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Flame holding downstream from a co-flow injector

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Abstract

We present numerical results on the flame attachment in the downstream vicinity of the co-flow injector lip that separates the reactive fluids at injection. Two stability diagrams show the domains where the flame is anchored, blown off, or extinguished, in terms of separating plate thickness and injection velocities of both fluids. Different anchoring modes—stagnation point counter-flow holding or edge flame anchorage—are described, depending particularly on the plate rim thickness. ***To cite this article: C. Nicoli et al., C. R. Mecanique 334 (2006).***
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Résumé

Accrochage d'une flamme en aval d'un injecteur co-courant. Nous présentons des résultats numériques concernant l'accrochage d'une flamme en aval d'un injecteur co-courant mélangeant deux gaz réactifs. Des diagrammes de stabilité sont proposés en fonction de trois paramètres importants : les deux vitesses d'injection des jets et l'épaisseur de la plaque de séparation des jets dense et léger. La flamme peut s'avérer accrochée, éteinte ou soufflée selon le domaine des paramètres étudiés. L'existence et la nature de la flamme sont alors discutées selon la géométrie de l'injecteur et les vitesses des gaz. En particulier, le mode d'accrochage (flamme attachée à un point de stagnation ou ancrage par flamme de bord) dépend fortement de l'épaisseur de la plaque séparatrice. ***Pour citer cet article : C. Nicoli et al., C. R. Mecanique 334 (2006).***
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Mots-clés : Mécanique des fluides numérique ; Combustion ; Flamme de diffusion ; Accrochage de flamme ; Couche de mélange dans les injecteurs

1. Introduction

Numerical results on the flame attachment in the near wake of a co-flow injector are reported in the present article. We are particularly interested in the case of rocket engines, where the fluids (hydrogen and oxygen) have very different densities and are injected in supercritical conditions. We study here the anchoring of the flame near the injection backplane. Recent experiments [1] (see also [2] and references herein) have been able to provide images of this

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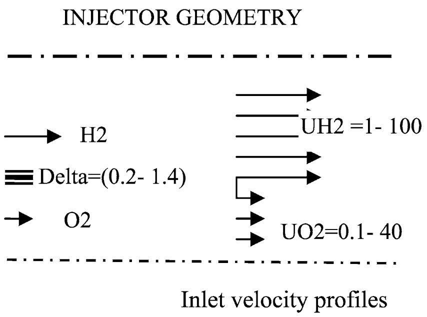


Fig. 1. Half period sketch of the series of plane co-flowing injectors (δ is the plate thickness in units of premixed flame thickness, L_F).

Fig. 1. Demi-periode du réseau d'injecteurs plans co-courants (δ est l'épaisseur des plaques séparatrices exprimée en épaisseur de flamme laminaire, L_F).

anchoring, and it was found that the flame was surprisingly close (considering the high hydrogen injection velocities) to the injector lip. Although many parameters control the characteristics of the flame, we focus in this work on those which appear as the most relevant in terms of flame attachment: thickness of the separation plate, velocities of both co-flowing jets.

2. Geometrical configuration

As previously described [3–5], we schematize the geometrical configuration typically used in industrial systems—an array of coaxial injectors in the combustion chamber—as a periodic series of two-dimensional plane injectors. A half-period sketch of the geometry studied is given in Fig. 1. Simulations are performed in the zone located between the dashed lines of Fig. 1, with the numerical method described in [6]. We simplify the calculation by using a one-step global chemistry and constant transport coefficients (see [5] for more details). The number of grid points used is typically 762×512. The low density gas (e.g., hydrogen) is injected with a large velocity, and dense gas with a low velocity (the profiles used are very stiff, and the calculation, with the Fourier/finite difference method used, begins in the injection plane, not upstream, which could produce a more realistic flow field). The stream temperatures used are 300 K for the heavy fluid and 400 K for the light fluid, leading to density variations more tractable numerically than those found in cryogenic experiments. Boundary conditions on the separation plate are zero velocities and temperature fixed to the injection temperature of the dense gas. In the present study, neither the light gas nor the dense gas can cross the separation plate, at the rim of which the water mass fraction is set to unity (for the sake of numerical facility).

It is well admitted that the Kelvin–Helmholtz instabilities created in the mixing layer are more important in cold conditions than with combustion. However, hydrodynamic instabilities can still remain even in hot conditions, as will be observed later. And, obviously, these observations will strongly depend on the three important parameters that characterise the shear of the flow: δ, the plate thickness (in units of L_F, the premixed flame thickness in stoichiometric conditions at 3000 K) and V_i, the injection velocities of both gases (in units of U_F, the premixed flame speed in stoichiometric conditions at 3000 K, which is approximately $10\ \mathrm{m\,s^{-1}}$), where i stands for either O_2 or H_2. Furthermore, δ is larger than the thickness of the boundary layers of both flows at inlet.

From now on, these three parameters are considered as the only ones of the study.

3. Existence and nature of the flame

To provide a certain given ratio of mass fluxes between both reactants, the light gas has to be supplied with a larger injection velocity than the dense one. We start our parametric study with the light gas velocity set to a very large value (say $80U_F$) and we analyse the flame stability diagram by varying δ and V_{O_2}, leading to values of V_{H_2}/V_{O_2} which can be as large as typical values used in experiments.

3.1. Stability diagram for a large injection velocity of the light fluid (H_2)

Our numerical results, summarized in Fig. 2, in the form of a stability diagram already used in related problems [7], clearly indicate that an increase of the heavy fluid velocity makes the anchoring more difficult, whereas a thickening

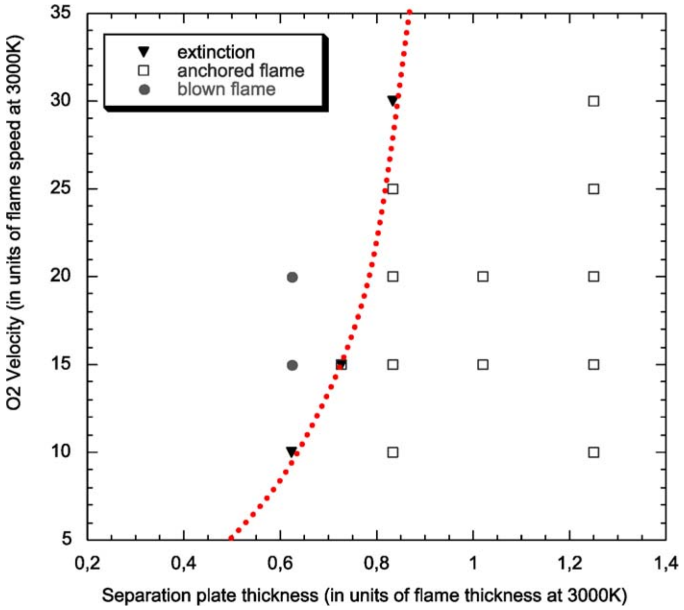


Fig. 2. Stability diagram of flames behind a plane injector, $V_{H_2} = 80$ (versus plate separation thickness and O_2 injection velocity).

Fig. 2. Diagramme d'existence des flammes en aval d'un injecteur plan, $V_{H_2} = 80$ (en fonction de l'épaisseur de la plaque de séparation et de la vitesse d'injection de O_2).

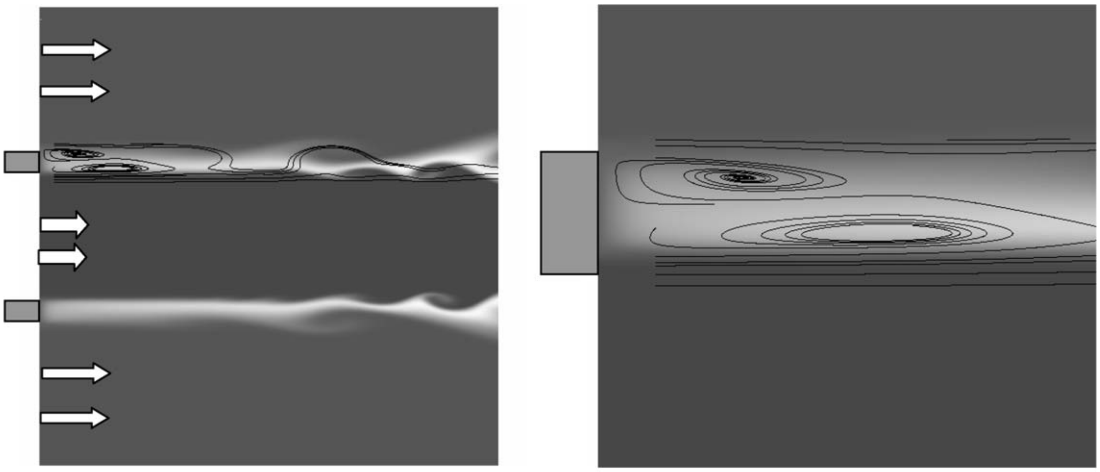
in separation plate thickness favours the flame stabilization. Although both variations tend to increase the Reynolds number, they have an opposite effect in terms of flame stability (as a matter of fact, they have an opposite action on flow shear). As seen in Fig. 2, the most important parameter controlling the flame stabilization is δ, the ratio of the separation plate thickness to the flame thickness. The role of this parameter was already emphasized in [8] for a different geometry (flame behind a step over a liquid reactant). In the present configuration, the same parameter was also used in [9], with different inlet profiles. By the way, we warn the Reader that the actual normalization used for length in Fig. 6 of Ref. [9] unfortunately does not correspond to that mentioned in the legend; so we take this opportunity to insist on the fact that, as shown in [8], the anchoring becomes much easier when $\delta \sim 1$ for large injection velocities.

A more careful analysis of our results shows that the recirculation zone (or the domain of small velocity) shrinks in the wake of the plate, when the (heavy fluid) velocity increases. Furthermore, the mixing properties due to hydrodynamic instabilities decrease. On the other hand, the widening of the plate thickness has a strong stabilizing effect due to the enlargement of recirculation zones. Note the latter are unstable at high Reynolds number because of wake instabilities, which cause a larger mixing in the vicinity of the injector.

These trends are in quantitative agreement with the diagram given in Fig. 2, which presents the features linked to hydrogen–oxygen flames with respect to dense fluid velocity V_{O_2} and plate separation thickness δ. Below a certain value of δ, no flame can be anchored. In other words, the stretch is too large to sustain the flame.

For a plate thickness larger than the scale of the reaction–diffusion length, the flame easily holds in the wake. Figs. 3(a) and (b) illustrate a typical situation for the parameters $\delta = 0.83$ and $V_{O_2} = 24$. In all these greyscale figures, the maximum value ($\sim$0.8 in nondimensional unit, or approximately 2400 K) is shown in white, the minimum value in black. The flame is anchored in a zone where two contra-rotating recirculations can be emitted—more or less periodically—in the wake to form Von Karman streets (a related steady solution of the velocity field in this geometry is given by Higuera and Liñan [10]).

As a stagnation point exists just downstream from these recirculations, a diffusion flame can be anchored close to it for a sufficiently large value of δ. Furthermore, note that flame attachment still remains even with an oscillating displacement of the stagnation point associated with vortex emissions. Actually, a detailed study of the flame structure (see the zoom in Fig. 3(b)) shows clearly that the flame existence is controlled by the mixing close to the stagnation point. Each recirculation brings its own chemical species, which diffuses close to the stagnation point. Fig. 3(a) also shows that downstream, the flame is a diffusion flame submitted to Kelvin–Helmholtz instabilities, causing the ripples seen in the figure.



(a) $(V_{H_2} / V_{O_2} = 3.3, \delta = 0.83, \rho_{O_2} / \rho_{H_2} = 16)$ (b)

Fig. 3. Temperature and streamline within a flame anchored in recirculation zone ((a) general view, (b) zoom; temperatures in units of 3000 K).

Fig. 3. Températures et lignes de courant dans une flamme ancrée dans la zone de recirculation ((a) vue globale, (b) zoom ; températures en unités de 3000 K).

The stability domain of the flame, as plotted in Fig. 2, is found relatively simple, essentially limited by a threshold value in δ (say, about 0.8). On the one hand, this feature has undoubtedly to be linked to the heat loss imposed by the fixed rapid light jet, which extinguishes the flame for a small plate thickness. Premixed flame thickness (or reaction–diffusion length) indeed supplies—for δ—the length scale of this typical limit. On the other hand, as soon as this threshold is crossed, ‘stagnation point’ anchoring insures satisfactory conditions for flame stability. Because thermal conditions are now fulfilled with respect to the high speed light jet, increasing dense jet velocity does not strongly modify heat losses. This explains why the transition is rapid in Fig. 2.

As for the Karman emission, one can wonder that it does not affect these thermal conditions. The flame could have been emitted with the recirculations; on the contrary, the flame does resist to vortex emission.

3.2. Stability diagram for a thin separation plate

In this subsection, the separation plate thickness is fixed to the small value $\delta = 0.22$ (i.e., a much smaller value than the limit of Fig. 2). Even with this small lip thickness, our numerical results show that there exist satisfactory injection conditions on both jets that allow the flame to anchor. The corresponding stability diagram is presented in Fig. 4 where the conditions for flame attachment stand under the curve of the figure.

One observes that the limit velocity of the dense jet increases as the light jet velocity decreases. The product of both limit velocities is more or less constant, slightly inferior to $10(U_L)^2$, as seen in the dotted curve of Fig. 4, which is approximately an hyperbola. Let us also remark that $10(U_L)^2$ is of the order of the square of a typical triple flame velocity.

In this small thickness case, the type of anchoring is completely different from the stagnation point holding of Fig. 3. In the case of cross-flow flames—which are not fundamentally different from the present co-flow flames when separation thickness is vanishing—similar flames have been often observed [2,11]. In our case, the conditions of existence seem to be more severe: as a result, injection velocities must be small to observe attachment, especially when the dense gas is not at low velocity (compared with reaction–diffusion speed).

Nevertheless, when attachment is observed, the flame is simply an edge flame [12,7]. There is not the typical mushroom shape of a triple flame. The reason is the absence of a sufficient mixing within both jets on length scales of the order of the reaction–diffusion length. Furthermore, the edge is localized in the region where velocity is minimal: i.e., just behind the injector rim.

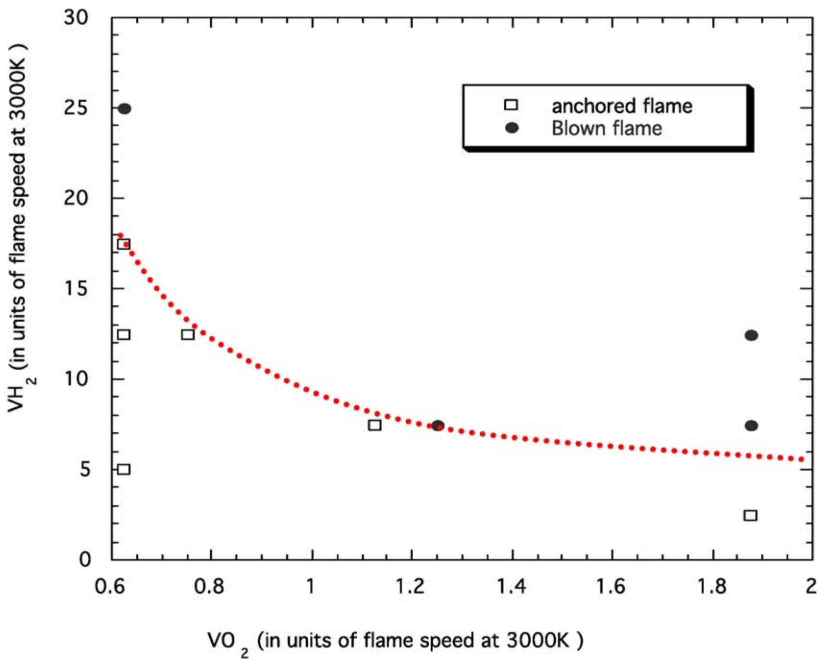


Fig. 4. Anchoring of a flame downstream from a co-flow plane injector, $\delta = 0.22$ (stability diagram versus injection velocities of H_2 and O_2).
Fig. 4. Ancrage d'une flamme en aval d'un injecteur plan co-courant, $\delta = 0.22$ (diagramme d'existence en fonction des vitesses d'injection de H_2 et O_2).

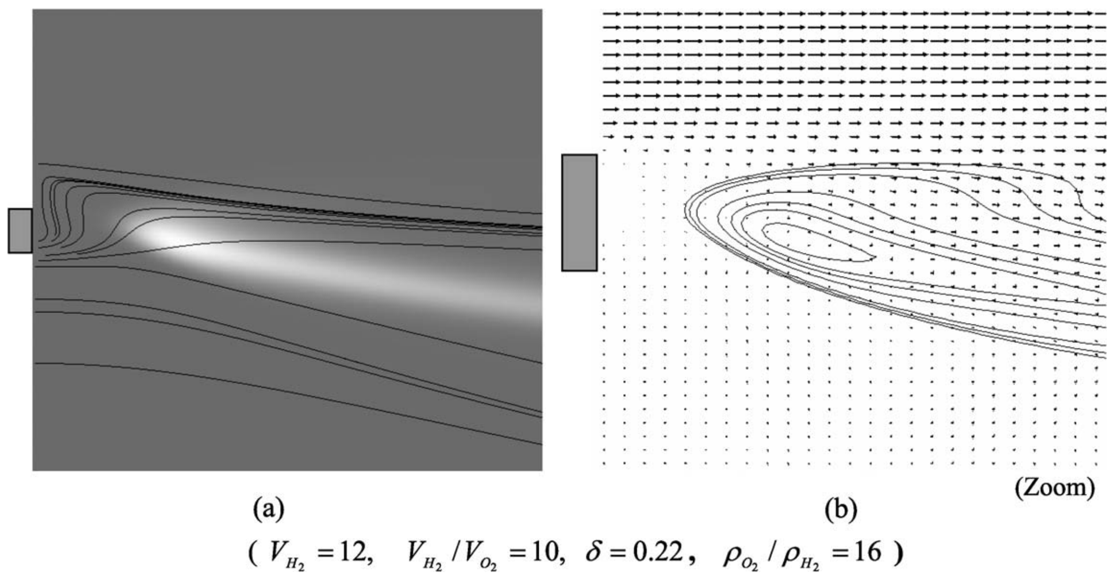


Fig. 5. Heat release within an edge flame anchored behind a low thickness separation plate.
Fig. 5. Production thermique dans une flamme de bord, accrochée en aval d'une plaque de faible épaisseur.

In Fig. 5(a), we observe that the diffusion flame moves towards the dense jet. This feature tends to pinch the dense jet and accelerates it. The zoom of Fig. 5(b) provides us with additional salient details. Edge flame positioning occurs in a zone of low velocity but not vanishing (the local velocity is of the order of the triple flame velocity). The holding point is also displaced towards the dense jet (where the velocity is weaker than in the light jet). We also observe velocity arrows which confirm that the dense jet is pinched and accelerated.

4. Conclusion

This two-dimensional study has emphasized the role of the separation plate thickness in the anchoring mode of a diffusion flame, downstream from a plane co-flowing injector. When a jet has a velocity much higher than the reaction–diffusion speed, attachment only occurs for separation plate of thickness at least of the order of the reaction–diffusion length. In this case of large plate thickness, anchoring arises through the positioning of a counter-flow diffusion flame at a stagnation point. When a small plate thickness is imposed, attachment requires weaker jet velocities. In such a case, anchoring occurs thanks to an edge flame which is located much closer to the plate lip.

This confirms the general trend that the stability domain versus the two injection velocities is strongly reduced when the injector rim thickness is small.

Acknowledgements

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