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Development of a flashback correlation for burner-stabilized hydrogen-air premixed flames

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With a growing need for replacing fossil fuels with cleaner alternatives, hydrogen has emerged as a viable candidate for providing heat and power. However, stable and safe combustion of hydrogen is not simple and as such, a number of key issues have been identified that need to be understood for a safe design of combustion chambers. One such issue is the higher propensity of hydrogen flames to flashback compared to that for methane flames. The flashback problem is coupled with higher burner temperatures that could cause strong thermal stresses in burners and could hinder their performance. In order to systematically investigate flashback in premixed hydrogen-air flames for finding a global flashback criteria, in this study we use numerical simulations as a basic tool to study flashback limits of slit burners. Flashback limits are found for varying geometrical parameters and equivalence ratios and the sensitivity of each parameter on the flashback limit and burner temperatures are identified and analyzed. It is shown that the conventional flashback correlation with critical velocity gradient does not collapse the flashback data as it does not take into account stretch induced preferential diffusion effects. A new Karlovitz number definition is introduced with physical insights that collapses the flashback data at all tested conditions in an excellent manner.

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1. Introduction

Since the industrial revolution, fossil fuels have paved the way for the rapid development of the world at large. But fossil fuels upon combustion emit hazardous gases, which in turn are detrimental to the environment. Therefore, in order to reduce such emissions, alternative energy sources need to be developed and investigated. For this purpose, significant contributions have been made towards the development of chemical models that can predict the combustion characteristics for a vast variety of fuels [1,2]. One such promising fuel is hydrogen, which can be generated from renewable sources, stored and used when and where needed [3–8]. But combustion of hydrogen is different from that of natural gas e.g. due to the differences caused by the low molecular weight of H₂ molecule and associated Lewis number, which is the ratio of thermal to mass diffusion. For lean H₂-air flames, the Lewis number is around 0.3, while for lean natural gas flames it is around 1. Another important property relevant for flame stabilization is the adiabatic flame speed $S_A$, which for H₂-air premixed flames has a 6 times higher value than that for natural gas flames at stoichiometric conditions. Hydrogen flames have also a much smaller quenching distance which allows the flame to propagate through small openings. These effects coupled with flow non-uniformities, heat transfer with flame holder and flame curvature, result in more difficult stabilization of H₂-air premixed flames. One of the main problems is the ability of hydrogen flame to flashback at higher volumetric flow rates as compared to methane flames, which is highly undesirable from the operations and the safety point of view. Another issue is the high burner temperature associated with hydrogen flames. For low-power applications, premixed flames are usually stabilized on top of perforated plates with holes and slits. Such a plate can be modelled for the case of a multi-slit burner, which has a 2D flame and flow structure and can be modelled with less requirement of computational resources.

Pioneering work on stabilization of premixed flames was done by Lewis and von Elbe [9] and later by von Elbe and

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Menster [10] for methane as well as H2-air flames for a number of burner designs. This theory is termed as the ‘critical velocity gradient’ theory in the literature as it relates the onset of flame flashing back with a gradient of velocity. The gradient of velocity just before the flashback limit is called the critical velocity gradient. In the experiments of von Elbe and Menster, the burner was externally cooled for H2-air flames, which suppresses the effect of increase in flame speed by pre-heating. Recent laminar direct numerical simulations [11–18], have highlighted the importance of the role of conjugate heat transfer between the fluid and the solid burner on flame stabilization. The critical velocity gradient theory also does not include the effects of flame stretch and preferential diffusion which are known to cause major changes in flame speed [19]. Also, it has been shown in Ref. [20] that the critical velocity gradient theory is only valid for thin flame holders. Therefore, there is a growing need for developing first-order models to capture the physics of flame flashback and collapse flashback conditions for a number of conditions.

Hydrogen flashback research is not just limited to laminar flames, as turbulent flames also suffer from so called ‘boundary layer flashback’ which occurs near walls [21,22], where the flow is almost laminar. In a recent study by Ebi et al. [23], it is shown that for swirling flames, flashback in the boundary layer mode can be described by laminar flame characteristics. Ebi et al. [23] tested a number of CH4−H2-air mixtures for a fixed burner geometry and found that a modified Karlovitz number that takes into account the ratio of flame extinction time scale and shear strain near the burner wall is able to collapse flashback data on a single correlation for a number of cases. Goldmann and Dinkelacker [24] extended the critical velocity gradient correlation for turbulent H2−NH3-air flames. They did this by estimating the flow time scale as a function of DarcyWeisbach friction factor for calculation of wall shear stress. Flame time scale was calculated using the ratio of flame thickness and laminar burning velocity. The ratio of flame to flow timescale proved to correlate flashback data for turbulent ammonia-hydrogen flames. Experiments have also been conducted for turbulent hydrogen-air unconfined flames by Baumgartner et al. [25]. They showed that unconfined flames have higher resistance to flashback than the confined flames and that the flashback propensity was dependent on the burner temperature.

Previous studies on laminar flames have employed multi/single slit/slot burners along with perforated plates focusing on the tip opening, blow-off and emissions problem [26–29]. Flashback for burner with a cylindrical configuration has been studied using experiments and the critical velocity gradient theory has been extended in Ref. [30]. It was shown that using the stretch corrected flame speed with the Markstein length of the mixture, tends to give better prediction of flashback limits than with laminar adiabatic unstretched burning velocity. However, this study focused only on the hole geometry and calculation of Markstein length using a thin-reaction zone assumption. For hydrogen-air flames, the reaction zone could be thick and as such the calculation of Markstein length could be better estimated from 1D stretched flame simulations.

In this study, our objective is to estimate the flashback limits for varying burner geometry parameters at a number of equivalence ratios in order to develop a flashback correlation based on relevant physical phenomena. For this purpose, laminar simulations with detailed kinetics, radiation and thermal diffusion effects are employed. Parameters are systematically varied for finding a wide range of conditions that can help in defining global flashback criteria. In the end, a new definition of Karlovitz number is used that takes into account the leading order physical phenomenon at the flashback limit and allows a collapse of the data at the flashback limit. The key novelty of this study can be summarized as:

- We use a detailed numerical model with inclusion of all major effects including the conjugate heat transfer between the flow and solid burner for the multi-slit configuration.
- Burner geometrical parameters are varied at various lean equivalence ratios for finding the flashback limits. The effect of the geometrical parameter on aerodynamic and thermal part of flame stabilization is also analyzed.
- Flashback data is correlated with a Karlovitz number which takes into account the effect of strain on flame displacement speed on the unburnt side for a wide variety of geometrical parameters at various lean equivalence ratios.

### 2. Numerical model

The planar computational model used in this study represents a multi-slit burner as shown in Fig. 1. Premixed gases enter from the bottom with a uniform inlet velocity with a temperature of 300K. Symmetry boundary conditions are applied on both the vertical sides of the domain. Conjugate heat transfer of the fluid with the solid burner is modelled in order to investigate the strong flame-burner interactions. The burner is modelled with properties of steel with thermal conductivity, \(k = 16.7 \text{Wm}^{-1}\text{K}^{-1}\) because of its usage in burners in domestic boilers. The outlet is modelled with a Neumann type boundary condition implying that there is no change in the field variables in the normal direction. The model used in this study does not assume symmetry at the center line of the slit. Symmetry is only assumed on the center line of the solid burner. Thus, this configuration can capture asymmetric flame propagation. Geometrical parameters of the burner are also shown in Fig. 1. Here, \(t\) is the plate thickness, \(W\) is the slit width and \(D\) is the distance between the slits. The variation range of these parameters along with fuel equivalence ratio \(\phi\) is described by the Table in Tab. 1. \(W\) is varied from 0.6 mm to 2 mm and \(D\) is varied from 0.5 mm to 2 mm, while the thickness of the plate is varied from 0.3 mm to 1.2 mm. This range of parameters were chosen as stable flames were found for all these situations. These parameters are varied along with the fuel equivalence ratio \(\phi\) variation from 0.5 to 1. The variation of adiabatic unstretched flame speed \(S_\text{f}\) along with flame thickness \(\delta_\text{f}\) (defined as \(\delta_\text{f} = \frac{S_\text{f} \cdot T_\text{a} - T_\text{b}}{\phi \cdot k_{\text{stoich}}}\)), as a function of \(\phi\) are shown in Fig. 2 for fuel lean conditions. Here \(T_\infty\), \(T_\text{a}\) and \(x\) are the adiabatic flame temperature, unburnt temperature and flame normal coordinate. It can be observed that \(S_\text{f}\) varies from 220 cms\(^{-1}\) to 50 cms\(^{-1}\) for \(\phi\) variation from stoichiometric to \(\phi = 0.5\) conditions. This difference is expected to cause difference in flow velocities at the flashback limit. The flame thickness can be observed to change less drastically between \(\phi = 0.7 – 1\).

Governing equations are solved using the commercial code Ansys Fluent [31] using a steady and coupled solver. We did some simulations with an unsteady solver for the reference burner geometry (\(W = 1\) mm, \(D = 1\) mm and \(t = 0.6\) mm) at \(\phi = 0.7\), with a time step of 2.5 \(\mu\)s and second order time discretization scheme. We found that the flashback limit was within the accuracy of 0.125 m/s of the inlet velocity compared to the steady solver, thus, giving confidence to our usage of steady solver results for calculation of the flashback limits. As in this study we focus on the question of why the flame flashes back and we do not focus on how the flame flashes back i.e. the initiation, moving of the flame

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation range</th>
</tr>
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<tbody>
<tr>
<td>(\phi)</td>
<td>0.5, 0.6, 0.7, 0.8, 0.9, 1.0</td>
</tr>
<tr>
<td>(W)</td>
<td>0.6, 1.2 mm</td>
</tr>
<tr>
<td>(D)</td>
<td>0.5, 1.2 mm</td>
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<tr>
<td>(t)</td>
<td>0.3, 0.6, 1.2 mm</td>
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in the channel and eventual further movement of the flame upstream, the choice of a steady solver is an acceptable trade-off for achieving the objective of this paper. Gravitational, and viscous work effects are not modelled as they were found not to play a major role. Soret or thermal diffusion effects are modelled by using a reduced model for H and H₂ species following [17,32]. Radiation heat loss from gas to the surrounding environment is modelled using an optically thin model for H₂O species [33]. Radiation heat loss from the solid burner to the cold environment is modelled as well assuming grey body radiation with emissivity of 0.83. Chemistry of H₂-air flames is modelled using the Konnov mechanism recently introduced in Ref. [34] which contains 15 species and 75 reactions. Constant Lewis number based mixture properties are used [35,36] in this study. The constant Lewis number values are calculated by simulating one-dimensional flat flames using multi-component transport model using CHEMID [37]. The constant Lewis numbers are calculated by spatially averaging the local values weighted with the diffusion flux. Lewis numbers are calculated based on the local Fickian diffusion flux, $\mathbf{J}_F^i$ calculated using multi-component model by:

$$Le_i = \frac{-\nabla \omega_i}{\mathbf{J}_F^i c_p}.$$  

Here $\mathbf{J}_F^i$ is the Fickian diffusion flux due to species gradients with $Le_i$ the constant Lewis numbers for species $i$ and $\lambda$ and $c_p$ the mixture conductivity and the specific heat capacity. The two dimensional steady reacting flow equations are solved on an equidistant structured grid with a 50 μm global grid resolution with an additional level of grid refinement in the flame zone resulting in a local resolution of 25 μm. These mesh resolutions proved to give grid independent and well resolved solutions for a wide range of equivalence ratios. It is to be noted that we tested the burner parameters of the references geometry in 3D with 2.5 mm length in the third direction and observed no thermo-diffusive instabilities. This supports the usage of 2D multi-slit model for flashback calculation. This model was previously validated in our earlier studies [16,38,39] where a detailed description of numerical methods is also available.

2.1. Calculation and identification of flashback limits

The reference burner geometry parameters are $W = 1$ mm, $D = 1$ mm and $t = 0.6$ mm. For calculation of the flashback limit, $\phi$ is fixed and a stable flame is first found at a higher velocity. Then the velocity is reduced systematically towards the flashback limit. The flashback limit is further refined using steps of 0.125 ms⁻¹. A sample set of such calculations is shown in Fig. 3 for $\phi = 0.7$ for the reference geometry by plotting temperature scaled with the adiabatic flame temperature $T / T_{\infty}$. In Fig. 3, $V_{\infty}$ is the uniform flow velocity prescribed at the inlet. It can be observed that as the flow velocity is decreased, the flame height decreases correspondingly (due to lowering of $V_{\infty}/S_0$). The burner temperature also rises as the flashback limit is approached resulting in a burner temperature of around 950 K. At $V_{\infty} = 2.375$ ms⁻¹, the flashback process is initiated in an asymmetrical manner and the burner temperature is found to shoot to around 1400K. In reality, the burner would melt at this temperature. In this study, we take the upstream (of the burner) stabilization of at least one flame foot as the indication that the flashback has occurred. The velocity value just before flashback occurs is taken as the flashback limit value.

2.2. Preferential diffusion and enthalpy changes

Next, flame stabilization is discussed by plotting changes in local enthalpy $h$, hydrogen elemental mass fraction $Z_H$ and hydrogen molecule consumption rate $\omega_{H_2}$ for the flashback limit case presented in Fig. 3. Enthalpy is normalized as $\hat{h} = (h - h_{in})/c_{p,u}(T_b^0 - T_{\infty})$, where $h_{in}$ is the inlet enthalpy and $c_{p,u}$ is the specific enthalpy at the unburnt side. $Z_H$ is scaled with inlet value as $Z_H = (Z_H - Z_{H,in})/Z_{H,in}$ and $H_2$ consumption rate is scaled with maximum consumption rate of a reference 1D flat flame $\omega_{H_2}$. These results are plotted in Fig. 4. From the enthalpy plot, it can be observed that the unreacted gas is highly pre-heated at the bottom and side walls of the burner plate. The top walls of burner plate gain heat lost from the flame and the burnt gas. Enthalpy changes inside the flame structure are less drastic than the heat transfer active region. Hydrogen elemental mass fraction shows almost 40 percent increase near the flame foot region indicating strong preferential diffusion effects. Near the tip of the flame, $Z_H$ shows weaker preferential diffusion effects, indicating well-known negative curvature effects associated with the flame tip of $Le < 1$ flames [19]. The scaled consumption rate shows that the flame burns stronger near the flame base and sides than the reference flat unstretched flame by almost 50 percent. At the tip of the flame, the flame burns weaker. These changes in local burning rate are a result of stretch induced preferential diffusion effects, which are crucial for determining the local flame speed near the flame.
base region and need to be accounted for in the development of a flashback correlation.

3. Results

In this section, flashback limits for different $\phi$, $W$, $D$ and $t$ are discussed with a focus on the relevant physics. As the burner can influence flame stabilization due to its aerodynamics and thermal characteristics, we will focus on finding which effect is the dominant one for flashback of $H_2$-air flames. First the effect of changes in $\phi$ on the flashback limit are discussed for the reference geometry.

3.1. Effect of equivalence ratio

For the reference geometry with $W = 1$ mm, $D = 1$ mm and $t = 0.6$ mm, flashback limits are found at 6 different $\phi$'s ranging from 0.5 to 1 with a step size of 0.1. The flashback limit cases are plotted in Fig. 5, where the scaled $H_2$ consumption rate $\tilde{\omega}_{H_2}$ is plotted. Note that all these flames are stabilized at different $V_{in}$'s. We can observe that the flame height does not change drastically at the flashback limit for flames at different $\phi$ values. The reaction zone becomes thicker as $\phi$ is decreased and the tip appears to be more open in the negatively curved regions. The flame base and side region can be observed to have a higher consumption rate than for 1D flat flames. $\tilde{\omega}_{H_2}$ can also be observed to progressively increase near the flame base region as $\phi$ is decreased, indicating possible stronger preferential diffusion effects near the flame base as the mixture becomes leaner. For $\phi = 0.5$, it is found that hydrogen is consumed 3 times faster than that for the respective 1D flat unstretched flame.

In order to scale the flashback limits, velocity in the slits $V_W$ can serve as a better scaling parameter than the inlet velocity $V_{in}$ due to the flow acceleration in the slits. $V_W$ can be estimated as:

$$V_W = V_{in} \frac{W + D}{W}.$$ (2)

The flashback limits for each case are plotted in Fig. 6a by scaling $V_W$ with $S_i$. It can be observed that $V_W$ does not scale well with the adiabatic unstretched velocity $S_i$ for flashback limit cases and the ratio between the two velocities increases with decreasing $\phi$. This indicates stronger preferential diffusion contribution to flame speed as the mixture becomes leaner as also observed in Fig. 5. In order to verify this, local flame displacement speed is calculated as $\rho_0 S_{D,u} = -\rho_0 \mathbf{v} \cdot \mathbf{n}$ at the unburnt side for the flame base region where only 1 percent of maximum heat release rate occurs. Here $\mathbf{v}$ and $\mathbf{n}$ are the local flow velocity and flame normal to iso-surface of $H_2$ mass fraction, respectively. The local value of $S_{D,u}$ is used to scale $V_W$ and is plotted in Fig. 6a as well. Here it can be observed that the usage of local flame displacement speed scales the flow velocity in a better way than $S_i$ and the value of scaled velocity varies between 2.5 and 2.1. Next, in Fig. 6b, local flame stretch rate at the unburnt side $K_o$ is plotted, calculated using $\rho K = -\nabla \cdot (\rho_0 S_{D,u})$ [36]. Here, $K$ is the flame stretch rate and it can be seen in Fig. 6b that $K_o$ decreases with a decrease in $\phi$ for the flashback limit cases. This is to be expected as for lower $\phi$ flames flashback occurs at lower flow velocity corresponding to lower strain values.

In order to model the stretch rate at the unburnt side, flow strain due to shear is calculated using the velocity gradient $g_e$ assuming a fully developed flow profile for laminar flow between
Here, $V$ is the component of velocity in the flow-direction and $x$ is the coordinate perpendicular to flame. It can be assumed that the stretch rate on the unburnt side can be predicted by the axial velocity gradient in the $x$-direction as $g_c = \left. \frac{\partial V}{\partial x} \right|_{x=W/2}$, similar to Ref. [23]. This result is plotted as a dashed black line in Fig. 6b for the flashback limit cases. It can be observed that this estimation is able to predict the local flame stretch rate $K_a$ in a quite good manner with slight differences and can be used to scale flashback limits. It is to be noted here that the main reason for using conditions at the unburnt side is because the stretch rate at the unburnt side can be estimated using $g_c$, while the conditions on the burnt side would require information from a numerical simulation.

Based on the above discussion, the effect of changes in $\phi$ on the flashback limit can be summarized as:

- As the mixture becomes leaner, stronger preferential diffusion effects enhance the flame speed; this causes the flashback limit velocities to scale less well with the adiabatic unstretched flame speed.
- A displacement speed that takes into account the local stretch rate, scales the flashback limits in a better way.
- Local stretch at the unburnt side can be predicted using the local velocity gradient of a fully developed flow profile between parallel plates.

### 3.2. Effect of slit width

The effect of a change in slit width is discussed in this subsection at three values of $\phi$ ($0.5, 0.7, 0.9$). The slit width $W$ is varied from $2 \text{ mm}$ to $0.6 \text{ mm}$ with fixed $D = 1 \text{ mm}$ and $t = 0.6 \text{ mm}$. The scaled hydrogen consumption rate $\widehat{\phi H}_2$ is plotted in Fig. 7 for $\phi = 0.5$ limit cases. The results at other $\phi$ were found to portray similar trends and are omitted here for the sake of brevity. It can be observed that as $W$ is decreased, the flame height at flashback drastically decreases indicating that flashback occurs at higher flow velocities for larger slit width. It can also be observed that $\widehat{\phi H}_2$ at the flame base region decreases as $W$ is decreased. Note that the $W = 0.6 \text{ mm}$ limit flame burns only 20 percent stronger than the reference flat flame. This indicates weaker preferential diffusion effects at the flashback limit for smaller slit width.

The flashback limit velocity $V_{W}$ scaled with $S_{L}$ is plotted in Fig. 8a for the three different $\phi$ conditions with varying $W$. It can be observed that there is no major difference between the scaled flashback limits as $\phi$ is changed. The scaled flashback limits only change in a major way as a function of slit width $W$. The unscaled flashback limits vary significantly as a function of equivalence ratio for the same geometry. For example, the flashback inlet velocity for $W=2 \text{ mm}$ is $7.5 \text{ ms}^{-1}$ for $\phi = 0.9$, while it is equal to $2.375 \text{ ms}^{-1}$ at $\phi = 0.5$. As the slit width is decreased, flashback occurs at lower velocities, thus, widening the stabilization limits. The local flow velocity is increased due to a smaller open area, which counters the enhancement in flame speed induced by the higher value of stretch rates. The estimated values of velocity gradient $g_c$ are shown in Fig. 8b. Here it is to be noted that unlike the flashback limit velocity, $g_c$ is a strong function of $\phi$ and a weak function of slit width $W$. Flashback occurs for each $\phi$ at almost a fixed $g_c$.  

**Fig. 5.** Scaled hydrogen molar consumption rate $\phi H_2$ for flashback limit cases at different equivalence ratios. $W = 1 \text{ mm}$, $D = 1 \text{ mm}$ and $t = 0.6 \text{ mm}$. Inlet velocity $V_{in}$ for the respective flame is printed in magenta color in each subplot.

**Fig. 6.** Velocity at the flashback limit $V_{W}$ scaled with adiabatic unstretched flame speed $S_{L}$ and velocity scaled with displacement speed $S_{D}$ at the unburnt side, calculated from CFD results (a); Stretch rate $K_a$ and estimated velocity gradient $g_c$ (b).
showing that the flow time scale is constant at the flashback limit even though the velocity changes as a function of the slit width. The flame time scale depends strongly on the flame speed induced by the stretch rate with a change in slit width $W$.

The effect of slit width $W$ on the flashback limit can be summarized as:

- The flashback limits are almost linear functions of the slit width.
- A higher velocity in the slits, as $W$ is reduced, balances the preferential diffusion enhanced flame speed due to higher strain, if $V_{in}$ is kept the same. Thus, at the same $V_{in}$, reducing slit width will make the flame burn stronger (increased fuel consumption rates) but also stable due to high velocity in the slits.
- This allows for the flashback limits to be wider for lower slit widths.
- The velocity gradient $g_{c}$ remains almost constant for each equivalence ratio with changing slit width indicating that it is indeed a similar velocity gradient, which occurs at lower velocities for smaller $W$, which is important for the flashback limit.
- The effect of changes in slit width is mainly related to the aerodynamic stabilization of the flame by the changing flow velocity and strain rate.

### 3.3. Effect of distance between slits

Next, the effect of the changing distance between the slits is investigated. This is again done for $\phi = 0.5, 0.7, 0.9$ and by varying $D$ from 2 mm to 0.5 mm with fixed $W = 1$ mm and $t = 0.6$ mm. The scaled $H_{2}$ consumption rate is plotted in Fig. 9 for all the investigated cases with the same color scale. $\phi$ decreases from the top to the bottom row. It can be observed that the flame height decreases with decreasing $D$ at fixed $\phi$ for $\phi = 0.9$ and $\phi = 0.7$ but this change is less drastic than that observed due to variation in slit width. Flames at the flashback limit for $\phi = 0.5$ show that the flame height almost remains constant with a decrease in $D$. The maximum value of $\omega_{H_{2}}$ also remains constant at a fixed $\phi$ and does not change in a major way with $D$.

In order to quantify the flashback velocity limits, $V_{W}/S_{1}$ is plotted in Fig. 10a as a function of $D$ at three equivalence ratios. We observe that unlike for changes in $W$, the flashback limits are a strong function of equivalence ratio as well but the magnitude of the overall change in $(V_{W}/S_{1})_{FB}$ is less with $D$ than for $W$. For $\phi = 0.7, 0.9$, the flashback limit decreases with a decrease in $D$ and increases with an increase in $\phi$. For $\phi = 0.5$, it is found that the area corrected velocity $V_{W}$ remains the same with variation in $D$ at the flashback limit. This also indicates by the same flame height in Fig. 9 with changing $D$. This is possibly caused by the increase in sensitivity of flame speed to stretch as the mixture becomes leaner, which in turn makes the thermal effect of change in $D$ to be of less importance.

In order to further investigate this behaviour, the maximum temperature in the burner, $T_{b,\text{max}}$, is plotted in Fig. 10b as a function of $d = D/2$. The change in $D$ is expected to modify the heat transfer to the top surface when the flame thickness $\delta_{f}$ approaches $D/2$. In such a case ($D \leq 2\delta_{f}$), burnt gases cannot lose heat to the burner at the top surface and only the heat lost from the flame is gained at the burner top surface. In Fig. 10b, it can be observed that there is a small change in burner temperature with a change in $d$ from 3 to 1.5. For $d \leq 1$, a sharp decrease in $T_{b,\text{max}}$ can be observed indicating that heat transfer from the burnt gases to the burner has been minimized for all three $\phi$’s.

The effect of a change in the separation distance $D$ can be summarized as:
• For $\phi \geq 0.7$, flashback happens at a lower area-corrected velocity with a decrease in $D$. This is caused by a decrease in heat loss from the flame and burnt gases to the burner, which in turn reduces the flame speed by pre-heating.

• For $\phi = 0.5$, preferential diffusion effects become dominant. This can be identified by the more intense consumption of $\text{H}_2$ than that of the 1D reference flame when leaner mixtures are used.

• The maximum burner temperature almost remains constant when the ratio of half the separation distance and the flame thickness is greater than 1. A decrease in burner temperature occurs when this ratio drops below 1.

• The change in $D$ causes mostly thermal changes in the stabilization mechanism, and its effect is less profound than that with changes in $\phi$ and $W$.

3.4. Effect of plate thickness

The results for changing plate thickness from $t = 0.3\, \text{mm}$ to $t = 1.2\, \text{mm}$ at $\phi = 0.5 – 0.9$ are shown in Fig. 11 by plotting temperature contours for the limit flames. It can be observed that the flame height first increases and then decreases slightly for $\phi = 0.9$ (top row) as $t$ is decreased. For $\phi = 0.5$, $0.7$ (bottom and middle rows), the flame height increases as $t$ is decreased. This behaviour can be directly understood from the temperature in the burner plate surrounded by the black rectangles. It can be observed that the maximum burner temperature decreases as the plate thickness is increased, because the burner is cooled due to extra surface area. This indicates that stronger pre-heated gas reaches the flame base for thin plates while this pre-heating is reduced for thicker plates and reduces flame speed enhancement.

The flashback velocity limits ($V_{fl}$) are plotted in Fig. 12a. It can be observed that the flashback limit is higher for thinner plates for $\phi = 0.5$ $0.7$, which can be explained based on the increase in burner temperature as $t$ is decreased, thus, increasing the enhancement in flame speed due to pre-heating. For $\phi = 0.9$, the flashback limit first increases and then decreases with $t$ as also can be observed from the flame height trends. However, this difference is small as compared to the changes in flashback limits for the lower equivalence ratios. In order to understand the non-monotonic behaviour of flashback limits for $\phi = 0.9$, flashback limits calculated without radiation heat loss from the solid burner (NRS) are also plotted in Fig. 12b. It can be observed that without radiation heat loss from solid, flashback happens at higher velocities compared...
to results with radiation included. Due to heat loss from the solid burner with radiation, flame and burnt gases lose extra heat to the burner (with radiation), thus, lowering flame speed even further than that without radiation heat loss. Thus, when radiation is not taken into account, flames lose less heat to the burner and flashback at higher velocities. Flashback limits are constant for \( t = 0.3 \) mm and \( t = 0.6 \) mm burners indicating that increase in the surface parameter \((2D + 2t)\) is not enough to change flashback limits within the limit of \( V_{\text{th}} = 0.125 \text{ms}^{-1}\). Coming back to the non-monotonic behaviour of the \( \phi = 0.9 \) curve in Fig. 12a, it can be argued that the change in trend for \( t = 0.3 \) mm, is caused by higher radiation heat loss from the burner and smaller surface parameter (less cooling via convection), which slightly reduces the flame speed more than that for \( t = 0.6 \) mm flame, thus reducing the flashback limit.

The maximum temperature in the burner is plotted in Fig. 12b. The same trends as in Fig. 11 is seen with change in \( t \), the burner gets cooler with increasing plate thickness. For \( \phi = 0.7, 0.9 \), similar temperatures are observed, while for \( \phi = 0.5 \), the burner temperatures are lower but follow the same trend with plate thickness. The effect of a change in plate thickness \( t \) can be summarized as:

- An increase in plate thickness cools the burner because of extra surface area. This cooling directly reduces the pre-heating of the flame base region, thus, causing a reduction in enhancement in flame speed from pre-heating and allowing for wider flashback limits.
  - It can be concluded that a change in \( t \) causes changes to the stabilization mechanism via thermal means, and its effects on flashback limits are less profound than that with changes in \( \phi \), \( W \) and \( D \).
  - Lower burner temperatures can be achieved using thicker plates.

4. Scaling flashback limits

In order to develop criteria for flashback limits for different geometrical parameters and equivalence ratio variations, a global correlation parameter is of high interest. Such a correlation is usually based on a critical velocity gradient as introduced by Lewis and von Elbe [9] and is illustrated in Fig. 13 for a flame close to flashback. For velocity profile 1, the gas velocity \( V_W \) is greater than \( S_{D,u} \) at distance \( \delta_q \) (quenching distance) from the wall, the flow pushes the flame away from the top face of the burner resulting in flame finding a new stabilization location. The flame in the thin region between \( x = 0 \) and \( x = \delta_q \) is dominated by heat loss resulting in the quenching of the flame and as such the flame speed at \( x = \delta_q \) is of relevance for flame stabilization. For velocity profile 2, \( V_W \) and \( S_{D,u} \) are equal at a \( \delta_q \) distance from the wall, resulting in flame stabilization. The velocity gradient of curve 2 is the critical velocity gradient for flame flashback. For velocity profile 3, gas velocity \( V_W \) is less than \( S_{D,u} \) at distance \( \delta_q \). This causes the flame to move upstream resulting in flame flashback.
A Karlovitz number can then be derived using a Taylor series expansion as done for example in Ref. [40] using the kinematic balance \( V(x = \delta_f) = S_{D,u} \), a no slip condition at the wall and a quenching distance that is directly proportional to the flame thickness as \( \delta_q \propto \delta_f \), \( x = \delta_f \) represents distance of one flame thickness away from the burner wall. The Karlovitz number is then given as:

\[
Ka = \frac{g_c \delta_f}{S_{D,u}} = \frac{\tau_{\text{flame}}}{\tau_{\text{flow}}}.
\]  

(4)

The flow timescale \( \tau_{\text{flow}} \) is interpreted as the inverse of strain rate and can be estimated based on the velocity gradient near the wall calculated using a fully developed flow between parallel plates as discussed in Section 3.1. In order to predict the flame timescale \( \tau_{\text{flame}} \), two approaches are used here resulting in two Karlovitz numbers as:

\[
Ka_1 = \frac{g_c \delta_f}{S_l},
\]

(5)

\[
Ka_2 = \frac{g_c \delta_f}{S_{D,u}}.
\]

(6)

Here, \( \delta_f \) and \( S_l \) are the flame thickness and flame speed of the reference adiabatic and unstretched flat flame, while \( S_{D,u} \) is the displacement speed of the stretched flame at the unburnt side for a stretch rate \( K = \frac{g_c}{S_l} \). This stretch corrected flame speed can be calculated based on the following model:

\[
\frac{S_{D,u}}{S_l} = 1 + L_M K.
\]

(7)

Here \( L_M \) is the Markstein length, which correlates the flame speed to the stretch rate. In this study this coefficient was calculated for reference flames using flat stretched flames using a 1D flame solver CHEM1D [37] with same settings in the 2D model. The results for such flames are shown in Fig. 14 where \( K \) is varied from 500 [1/s] up till no stable solution is achieved. \( S_{D,u} \) is taken at the unburnt side where 1 percent of the maximum heat is released for the reference flat adiabatic unstretched flames. The slopes from lines are calculated between \( K = 2000 \) and the maximum value for each \( \phi \). The estimated strain \( g_c \) is then used to calculate \( S_{D,u} \). Note that we have coupled the flow and flame timescales by using \( g_c \) as the flame stretch rate and then computing \( S_{D,u} \) corresponding to \( g_c \).

![Figure 13](image1.png)

Fig. 13. Illustration of flashback condition according to Critical Velocity Gradient theory. Blue line marks roughly the flame location, red is the flame speed \( S_{D,u} \) distribution. Green lines are axial velocity profiles for different scenarios as discussed in the text.

![Figure 14](image2.png)

Fig. 14. Variation of scaled flame speed at the unburnt side \( S_{D,u}/S_l \) with varying stretch rate for flat stretched 1D flames.

![Figure 15](image3.png)

Fig. 15. Scaled Karlovitz numbers at the flashback limit for all parametric variations in this study as a function of equivalence ratio.

Karlovitz numbers calculated at the flashback limits scaled with their respective values at stoichiometric conditions are plotted in Fig. 15 for \( Ka_1 \) using \( S_l \) and \( Ka_2 \) with an estimation of \( S_{D,u} (Ka = \frac{S_{D,u}}{Ka/\phi_{\text{mb}}}) \). It can be observed that the symbols marking \( Ka_1 \) do not globally collapse and can be observed to increase linearly with decreasing \( \phi \). On the other hand, \( Ka_2 \) collapses the data in an excellent manner around \( Ka_2 = 1 \) for all the parametric variations done in this study. This clearly shows that the inclusion of an enhancement in the flame speed by stretch has the leading order effect on flashback of H2-air premixed flames and a more physical estimation of this flame speed can be used to collapse flashback limit data for a wide variety of cases.

5. Conclusions

We performed a detailed investigation into flashback phenomena of H2-air premixed flames stabilized on multi-slit burners by varying equivalence ratio, slit width, distance between slits and plate thickness. It is found that at the flashback limit, the flame speed depends strongly on the stretch induced preferential diffusion effect as a leading order effect, while thermal effects resulting from the difference in heat transfer from flame and burnt gases to flame base are of secondary importance but still not negligible. A Karlovitz number including a preferential diffusion correction and a coupling between flame and flow timescales is able to collapse the flashback data at a constant value for a wide range of parametric variations. This investigation has extended the flashback correlation introduced by Lewis and von Elbe [9] for \( Le < 1 \) burner stabilized flames.
It is to be noted here that in this study, we have not varied the burner temperature and have modelled the conjugate heat transfer between the burner plate and the flame. This makes the burner temperature to be part of the solution dependent on the flame stabilization process of an infinitely wide slit. In real burner setups, however, due to the presence of finite slits and other heat sinks, plate temperature could be different. Although, our investigation in this study shows that a correlation based on the aerodynamic aspects of flame stabilization can lead to collapsing of the flashback data, future work focusing on the impact of burner plate temperature on the flashback limits could contribute towards the generality of the developed correlation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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