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Flame stabilization regimes for premixed flames anchored behind cylindrical flame holders

F.H. Vance*, Y. Shoshin, L.P.H. de Goey, J.A. van Oijen

Mechanical Engineering, Eindhoven University of Technology, Eindhoven, the Netherlands

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Abstract

The objective of this study is to construct a regime diagram for laminar flames stabilized behind flame holders with respect to the presence of a recirculation zone (RZ), trend of heat loss to the burner, and flow strain and flame curvature effects. This is achieved by varying the radius of the cylindrical flame holder and the mixture velocity between the flashback limit and the blow-off limit at a fixed equivalence ratio. It is found that for all flame holders, a RZ vortex is not present near the flashback limit. At flashback, flow strain is almost zero and the flame curvature is found to be the main contributor to flame stretch. With increasing mixture velocity, the heat loss to the flame holder decreases for smaller radii and a RZ does not appear till blow-off occurs. For flame holders with radii greater than twice the flame thickness, the heat loss to the flame holder first decreases with increasing mixture velocity without a RZ. A further increase in the mixture velocity does not result in blow-off but instead, a RZ appears behind the flame holder reversing the heat loss trend. In this scenario, flow strain is found to increase significantly and becomes the major contributor to flame stretch, although curvature effects are still present. With the RZ present, the blow-off limits are significantly extended and the stabilization mechanism is altered. The RZ vortex shields the flame base from intense pre-heating resulting from the increase in heat loss to the flame-holder while it provides support to the flame leading edge by recirculation of hot products. The results obtained from this study are used to construct a regime diagram, which offers a broader view of the whole flame stabilization process and its mechanisms.

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Keywords: Flame stabilization; Flashback; Blow-off; Recirculation zone; Heat loss

1. Introduction

The critical boundary velocity gradient theory of Lewis and von Elbe [1] supported in [2] by correlating the data at blow-off conditions for a wide variety of fuels and burners, is the earliest attempt

to construct a flame stabilization theory. However, Hertzberg [3] has shown that this correlation is only valid for very thin flame holders approaching zero thickness. Also, this theory does not describe the combined effect of stretch rate, preferential diffusion and conjugate heat transfer between the flame holder and the flame. Another view is provided by Kawamura and co-workers [4]. They have posed the existence of a critical curvature at the flame foot/base before the flame blows off. This idea has

* Corresponding author.

E-mail address: f.h.vance@tue.nl (F.H. Vance).

been confirmed by Kedia and Ghoniem [5] by analyzing blow-off of a Bunsen type flame stabilized behind a perforated plate. The limitation of the critical velocity gradient theory is also highlighted in Ref. [5] as it does not take into account the flame curvature and thus cannot explain blow-off phenomenon. In most of such studies, usually done at low Reynolds numbers and small flame holders, a recirculation zone (RZ) is either absent or does not interact with the flame in a strong way and as such its role in flame stabilization is usually ignored.

Another flame stabilization mechanism studied in the literature is stabilization in the presence of a RZ, where recirculation of hot products from the burnt side towards the unburnt side help igniting the flame to keep the flame stable [6–9]. This is understood to be one of the main mechanisms, with which a flame can be stabilized especially in the case of turbulent flames. Laminar bluff-body stabilized flames with a RZ have been studied by Kedia and Ghoniem [6,10] to understand flame anchoring and blow-off mechanisms. They have shown that conjugate heat transfer coupled with local preferential diffusion effects is crucial for flame stabilization and proposed that the flame stabilizes where necessary ignition conditions are present. In their case this region was inside the recirculation zone. An explanation for blow-off of flames stabilized with a RZ is related to the balance between recirculation of hot products and heat generated from chemical reactions [11]. A review of such earlier studies has been presented in Ref. [12] in the context of turbulent premixed flames stabilized behind bluff bodies.

Besides the presence of a RZ, heat loss to the flame holder is also an important factor in flame stabilization. Local heat loss lowers the flame speed allowing the flame to stabilize in regions of low velocity. Flames stabilized behind thin rods have been studied by Sung et al. [13] and it was shown that the rod temperature decreases with an increase in the flow velocity. Near the blow-off limit, they found that heat loss to the flame holder was negligible and thus they concluded that the flame can stabilize without heat loss by modification of the flame speed only by flame curvature and straining effects. In their study, the flame base was not influenced by the presence of a RZ. An extensive study into the role of conjugate heat transfer (CHT) between the solid bluff body and flow was presented by Berger et al. [14] for the same configuration as in Ref. [6,10]. The role of the recirculation zone was highlighted in terms of dilution with hot products, recirculation of heat and creating a region of low velocity for flame stabilization confirming the explanations given in literature. In most of the studies involving heat transfer to and from the solid flame holder, the role of pre-heating of the gas mixture that arises due to the heat conducting flame holder is seldomly discussed. Its impact on the flame speed in the presence/absence of a RZ has also never been systematically investigated in literature.

In this study, our motivation is to understand the contributions of flame curvature, flow strain and heat recirculation through the flame holder and RZ, on the flame stabilization process in the presence and absence of a RZ. This knowledge is then used to construct a flame stabilization regime diagram. This objective is achieved using 2D direct numerical simulations in the laminar flow regime by varying the mixture velocity and radii of cylindrical flame holders. Previous studies employed Cartesian geometries in which flame curvature does not play a major role. Furthermore, they did not investigate the complete stabilization range from flashback to the blow-off limit for different flame holder sizes, either focusing on thin rods or larger bluff bodies. This study therefore will bridge the gap between the two stabilization mechanisms in the literature, i.e., flames stabilized by heat loss and stretch without a recirculation zone, and flames stabilized by a recirculation zone. This study provides a broader picture for understanding and predicting the flame stabilization process with respect to different theories available in the literature.

2. Numerical model

The numerical model used in this study is based on the experimental geometry used in our previous study [15] and shown in Fig. 1. The geometry consists of a cylindrical bluff body with diameters varying from 1 mm to 8 mm, enclosed inside a cylindrical glass tube with diameter of 21 mm. The computational domain is modelled as an axis-symmetric 2D slice of this 3D geometry. Conjugate heat transfer of the fluid with the solid bluff body (thermal conductivity, $k = 109$ W/K m) is also modelled. The solid bluff body is modelled as an axis-symmetric 2D slice as well, with the axis of rotation at the center-line of the bluff body and with boundary conditions ensuring conservation of energy at the interface between solid and fluid domains. The wall of the enclosing tube is modelled as an isothermal no-slip wall with a temperature of 300 K. This external wall in the experiments corresponds to a glass tube with a low thermal conductivity and all the flames presented in this study do not interact with this wall except for the downstream sections. 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 steady equations are solved using the SIMPLE algorithm with a finite volume solver and a second-order upwind discretisation scheme. The mixture consists of a CH_4/air and the fuel equivalence ratio ϕ is fixed at 0.68 throughout this study. Chemistry for CH_4/air flames is modelled using the DRM19 mechanism [16] which contains 21 species and 84 reactions. Constant Lewis number based mixture properties are used [17,18]. Constant Lewis numbers are calculated by simulating

Fig. 1. Experimental setup (left) and computational model (right) for flames stabilized on cylindrical flame holders. $R=4$ mm for the flame holder shown here.

one-dimensional flat flames using mixture-averaged properties using CHEM1D [19]. Gravitational, radiation and Soret diffusion effects have been neglected in this study. For a steady, laminar, reactive flow, the following equations for continuity, species conservation, momentum and energy are solved:

$$\nabla \cdot (\rho \mathbf{v}) = 0, \quad (1a)$$

$$\nabla \cdot (\rho \mathbf{v} Y_i) - \nabla \cdot \left(\frac{\lambda}{Le_i c_p} \nabla Y_i \right) = \omega_i, \quad (1b)$$

$$\nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \bar{\tau}, \quad (1c)$$

$$\begin{aligned} \nabla \cdot ((\rho E + p) \mathbf{v}) \\ = \nabla \cdot (\lambda \nabla T) - \nabla \cdot (\sum_i h_i \rho D_{im} \nabla Y_i) + \omega_T. \end{aligned} \quad (1d)$$

Here $\mathbf{v}$ is velocity vector, ρ is the density, Y_i are the species mass fractions, ω_i are the species source terms, p is the pressure, T is the temperature, h_i are the species sensible enthalpy, D_{im} are diffusion coefficients for the species, $\bar{\tau}$ is the stress tensor, p is the pressure, E is the total energy, h is the enthalpy, h_i is the species enthalpy and ω_T is the thermal heat release rate. Fluid is treat as a non-Newtonian ideal gas. The conduction equation is solved inside the solid bluff body using:

$$\nabla \cdot (k \nabla T) = 0. \quad (2)$$

Here k is the thermal conductivity of the solid body. Transport properties modelled are calculated based on the following relations [17,18]:

Table 1

Flashback and blow-off velocity limits for flame holders of different diameter (D) at $\phi = 0.68$. $\hat{R} = \frac{D}{2\delta_F}$.

D [mm]	$\hat{R}$	V_{FB} [m s ⁻¹]	V_{BO} [m s ⁻¹]
1	0.79	0.51 (0.5)	0.675 (0.7)
2	1.57	0.5 (0.45)	1.3 (1.4)
4	3.15	0.5 (0.45)	3 (3.25)
8	6.3	0.5 (0.45)	3.75 (4)

$$\lambda = 2.58 \times 10^{-5} c_p \left(\frac{T}{298} \right)^{0.69} [\text{W m}^{-1} \text{K}^{-1}], \quad (3a)$$

$$\mu = 1.67 \times 10^{-8} c_p \left(\frac{T}{298} \right)^{0.51} [\text{Kg m}^{-1} \text{s}^{-1}]. \quad (3b)$$

The reacting flow equations are solved on an equidistant structured grid with a 100 μm global grid resolution. A two-level grid refinement is applied based on the temperature gradient resulting in a local resolution of 25 μm in the flame zone. These mesh resolutions proved to give grid independent and well resolved solutions. A validation between experiments and simulations has been included in the supplementary materials.

3. Results and discussion

For establishing a flame in the simulations, the flame is ignited by specifying a high temperature patch near the rear end of the bluff body for one case for each radius, and then this result is used as an initial condition for cases at higher inlet velocities until the flame blows-off. For the flashback limit, the inlet velocity V_{in} is lowered until the flame stabilizes at an undesired location upstream of the flame holder. The four cylindrical flame holders of different sizes studied here are presented in Table 1. Blow-off V_{BO} and flashback V_{FB} velocity limits are also shown in Table 1 and are defined as the last V_{in} for which a stable flame is observed using the numerical model. The lowest and highest velocities tried for flashback and blow-off, respectively, are shown inside brackets. It can be observed that flashback limits are almost the same for all four flame holders while the blow-off limit increases as the radius of the flame holder is increased. A non-dimensional radius of the flame holder is also defined in Table 1 as $\hat{R} = \frac{D}{2\delta_F}$ with $\delta_F = 0.635$ mm, being the flame thickness computed using the definition based on maximum temperature gradient [20] for a corresponding 1D flat flame at $\phi = 0.68$.

3.1. Analysis of limit flames

In this subsection, the limit flames which are presented in Table 1 are discussed in detail. Fig. 2

shows a contour plot of the heat release rate $\hat{\omega}$ scaled with the maximum value for the corresponding flat flame, for the limit flames near flashback (right side) and blow-off (left side) for four different bluff body radii along with streamlines. Radial and axial axes are scaled with the flame thickness $\hat{r} = r/\delta_F$, $\hat{z} = z/\delta_F$. First, the results for $\hat{R} = 0.79$ are discussed. Near the flashback limit, the flame base stabilizes in the wake region of the slender cylindrical flame holder at a small distance above the top face. The flame base can be observed to be curved. For the blow-off limit, it can be observed that the angle between the radial axis and flame increases slightly. The flame stand-off distance defined as the distance between the flame leading edge and the flame holder top surface, increases from the flashback to the blow-off limit. The scaled heat release rate $\hat{\omega}$ is almost equal to 1 for most part of the flame, except near the flame holder, where heat losses decrease the local burning rate. It can also be observed that no recirculation vortex forms behind the flame-holder. It was found that it is absent for all flames between the flashback and blow-off limits for $\hat{R} = 0.79$.

For flames stabilized behind the flame holder with $\hat{R} = 1.57$, it can be observed that near the flashback limit, there is no RZ formed and the flame angle is slightly lower than that for the $\hat{R} = 0.79$ flame near flashback. $\hat{\omega}$ is again close to unity for most part of the flame, except for near the flame base where it is lower. The flame blow-off angle is somewhat higher than the flashback angle resulting from the flame stabilizing at a higher inlet velocity than that for the $\hat{R} = 0.79$ blow-off limit case. A recirculation zone is formed at the blow-off limit but it can be observed that the flame leading edge is completely outside this recirculation vortex and thus, it is expected that it will not have a significant contribution to the flame stabilization process.

For the $\hat{R} = 3.15$ limit flames, we observe again that near flashback no RZ is formed, and $\hat{\omega}$ is close to unity except for the flame leading edge which is open now. Here, open flame leading edge refers to the non-merging of flame fronts at the flame base. The flame angle is slightly lower than it is for the $\hat{R} = 1.57$ flame near flashback. Near blow-off, the difference between flame angles for flashback and blow-off limit is greater than that for $\hat{R} = 1.57$. A RZ now appears at the blow-off limit and the flame foot is anchored inside this RZ. At the downstream sections of the flame, $\hat{\omega}$ is less than 1, indicating Lewis number or heat loss effects. With $\hat{R} = 6.3$, the flame angle near the flame-holder near flashback is again reduced compared to the $\hat{R} = 3.15$ flame but $\hat{\omega}$ is now greater than 1 indicating a strong contribution from Lewis number or pre-heating effects. Again no RZ is formed near the flame flashback limit. At the blow-off limit, a larger RZ than that for $\hat{R} = 3.15$ appears, resulting from strong flow-separation effects at high velocities. For this

Fig. 2. Scaled heat release rate $\hat{\omega}$ with overlaid streamlines for flame holders of different radii $\hat{R}$. The right side plot for each figure is the flashback limit flame while the left side plot is the blow-off limit.

case, the flame burns less strongly as $\hat{\omega}$ is close to 0.9 even at downstream sections of the flame. The flame leading edge resides inside the RZ and the flame angle is almost parallel to the streamwise direction.

In summary, flames near flashback do not stabilize inside a RZ for all flame holder sizes. Near blow-off, two different results in terms of RZ are observed. Flames stabilized on smaller radii do not appear to be affected by a RZ while for larger radii, the flame foot stabilizes inside a RZ. In the next subsections, we further investigate the differences in flame stabilization mechanism between flame flashback and blow-off limit for the presented cases.

3.2. Heat loss and RZ length

In order to develop a deeper insight in to the stabilization phenomena, we look at the RZ length L_{rz} (calculated as the re-attachment length along

the axis of symmetry) and integrated heat flux to the top face of the flame holders Q_{top} in this section. Fig. 3 shows the variation of Q_{top} and the corresponding L_{rz} as a function of $\hat{V}$, which is the ratio of V_{rim} and adiabatic burning velocity $S_L = 19.1 \text{ cm s}^{-1}$. The average flow velocity near the rim of the flame-holder V_{rim} is estimated using mass conservation as $V_{rim} = \frac{A_{inlet}}{A_{rim}} V_{in}$. Here A_{inlet} and A_{rim} are the area of the tube inlet and area of the channel between flame holder and tube outer wall. It can be observed that for $\hat{R} = 0.79$, the heat loss decreases with an increase in $\hat{V}$ until the flame blows off and that no RZ is formed. For $\hat{R} = 1.57$, the heat loss again decreases with increasing $\hat{V}$ but at the blow-off point a small RZ is formed as can be observed in Fig. 2 as well. However, this does not change the heat loss trend significantly. For $\hat{R} = 3.15$, the heat loss first decreases and then increases, with increasing $\hat{V}$ towards the blow-off limit. This change in trend happens just

Fig. 3. Heat flux (integrated) to the top face of the flame holder divided by the top surface area Q_{top} (solid lines with + symbols) and length of the recirculation zone L_{RZ} (dashed lines with o symbols) for flames stabilized behind flame-holders of different radii between flashback and blow-off limits. A zoomed-in insert plot for Q_{top} for $\hat{R} = 0.79$ and 1.57 is also shown.

at the onset of the appearance of a RZ. The same behaviour can be observed for flames stabilized behind the $\hat{R} = 6.3$ flame holder. This change in trend of heat loss to the flame-holder represents a switch of mechanism of stabilization. Overall, with increasing radius of the flame-holder, wider blow-off limits are observed. Previous numerical and experimental studies that involved conjugate heat transfer or the measurement of burner temperature (or heat flux) [5,14,21,22], all presented small sections of the velocity range between flashback and blow-off limits. According to our knowledge, this is the first time a detailed trend of heat loss (with RZ present or absent) has been studied for flame holders of different sizes between the flashback and blow-off limits. In the next subsection, we investigate the circulation of heat through the flame holder.

3.3. Heat circulation through the flame holder

The heat flux to the top surface of the flame holder heats up the burner and this heat is therefore transferred back to the gas at the side and bottom faces of the flame holder. In order to visualize the heat redistribution through the flame holder near the flame base region, Fig. 4 shows the contour plot of temperature along with a flame location (red line, 10 % of maximum heat release rate) and the pre-heating of the unburnt mixture is visualized with the help of an iso-contour of 5 % increase in normalized enthalpy $\hat{h}$ (white line), which is defined as $\hat{h} = \frac{h-h_{in}}{(c_{p,b}T_b^0 - c_{p,u}T_u)}$. Here, h is the total (sensible+chemical) enthalpy, h_{in} is the enthalpy at the inlet, T_u and T_b^0 are the unburnt and adiabatic flame temperature, and $c_{p,u}$, $c_{p,b}$ are the specific heat capacities of the unburnt and burnt

mixture. Results are shown for the four flashback and blow-off limit cases.

It can be seen that for the flashback cases, flame holder temperature increases proportionally with $\hat{R}$. The heat is transferred back to the flame via side and bottom faces of the flame holder. This can clearly be seen in Fig. 4 where the white line occupies a wider area for wider flame holders. This pre-heating significantly affects the local burning just downstream of the flame leading edge as observed with $\hat{\omega} > 1$ for $\hat{R} = 6.3$ in Fig. 2.

For the blow-off limit cases, it can be observed that for $\hat{R} = 0.79, 1.57$ the flame holder temperature is very close to the unburnt gas temperature (decreasing with increase in mixture velocity). This results in a negligible pre-heating effect which might reduce support to flame sections downstream of the flame leading edge. The white line in the flame zone shows the change in enthalpy resulting from local Lewis number effects. With a RZ being present for $\hat{R} = 3.15$ and 6.3 near blow-off, the heat loss to the top face of the flame holder increases with an increase in inlet velocity as shown in Fig. 2. As such, a significant amount of pre-heating is expected to affect different sections of the flame. It can be seen that a significant portion of the side-walls for $\hat{R} = 6.3$, is also subjected to heat loss from recirculating hot burnt gases. Near the upstream corner of the flame holder the pre-heating contour can be observed but this pre-heating does not reach the flame base as was observed for the flashback cases. This heat is transferred to the incoming gas and is convected towards the far downstream sections of the flame. Thus the RZ not only recirculates hot gases but also shields the flame base from the heat coming from the flame holder. This is an interesting result and could have applications where an enhancement in burning rate needs to be contained at the flame base.

Fig. 4. Contour plot of temperature in K along with iso-contour of 10 % of scaled heat release rate (red) and 5 % increase in $\dot{h}$ (white) zoomed-in on the region surrounding the flame holders with different $\hat{R}$. Flashback cases are on the right and blow-off on the left of each figure.

Fig. 5. Stretch due to curvature K_c (black lines) and flow strain K_s (blue lines) for flashback limit cases.

3.4. Flame curvature and flow strain effects

Apart from heat loss and gain resulting from heat circulation through the flame holder, flames stabilized on flame holders are also subjected to flame stretch. The stretch rate, K , calculated for stationary flames using $K = \nabla_t \cdot \mathbf{u}_t$, where ∇_t is the tangential component of the ∇ operator, $\mathbf{v}$ and $\mathbf{n}$ are local flow velocity and flame normal with $\mathbf{u}_t$ being the tangential component of the gas velocity [20]. The flame stretch rate K contains contributions from flow strain K_s along with flame curvature effects K_c . Curvature K_c and strain contribution K_s are calculated following Ref. [20]

$$K_c = -S_d(\nabla_t \cdot \mathbf{n}), \quad (4a)$$

$$K_s = \nabla_t \cdot \mathbf{v}, \quad (4b)$$

S_d is the local displacement speed. These contributions calculated at the inner layer of the flame on a fuel based progress variable Y are shown in Fig. 5 for flashback limit cases. It can be observed that

the flow strain contribution has a slightly negative value near the flame leading edge. This is the region where flame quenching happens and just downstream of this edge, in the flame base region and further downstream, the strain contribution is almost zero. The contribution from curvature is almost equal to the total stretch rate except for the small leading edge part of the flame. This distribution of flame curvature and flow strain happens as a result of the flames stabilizing at low velocities resulting in negligible strain as strain is directly proportional to the flow velocity gradient. The curvature induced stretch rate on the other hand depends on S_d/R_f where R_f is the radius of curvature of the flame surface. R_f can be induced by the flame itself depending on the local displacement speed such that a kinematic balance between the flow and the flame velocity is established. The dominance of the curvature contribution near flashback shows that velocity gradients due to flow strain do not play a crucial role at the low-velocity stabilization limit.

Contributions from flow strain and flame curvature to stretch for blow-off limit flames are shown

Fig. 6. Stretch due to strain K_s scaled with total stretch rate $K = K_s + K_c$ at the blow-off limit cases. Black lines are for cases with RZ present and blue lines for cases with RZ not present.

in Fig. 6 by plotting $K_s/(K_s + K_c)$. Here, we have suppressed null values of strain at low $\hat{z}$ for a better visual presentation. The following observation can be made about the distribution of both K_s and K_c at the blow-off limit: for $\hat{R} = 0.79$, the flow strain contribution is still small and for $\hat{R} = 1.57$ it has a higher contribution near the flame base than that for $\hat{R} = 0.79$. For flames stabilized with a RZ (black lines), the flow strain increases with $\hat{R}$ resulting from the higher velocity at the blow-off limit such that for the $\hat{R} = 6.3$ limit flame, most of the stretch is caused by the flow strain. Overall, flow straining becomes the major contributor towards the stretch rate as compared to flame curvature near the blow-off limit with increasing flame holder radius.

4. Regime diagram

As shown in the previous subsections, it can be argued that there are two stabilization mechanisms for flames anchored behind cylindrical flame holders based on the presence of a RZ and the associated trend of heat circulation with an increase in mixture velocity. These trends along with results presented in the previous subsections are used to construct a flame stabilization regime diagram in Fig. 7 with $\circ$ symbols showing the simulated cases. Flashback and blow-off limits at which stable flames were not found are used to construct the outer boundary of the regime diagram. While the transition between two stabilization regimes are constructed as average between cases for which a RZ was absent and just emerges for $\hat{R} = 3.15, 6.3$. The region between $1.57 < \hat{R} < 3.15$ and $\hat{V} > 6$ is marked with a changing color range between the two mechanisms as currently the exact boundaries there have not been investigated in this study.

However, the remaining boundaries are more accurate and bound clearly the two stabilization regimes. The main trends in the regime diagram are summarized as follows with the help of Fig. 7:

1. Flames stabilized without RZ can be characterized by a **decrease** in heat loss with an increase in the mixture velocity.
2. The curvature contribution of flame stretch increases from the blow-off to the flashback limit.
3. Flow strain effects are negligible at flashback but dominate the total stretch at blow-off when a RZ is present.
4. RZ stabilized flames are characterized by an **increase** in heat loss to the flame holder with an increase in the mixture velocity.

It can be noted from Fig. 7 that the mechanism of flames stabilized without RZ does not exist only for small diameter flame holders but also for flame holders with large diameters as long as the velocity is low enough. Near flashback, flames stabilize without RZ while near blow-off they can stabilize in either mechanism depending on the presence of a RZ and the location of the flame leading edge.

The stabilization regime diagram presented in Fig. 7 is of general nature due the generality of the phenomena involved. Here, we will discuss some of the possible limitations and quantitative effects that could change the specific limits of the regime diagram:

- **Radiation:** We do not expect radiation to change the major trends presented here but it could slightly shift the stabilization limits.
- **2D assumption:** Our model consists of a 2D axisymmetric slice and as such includes 3D geometrical aspects as well. Therefore, we do not expect major changes in the regime diagram when 3D geometries are investigated.

Fig. 7. A regime diagram for flame stabilization constructed using cases presented in this study. Main influencing factors are also shown with arrows and simulated cases are presented with $\circ$ symbols.

- *Other dimensions:* The effect of Lewis number, flame holder height, material and equivalence ratio need to be further investigated. Such a study could possibly extend the dimensions of the stabilization regime diagram.

5. Conclusions

A detailed investigation into the stabilization of premixed flames behind cylindrical flame holders has been carried out. It is found that flames stabilize in two distinct regimes characterized by the presence/absence of a recirculation zone. A regime diagram based on the trends of flow strain, flame curvature and heat loss to the flame holder has been constructed that can help in the development of a universal flame stabilization theory.

Declaration of Competing Interest

None.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.proci.2020.07.008](https://doi.org/10.1016/j.proci.2020.07.008)

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