Experimental Observation of Different Stabilisation Regimes of Laminar Partially Premixed Flames.

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Abstract

Phenomena responsible of partially premixed laminar flame stabilization are investigated on a particular configuration of a cooking model burner. The structure of the flame is investigated by means of Planar Laser Induced Fluorescence on OH radicals. The evolution of the flame structure is studied toward the blow-off by keeping the gas thermal power constant and varying the fuel equivalence ratio. The flame evolves from a mainly diffusion flame for a stable case to a mainly premixed one close to the blow-out. Flames outlines are also extracted from the LIF mean images for each operating condition. During the transition to the flame lift-off, a change of stabilization regime is pointed out, from a stable flame attached to the burner, to a lifted flame controlled by the local aerodynamic characteristics of the flow. The results provide thus some keys of understanding in the lift-off and blow-out phenomena in this configuration.

Introduction

Partially premixed flames have been extensively studied these last ten years [1-4] because of their important role in turbulent diffusion flame stabilization. This combustion regime occurs in many practical devices and most of the works have been conducted on non-premixed flame configurations. Although most of the domestic gas burners, such as ovens, cooking stoves or boilers generate laminar partially premixed flames [5-8], there are few studies concerning stability of such rich premixed flames where pure premixed and diffusion reactive zones coexist.
Gas cooking burner designers intend to create new design appliances always more performing. Nevertheless, the lack of understanding in the involved physical phenomena has limited the burner innovation. Characterization of flame stability is thus one of the crucial issues to design high-performance burners. The aim of this study is to point out the physical phenomena responsible of partially premixed flame stabilisation on domestic cooking burner. We intend to determine flame stability criteria from laboratory experiments on a simplified model burner in the aim of providing some guidelines for the design of new burners.

Experimental Set-Up

The laboratory model burner presented here is a simplified representation of a commercial gas burner, which would have been rolled out in a two-dimensional configuration. The model burner consists of twenty rectangular slots, linearly arranged. It allows easy modification of geometry while preserving characteristics of the central flame surrounded by identical neighbour flames. It operates with a nominal thermal power of 2 kW and a fuel equivalence ratio of 1.7. Methane and

air flow rates are independently controlled and measured before being mixed and then supplied to the burner via a tranquillisation chamber. All experiments are performed in still open air.
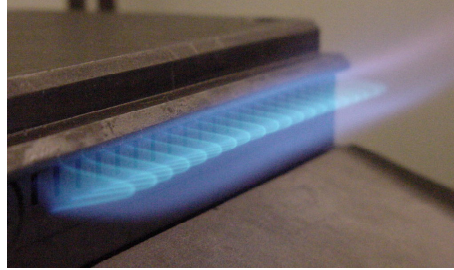

Figure 1: Flames generated by the burner.

Photograph of typical flames generated by the 2D burner is presented figure 1. The mixing of gas and air is introduced into the burner with an equivalence ratio over the stoichiometry, as a consequence, the flame structure consists of two main parts. The first combustion zone consists of a premixed flame front in which part of the initial rich mixing is burned. Then, the unburned fuel excess reacts with the entrained atmospheric air, forming an enveloping diffusion flame. These two combustion zones join together in bottom and top double points. The top edge of the flame is attached to the burner flame-holder.

Stability diagram.

In an attempt to determine the burner global stability limits, the different burner stability-operating conditions have been first defined. Stable combustion is considered if the jet exit velocity ranges between two critical limits. The stability limits defined here are the "pure diffusion flame", for which the first premixed flame front disappears, and on the second hand, the lift-off limit, which leads to blow-out. The stability zone limits are investigated point by point. The lift-off limit is defined since one of the flames is lifted. Flame stability diagram of the burner with methane is presented as function of the thermal input power and jet fuel equivalence ratio on figure 2.
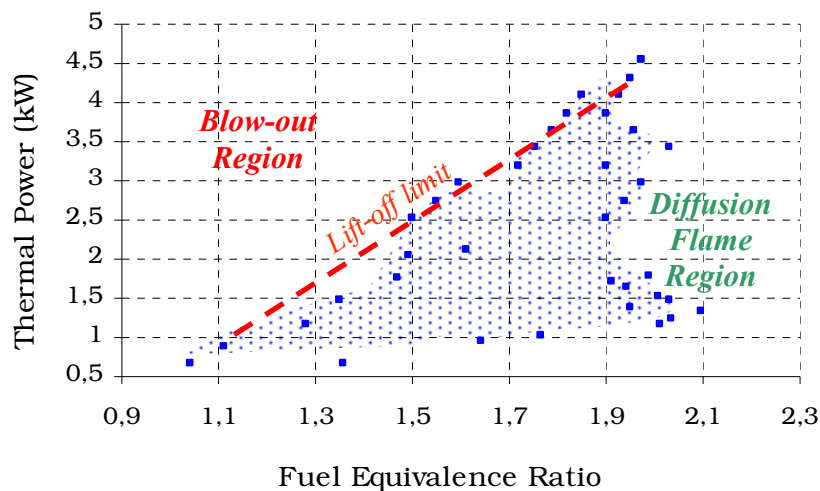
Figure 2: Stability diagram of the model burner.

A classical domestic burner stability map is recognized, as far as the shape and the fuel equivalence ratio range are concerned [7,9]. In this study, we will focus more particularly on the lift-off limit, since it leads to the blow-out, which represents a safety critical limit.

In order to deepen this first global flame stability characterisation, the flame structure is investigated in details when evolving through blow-out. These local studies are achieved by means of laser diagnostics.

**Flame regime evolution toward the blow-out.**

The reaction zones are visualized thanks to Planar Laser Induced Fluorescence (PLIF) of the OH radicals [10,11]. The experimental set-up consists of a dye laser (Sirah PrecisionScan) pumped by a frequency doubled Nd-YAG laser (Spectra Physics). The laser output yields 15mJ/pulse and is tuned to excite the $Q_1(5)$ transition of the $A^2\Sigma$ (v=1) $\leftarrow$ $X^2\Pi$ (v=0) band. LIF images are then collected by a Princeton Instruments IMAX ICCD camera (512 pxl^2- 16 bits) equipped with WG305 and UG11 colored Schott filters. The UV laser sheet is focused and slot centred on the central adjoined flame to be representative of the axisymetric configuration.

Flame structures are investigated for several operating conditions that are chosen to evolve from a typical stable partially premixed flame to a non-stable case, close to the blow-off limit. In order to isolate the effect of different combustion input parameters such as the thermal power, the premixed jet momentum flux or the fuel equivalence ratio on the lift-on phenomenon, several series of experiments are realized. As these input conditions are interdependent, when keeping one of them constant, the two others are consequently modified. Although other parameters have shown similar results, only the flame structure evolution at constant thermal power is presented in this paper. When evolving from a stable flame toward blow-out by keeping the thermal power constant, it is seen on figure 2 that the fuel equivalence ratio must be decreased, inducing an increase of air flow-rate and jet exit velocity.

The figure 3 presents a mean image of a stable case flame. The mean images are obtained from 250 instantaneous images and are corrected for the background noise as well as for the laser sheet energy repartition.
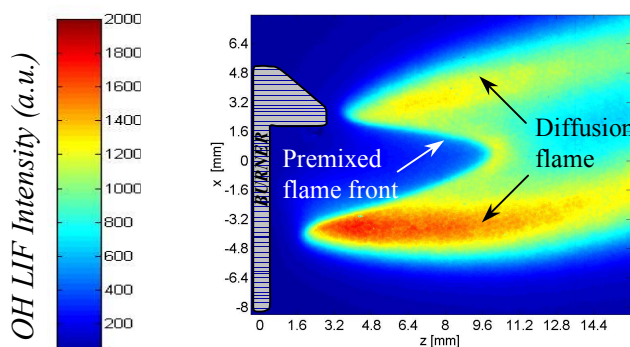
**Figure 3:** OH PLIF mean image of a stable flame [P=1.28kW ϕ=1.35]
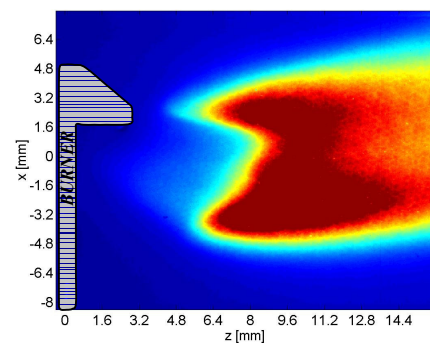
Figure 4: OH PLIF mean image of a non stable flame [P=1.28kW ϕ=1.19]

On figure 3, the two different combustion zones described previously are clearly visible: a central premixed flame surrounded by two diffusion branches. On both top and bottom sides, premixed and diffusion flames are stabilized on the burner, in common double points. This image reveals

that the OH LIF signal is more important in the diffusion flame compared to the premixed flame front. The most intense reaction zone is observed in the lower part of the diffusion flame, where the entrained air must be the more effective. In the case of a non-stable flame close to the blow-out (Figure 4), the global collected signal is more important than for the stable case. The flame consists now of a premixed part as much intense as the diffusion part of the flame.

The flame regime is thus modified toward the blow-out limit. The flame evolves from a mainly diffusion flame for the stable case, toward a mainly premixed one, for the non-stable case.

Flame structure evolution toward blow-out.

In order to deepen this qualitative description of the flame structure, some numerical processings are performed on OH images so as to obtain flame outlines coordinates. Flame contour positions are extracted from the PLIF mean image by means of a method based on the grey level threshold. Different images processings have been compared to ensure the independency of the results from the methods. Flame outlines are presented in figure 5 for different combustion conditions at constant thermal power.
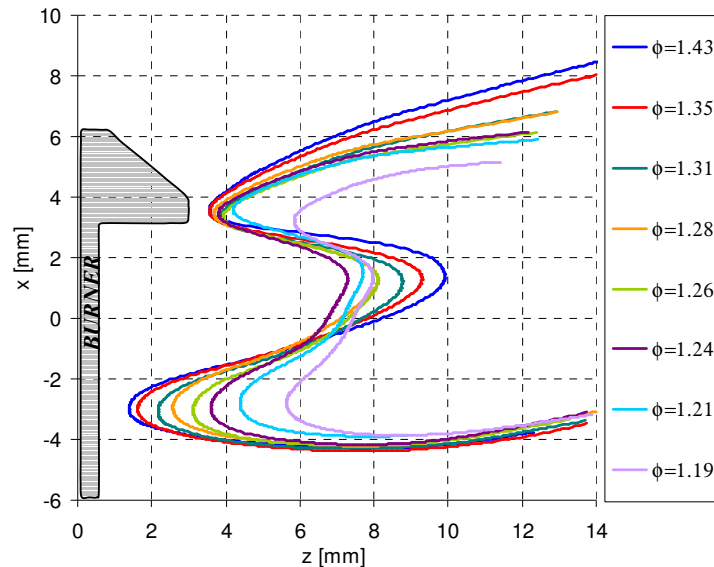

Figure 5: Flame outlines for constant thermal power.

Analyses of the flame contours extracted from PLIF mean images show that, for a constant thermal power, the position of the upper diffusion branch slightly evolves in the gas flow toward the jet center and probably follows the stoichiometric line as the equivalence ratio decreases. Vertical expansion of the lower diffusion branch does not evolve very much for different fuel equivalence ratios, except for the blow-out critical case (ϕ=1.19). Between the two diffusion branches, a premixed flame front is stabilized. It appears on figure 5 that the structure of this premixed front tends to flatten when the equivalence ratio decreases toward the stoichiometric value. The position and structure of this premixed flame front follow the local flow velocity and fuel equivalence ratio to stabilize at the maximum flame propagation speed. It seems that the evolution of the flame edges are strongly involved in the flame stabilization phenomenon. The study is then focused on three particular points of the flame contour: the flame tip and the two flame edges, their displacements in the flow are investigated when varying the fuel equivalence ratio.

**Flame edges and flame tip displacements in the flow toward blow-out.**

The relative horizontal distance between these three particular points and the burner is deduced from instantaneous PLIF images. In figure 6, the distance of bottom and top edges and the flame tip to the burner slot position (z_o), is presented as function of the equivalence ratio, for a constant thermal power experiment.
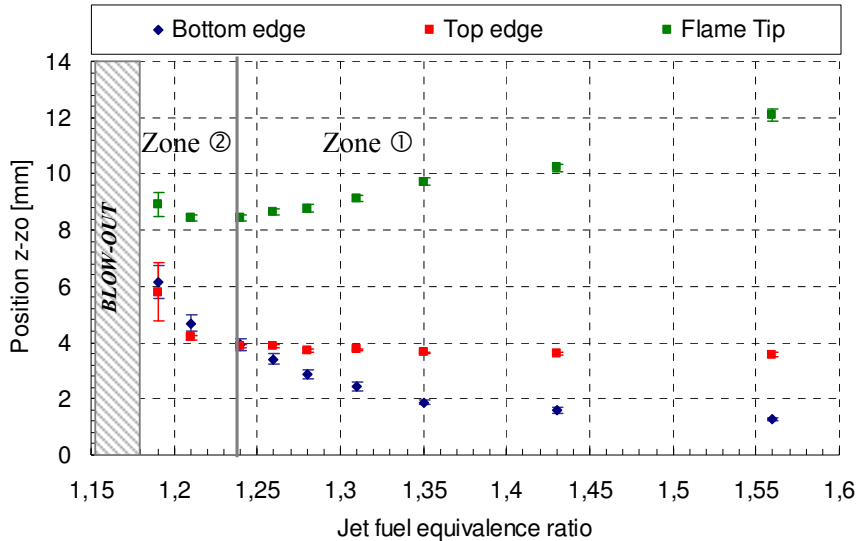
Figure 6 : flame / burner distance versus fuel equivalence ratio.

Figure 6 shows that the flame tip and the flame edges present different evolution when the equivalence ratio decreases. Indeed, in the first zone (zone ①), the flame tip moves linearly toward the burner. For the same equivalence ratio range, the position of the top flame edge is not modified. Concerning the position of bottom edge, it presents two different behaviours. For equivalence ratios up to 1.33, the bottom flame moves slightly downstream in the flow. When decreasing the fuel equivalence ratio, the evolution of the bottom edge displacement seems to become exponential. Finally, in the second zone (Zone ②), for equivalence ratio lower than 1.24, the three points evolve in the same direction and the whole flame moves away of the burner.

First of all, the linear evolution of the flame tip is described. When keeping the thermal power constant, the jet exit velocity increases and the fuel equivalence ratio decreases, inducing an increase of the flame propagation speed. The central premixed part of the flame can be compared to a horizontal Bunsen flame for which, the idealized relation between the flame tip half-angle θ, the flame propagation speed S_L° and the flow velocity V_o, is: $sin\theta = S_L^{\circ} / V_o$ [5]. On figure 7, the values of the ratio S_L° / V_o calculated for the 2D burner are plotted as function of the fuel equivalence ratio.
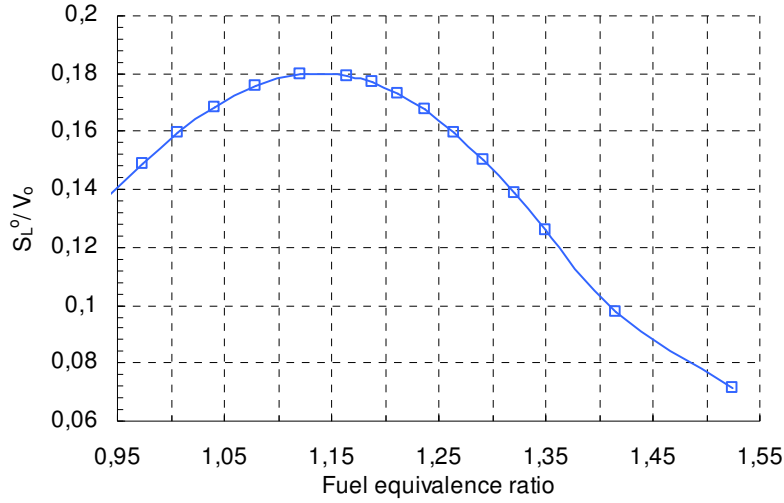
Figure 7: S_L° / V_o versus equivalence ratio for the burner configuration at constant thermal power.

When decreasing the fuel equivalence ratio (for $\phi > 1.1$), S_L° / V_o increases so that the flame angle increases, forcing the flame tip to move toward the burner. For lower fuel equivalence ratio ($\phi < 1.24$), the figure 6 has shown that the flame tip starts to move downstream in the flow. Indeed, when decreasing the fuel equivalence ratio and approaching the value corresponding to the maximum propagation flame speed, the ratio S_L° / V_o starts to bend. The curve behaviour is modified and the flame behaviour is changed as well.

Concerning the flame edges, when decreasing the premixing fuel equivalence ratio, the bottom flame base starts to move away from the burner, while the top edge remains attached to the burner flame-holder. For lower fuel equivalence ratio, (zone ②), it is observed that the two flame edges are stabilized at equivalent distances and the whole flame starts to move downstream in the flow till a limit for which the flame is extinguished.

This behaviour puts forward a change in the physical phenomena leading to the flame stabilization. Indeed, for large ϕ, the flame is stable and attached to the burner at both top and bottom sides. For lower fuel equivalence ratio, the flame remains stable with a top edge attached to the flame-holder, even if the bottom edge is lifted off. By comparison with the same experiments carried on a Bunsen burner configuration, it is observed that the top half-part of the 2D flame presents similar characteristics. Indeed, the Bunsen flame edges are attached to flame-holders while the flame tip is stabilized in the flow according to the local flow velocity and propagation speed. During this combustion regime, the thermal transfer between the flame and the burner must be effective and involved in the flame stability. In order to deepen these observations, the bottom flame base position has been investigated for different burner materials.

Bottom flame edge position for different burner materials

The slots-compound burner part has been duplicated in brass, copper and refractory steel. These materials have been chosen to present different thermal conductivities and hence to change local thermal transfers. The position of the bottom flame edge is obtained from OH chemiluminescence imaging. The easy implementation of this technique allows one to perform numerous measurements at different equivalence ratios for the three burner configurations. It has been checked that OH PLIF and OH chemiluminescence imaging give similar results in this

specific 2D geometry: absolute values of the bottom flame edge position differ by less than 1 mm and the evolution is exactly the same.
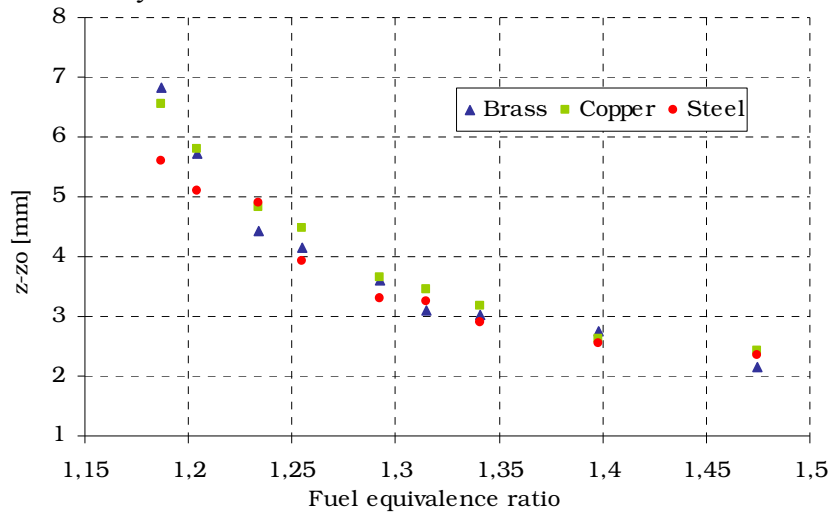
Figure 8 : bottom flame edge position versus equivalence ratio for different burner materials.

It is observed that when varying the burner material, the bottom edge position is not significantly modified (figure 8). Although a strong correlation has been noted between the flame position and the burner wall temperature, the position of the bottom flame edge is not controlled by the amount of thermal transfers between the flame and the burner wall. The bottom edge is thus not attached by a flame-holder process and is stabilized by others phenomena. In this region of the flame, it has been observed from velocity measurements that the part of entrained air is considerable and must be strongly involved in the stabilization phenomenon. The bottom flame edge position could be stabilized in a region where the local flow velocity balances the maximum laminar flame propagation speed corresponding to the local equivalence ratio.

When decreasing the fuel equivalence ratio, the two flame edges stabilize at equivalent distances and it has been observed on figure 5 that the premixed flame front is now strongly flattened. Then, a further decrease of fuel equivalence ratio tends to change the behaviour of the flame, which move slightly away from the burner. During this new regime, the flame is totally lifted off. Its stabilization is controlled aerodynamically in the flow by the local conditions of velocity and mixing, till a limit for which the flame is extinguished. Same behaviour is also observed when varying thermal input power or premixing momentum flux from stable flame to blow-out.

Conclusion

Partially premixed flames generated by a two-dimensional domestic slot burner have been studied. The complex structure of these flames is composed of a premixed flame front stabilized between two diffusion branches. Premixed and diffusion parts of the flame join together in common double points. The global operating ranges have been first established and the stability limits have been defined.

The flame structure has been analysed by means of OH Planar Laser Induced Fluorescence experiments. Several combustion parameters have been modified to analyse their effects on the flame structure evolution toward the blow-out. It has revealed that for a constant gas thermal power the flame regime is modified. The flame evolves from a mainly diffusion flame to a

mainly premixed one, close to the blow-out. Flame outlines have been extracted from the mean OH PLIF images and have revealed that the structures of the diffusion branches are not significantly modified by a variation of fuel equivalence ratio. However, the premixed flame front tends to flatten and the bottom flame base is strongly lifted-off.

The relative distances of the flame edges and the flame tip to the burner have been investigated in details and different stabilization regimes have been put forward. For high equivalence ratios the flame is stable and attached to the burner. The top edge flame is attached to a flame-holder, the flame tip is stabilized in the flow and the lifted off bottom edge flame is stabilized in the flow by other phenomenon than thermal transfers. Indeed, burner flame edge position measurements have shown that, the thermal conductivity properties of the burner material has no influence on the flame position. When the equivalence ratio is decreased, the stabilization regime is changed. The premixed flame front is now strongly flattened and the flame edges stabilize at equivalent position. The flame is stabilized aerodynamically in the flow by the local conditions of velocity and mixing, behaving like a planar non-stable flame. For lower fuel equivalence ratios, the whole flame moves away from the burner till a limit for which it extinguishes. These results provide some keys in the understanding of laminar partially premixed flames stabilization phenomena and can be used as guidelines for the design of new burners.

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