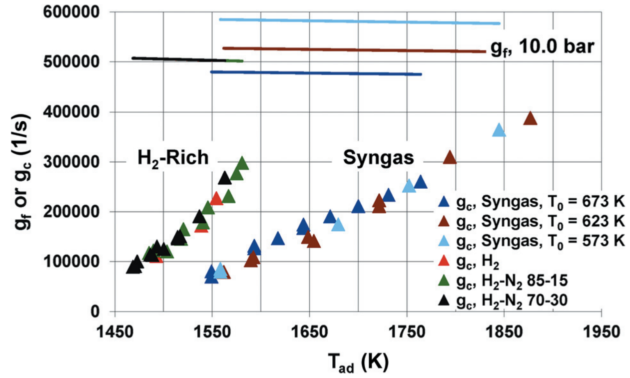

Fig. 8 The velocity gradients g_f and g_c (symbols) plotted against T_{ad} for the syngas and H_2-rich mixtures at 10 bar

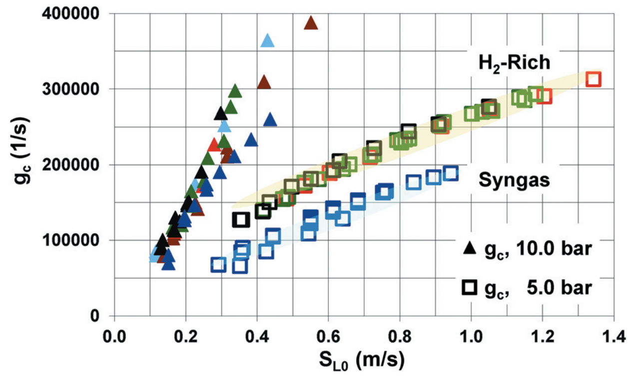

Fig. 9 The velocity gradient g_c plotted against S_{L0} for the syngas and H_2-rich mixtures. For the syngas, the color coding indicates the respective preheat temperature. Dark blue: $T_0 = 673$ K; brown: $T_0 = 623$ K; and light blue: $T_0 = 573$ K. For the H_2-rich mixtures, the color coding indicates the compositions (refer to Fig. 8).

The predicted flashback limits (Φ_{FB}) at the same preheat temperature ($T_0 = 623$ K) for both the syngas and H_2-rich fuel gases are plotted in Fig. 7. In terms of the flashback occurrence, it is obvious that the operational envelope for the H_2-rich fuels is much narrower than that of syngas. By evaluating the respective adiabatic flame temperature (T_{ad}) of the mixtures (see Fig. 8), it is found that the flashback propensity cannot be justified by the difference in T_{ad}. While the T_{ad} reaches over 1850 K for the syngas mixture at 10 bar without flashback, the T_{ad} for the H_2-rich flame is more than 250 K lower at the richest manageable Φ. Another relevant explanation for the higher flashback propensity is the increased burner tip temperature [11]. Although there was no dedicated thermocouple installed directly at the burner tip in our test facility, the burner head temperature was monitored at the location slightly upstream of the combustor inlet. Since the burner head was actively cooled by water, it is believed that the burner tip temperature shall not influence the estimated flashback limits in a significant manner. Accordingly, the distinct flashback propensity should mainly be attributed to the characteristics of S_T for the syngas and H_2-rich fuel gases.

How are the different flashback propensities for syngas and H_2-rich mixtures manifested in terms of the different S_T characteristics? In Fig. 9, the velocity gradient of the flame (g_c) is plotted against the unstretched laminar flame speed (S_{L0}) at 5 and 10 bar. Note again that for the syngas, only the g_c at $T_0 = 673$ K is plotted at 5 bar since a similar trend is exhibited for the g_c at $T_0 = 573$ K and 623 K. At the conditions (equivalence ratio and pressure) where both mixtures exhibit the same S_{L0}, the g_c of the H_2-rich mixtures is already higher than that of the syngas. This is an indication that the flashback propensity cannot be justified by the difference in the unstretched laminar flame speed either. The higher g_c of the H_2-rich mixtures is obviously dictated by their higher turbulent flame speed compared to the syngas. The phenomena are attributed to the fact that the H_2-rich mixtures are subject to higher preferential diffusive-thermal effects [24] since their Lewis number is lower than that of the syngas.

The selection of the S_T instead of S_{L0} as the representative velocity scale can be further justified by a preliminary investigation of the length scales. The analysis shows that the thickness of the viscous sublayer (δ_{sub}) adjacent to the wall of the premixing pipe remains below 40% of the unstretched laminar flame thickness (δ_{L0}) over the investigated mixtures and conditions. Since the penetration distance for hydrogen and hydrocarbon fuels has been found to be roughly on the same order of magnitude as the flame front thickness [5], it is unlikely that the flame front is stabilized under laminar conditions upon the occurrence of the turbulent boundary layer flashback. Note that besides S_T and S_{L0}, another candidate for the velocity scale is the stretched laminar flame speed. Further investigation on the stretch effects would be required to clarify the validity of this alternative.

Conclusions

A methodology for correlating the flashback propensity and the turbulent flame speed (S_T) of the H_2-rich fuel gases is proposed. This is based upon the experimental investigation of the turbulent lean-premixed nonswirled confined jet flames under gas turbine relevant conditions. Flashback in the turbulent boundary layer occurs when the velocity gradient of the flame (g_c) exceeds that established by the flow (g_f). While the former (g_c) is an indication of the flashback propensity, the latter (g_f) represents the capability with which the flow can counteract the opposed flame propagation. In the present paper, it is proposed that g_c can be calculated based on S_T divided by the product $\mathrm{Le} \times \delta_{L0}$, where Le is the Lewis number and δ_{L0} is the calculated thermal thickness of the one-dimensional laminar flame. The flow velocity-based g_f is evaluated by the conventional Blasius correlation for fully developed turbulent pipe flow. Accordingly, the flashback limit (Φ_{FB}) at the respective pressure level is estimated as the equivalence ratio at which the two velocity gradients match.

The derived flashback limits show that the present approach provides reasonable estimations of the operational limits for both syngas and H_2-rich fuel gases. The reduced operational range at higher pressure and the reduced flashback propensity by decreasing the preheat temperature (T_0) are both well reproduced. Another characteristic, that flashback occurs at much leaner conditions for the H_2-rich fuels compared to syngas, is also captured. The different flashback propensities between the H_2-rich and syngas mixtures are found to be justified by neither the adiabatic flame temperature (T_{ad}) nor the unstretched laminar flame speed (S_{L0}). Instead, the turbulent flame speed is capable of correlating the observed difference. Compared to the syngas, the more pronounced preferential diffusive-thermal effects for the H_2-rich fuel gases result in higher S_T, hence, the higher flashback propensity.

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Nomenclature

c = progress variable
d = diameter of the combustor inlet
D = diameter of the combustion chamber
d_q = quenching distance
F_L = flame length
g_c = (critical) velocity gradient of the flame
g_f = velocity gradient of the flow
Le = Lewis number
S_{L0} = unstretched laminar flame speed
S_T = turbulent flame speed
T_{ad} = adiabatic flame temperature
T_0 = preheat temperature
u_0 = bulk velocity at the combustor inlet
x = exponent of the power regression curve for g_c
δ_{L0} = (unstretched) laminar flame thickness
$\delta_{L\nu}$ = viscosity-based laminar flame thickness ν/S_{L0}
δ_{sub} = thickness of the viscous sublayer
ν = kinematic viscosity
Φ = equivalence ratio
Φ_{FB} = flashback limit

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