TURBULENCE EFFECT ON THE FLAME-WALL INTERACTION

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ABSTRACT

The flame-wall interaction is experimentally studied in the particular case where fresh gases separate the flame from the wall. The purpose of this work is to analyze, by means of a phenomenological approach, the different physical mechanisms involved when a turbulent premixed V-shaped flame interacts with a boundary layer. The aerodynamic description of the interaction has been emphasized, consequently most of the results arises from detailed description of the velocity field and from image processing of laser tomographies. This study put in advance two main phenomena. First, a global deflection of the flame due to the boundary layer development is shown. Second, there is a significant influence of the boundary layer turbulence characteristics on the shape and on the behavior of the flame front.

INTRODUCTION

All the studies dealing with turbulent reacting flows expanding in a combustion chamber are always confronted with the problem of the flame-wall interaction. This domain constitutes an important and complex part of the turbulent combustion analysis since it involves aerodynamic, thermal and kinetic phenomena. Most of the previous studies have been undertaken in the particular case of stagnating flames where burnt gases separate the flame from the wall (Yahagi et al. 1992, Escudié and Haddar 1993). Only a few of them are devoted to numerical or experimental approaches of the flame front propagating towards the wall (Lu et al. 1990, Ezekoye et al. 1992, Bruneaux et al. 1996). The purpose of this work is to fill this gap by investigating, experimentally, the interaction between a premixed turbulent V-shaped flame and a vertical plate. Fresh gases are then flowing between the flame and the wall, and the way in which the flame front and the boundary layer evolve is of great interest. In order to emphasize the aerodynamic process, thermal exchanges with the wall have been reduced by using an isothermal plate. In such a configuration the study of the influence of the boundary layer characteristics on the flame/wall interaction can be improved and the laminar and turbulent cases will be better described.

EXPERIMENTAL CONDITIONS

A lean premixed hydrogen-air flow (equivalence ratio ø:0.18) is provided at the exit of a square burner (110x110 mm^2). To generate turbulence, a grid is set 5 cm upstream the exit section. The experimental conditions selected for this work give a mean axial velocity of the premixed flow and a turbulence intensity level respectively equal to 5 m/s and 4% at the burner exit. As shown in Figure 1, the flame is stabilized on a platinum wire (diameter: 0.4 mm) and V-expanding next to a vertical adiabatic plate. To avoid disturbances on the stabilization process, the leading edge of the plate has been fixed 50 mm downstream from the flame-holder. The transverse distance between the flame-holder and the plate can be adjusted according to the boundary layer characteristics. These characteristics are principally depending on the laminar (LBL) or the turbulent (TBL) development of the boundary layer, which is linked to the shape of the plate at the leading edge. For a thin edge the boundary layer develops in the laminar regime and the evolution of the thickness follows classical Blasius similarity. A bold edge creates a fully turbulent boundary layer at 80 mm over the leading edge. As a consequence, in this paper, the main analysis related to the interaction between the flame front and the boundary layer will be achieved downstream from this transition zone, in a study area set between two stations: X=160 mm and X=220 mm.

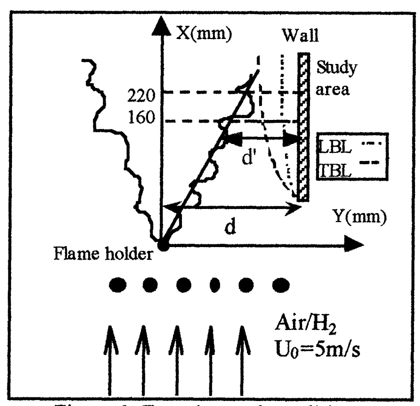


Figure 1. Experimental conditions.

Visualizations based on laser tomography and image processing are used to analyze the evolution of the flame front interface. A laser sheet, created by a 4W argon ion laser with a rotating mirror, lights the incense particles seeding the flow. The interface between burnt and unburned gases corresponds to the isothermal line of particles combustion, and can be approximated as a mean flame front position. The resulting photographs are digitized and transferred to a computer for storage and processing. In addition, a two-component laser Doppler anemometry system gives a detailed description of the aerodynamic flow. The flow is then seeded by ZrO_2 particles, and data are delivered by two synchronized FFT-processors.

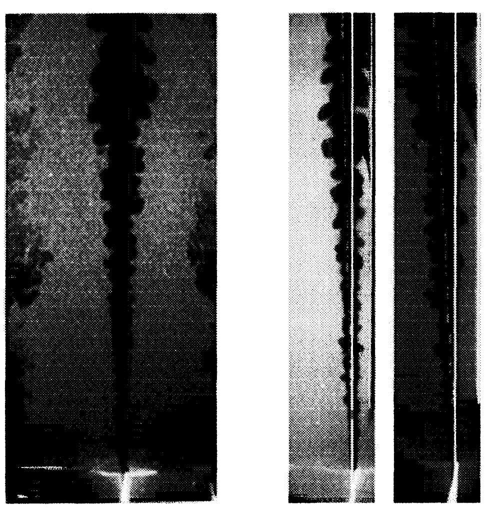
RESULTS AND DISCUSSION

To discuss about the interaction between a turbulent flame and a boundary layer developing along a plate, first it is necessary to define the characteristics of each one. The laminar flame V-expanding in a lean premixed hydrogen-air flow is well known and has been described in Escudié (1988) and François et al. (1997). The laminar velocity and thickness of the oblique flame are $S_L \infty 0.2$m/s and $\delta_L \infty 0.8$mm, respectively. In the turbulent case, when the flame is freely expanding the flame front clearly belongs to the classical flamelet domain (Borghi, 1985), as shown by the tomography presented in Figure 2. (a). Concerning the boundary layer, the arrangement is such that when the main flow is turbulent, the boundary layer development can be either laminar (LBL) or turbulent (TBL). For the two cases, the evolution of the boundary layer thickness δ_{BL} is plotted in Figure 4. and shows a typical larger expansion in the turbulent event. Due to the flame proximity and to a resulting earlier transition, this enlargement is more sensitive in the experimental reacting case in comparison with the theoretical prediction.

Taking into account this boundary layer development with the turbulent flame expansion, the flame-wall interaction study is here approached by two ways. First by looking to the global evolution of the flame with respect to the plate, second by investigating in detail a specific area of the interaction zone.

Effect of the Wall on the Flame Expansion

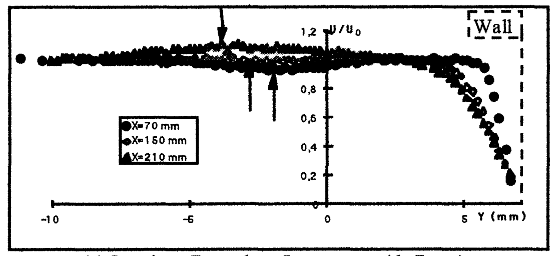
Information about the global evolution of the flame may be extracted from the axial and transverse velocity results.



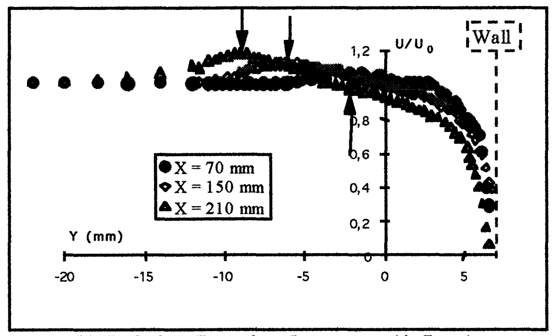
(a) Free single flame

Flame-wall interaction
(b) LBL d=4.9 mm
(c) TBL d=5.2 mm

Figure 2. Visualizations by laser tomography.



(a) Laminar Boundary Layer case (d=7mm)



(b) Turbulent Boundary Layer case (d=7mm)

Figure 3. Evolution of the mean axial velocity profiles.

For a given distance between the flame-holder and the plate (d=7 mm), Figure 3. shows the mean axial velocity profiles obtained for three stations downstream the flame-holder X=70, 150, 210 mm, and for the laminar (a) and turbulent (b) boundary layer cases. A displacement of the flame center position (arrowhead) away from the wall is clearly observed. The turbulent boundary layer thickness being larger than the laminar one, this shift is also larger in the turbulent case. In both cases, the competition between the flame and the boundary layer development is dominated by the boundary layer. As plotted in Figure 4. that leads to a deflection of the flame all the more large because the boundary layer is thick. A visualization of this effect is presented in Figure 2 (b, c). where are superimposed a vertical line indicating the non disturbed mean flame position and a dotted line corresponding to the deflection induced by the plate. It can be observed that a significant interaction between the turbulent flame front brush and the boundary layer only occurs far downstream.

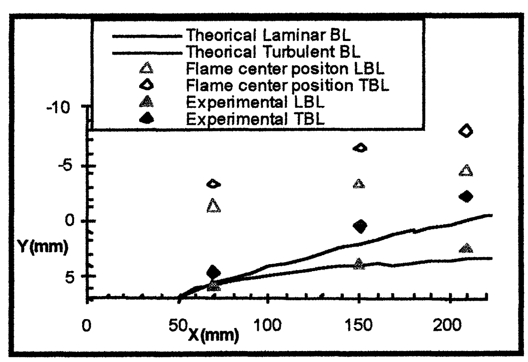


Figure 4. Evolution of the flame center position in comparison with the boundary layer expansion.

As a consequence a detailed analysis of the interaction will prevail in this area set between X=160 mm and X=220 mm.

Evolution of the Flame Front Shape as a Function of the Boundary Layer Characteristics

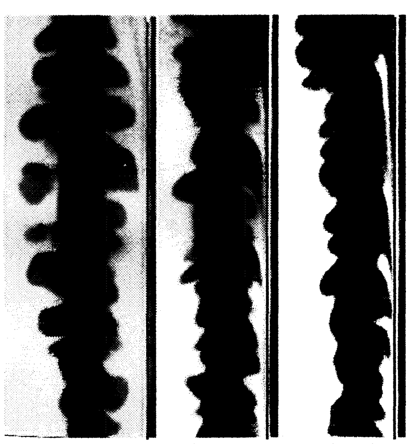
The analysis of the interaction process between a turbulent V-shaped flame and a boundary layer has been previously studied by Escudié and Richard (1997). A nondimensional parameter, defined as the turbulent flame brush δ_T divided by the boundary layer thickness δ_{BL} has been introduced as the Interaction parameter I: $I= \delta_T/\delta_{BL}$. Depending on the station checked downstream along the plate, this ratio varies from values less than to larger than unity. In the case of a laminar boundary layer, Escudié and Richard (1997) have noticed that increasing the interaction parameter was favorable to the interaction process insofar as it allows to show an increase of the flame front interface.

In our study, due to the turbulence development of the boundary layer, there is also a change in δ_{BL}. That leads to different values of the interaction parameter at the same station and to a different evolution all along the plate. Table 1. shows that the laminar case allows a large variation of the interaction parameter while the turbulent one always induces values less than unity.

Turbulent Flow	4%
Laminar Boundary Layer (LBL)	$I < 1, I = 1, I > 1$
Turbulent Boundary Layer (TBL)	$I \leq 1, I < 1$

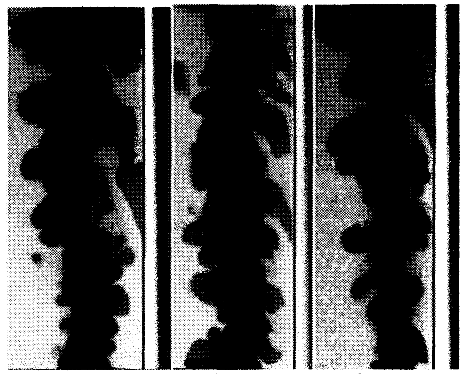
Table 1. Evolution of the interaction parameter downstream along the plate for a laminar (LBL) or a turbulent (TBL) boundary layer.

Moreover, by focusing on the downstream area previously defined, this parameter is found clearly larger than unity in the laminar case (I=1.2) and less than unity in the turbulent one (I=0.6). However, tomographic visualizations performed in this region (cf. Figure 5.) for the laminar and the turbulent boundary layer development show a significant evolution of the flame front interface in both cases.



d'=9.7mm d'=4.9mm **d'=3.8mm d=7 mm**

(a) Laminar Boundary Layer



d'=5.2 mm d'=2.7 mm **d'=2.5 mm d=7 mm**

(b) Turbulent Boundary Layer

Figure 5. Visualization of the flame-wall interaction when the flame is moving close to the wall. 160 mm < X < 220 mm

In particular, when the flame and the wall are sufficiently close, an increase of the interface assumed to account for the flame front can be observed. Then "tongues" of burnt gas, separated by thin spaces of fresh gas, appear in the near wall interaction region. Moreover, the major effect of the turbulent characteristic of the boundary layer seems to be a more wrinkled flame front.

This behavior has been quantified by measuring the length of the flame front interface, owing to image processing. Results, plotted in Figure 6., show the evolution of the non dimensional parameter $L=L_I/L_0$, defined as the ratio of the interface length in the interaction case over the interface length in the free case, when the mean distance between the flame and the wall (d') is vanishing. The effect of the interaction phenomenon on the flame front length is then traduced by an increase of L, which can reach values greater than one, respectively, 1.2 and 1.3 in the laminar and the turbulent case. Even though these values are comparable, they are not obtained for the same distance between the flame and the wall. The laminar boundary layer case induces higher values when the flame is close to the boundary layer, whereas a similar behavior is obtained for smaller distances in the turbulent case.

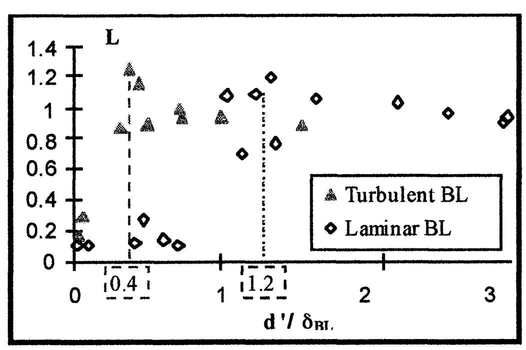


Figure 6. Evolution of the flame front length as a function of the flame-wall distance in the laminar and turbulent boundary layer development (160mm<X<220mm).

To explain such an increase of L a phenomenological approach has been developed. Three main effects have to be taken into account. First, the transverse gradient of the mean axial velocity leads to a slowdown of burnt gases in the boundary layer, that can induce a sloping of the flame front wrinkles and the emergence of "tongues". Second, an increase of the turbulence intensity in the boundary layer can also participate in enhancing the flame front wrinkle. Third, due to a vanishing velocity in the near wall region as well as an increasing flame propagation velocity related to strength and curvature (Chung and Law, 1988), the flame can propagate in the upstream direction inside the boundary layer. To elucidate the consequence of each of these effects on the flame front behavior, a detailed analysis has been developed.

Physical Analysis of the Flame front Behavior

The purpose of this section is a comparative analysis of the turbulent and laminar boundary layer cases, with the aim of estimating the relative importance of the phenomena previously introduced.

The study of the laminar and turbulent boundary layer cases has provided two maxima values of the interface length L for two distances between the mean flame front position and the wall equal to d'=3.8 mm ($d'/\delta_{LBL}=1.2$) and d'=2.5 mm ($d'/\delta_{TBL}=0.4$), respectively. In fact, these values correspond to the same distance between the flame-holder and the wall d=7 mm and consequently the physical analysis of the flame front behavior will be devoted to this particular station previously visualized in Figure 5 (a, b).

Effect of the transverse velocity gradient.

The first phenomenon to take into account for the analysis of the interaction process is the transverse gradient of the mean axial velocity dU/dY (s^{-1}). Due to this effect, when the flame is close enough to the wall to penetrate into the boundary layer, then burned gases are slowed down and the flame front wrinkles take a specific direction towards the upstream flow.

Results plotted in Figure 7. show a different behavior of the transverse velocity gradient depending on whether the boundary layer is laminar or turbulent. Even though the maximum value reached in the laminar case is lower than in the turbulent one, a progressive increase is noticed. That gives a preferential importance to this effect over a large part of the boundary layer in the laminar case.

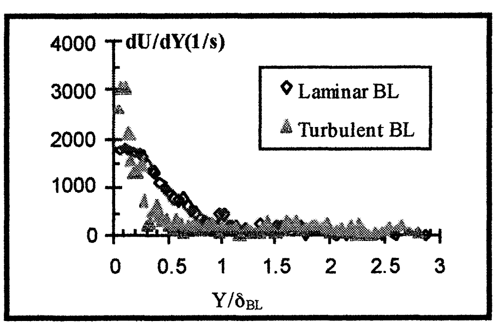


Figure 7. Evolution of the transverse velocity gradient in the laminar and turbulent boundary layer cases. (X=210 mm, d=7 mm)

This can be observed in Figure 5 (a,b). where the tilting of the flame front wrinkle becomes more visible in the laminar case (Fig. 5. a).

Effect of the turbulence level in the boundary layer.

The second effect which has to be considered is the turbulence intensity inside the boundary layer. Figure 8. shows that the rms values are comparable to the external ones in the laminar case, although a slight increase is noted in the steep velocity gradient region. Obviously, the turbulent boundary layer case induces higher values in the whole boundary layer. Principally, that leads to a more wrinkled flame front as a result of the classical effect of turbulence on combustion. The preponderance of the turbulence intensity over the flame front shape can also be clearly observed on the visualizations (Fig. 5).

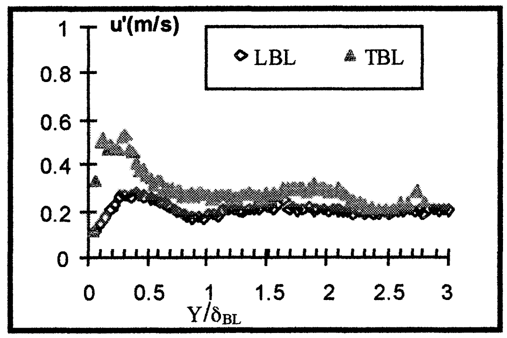


Figure 8. Evolution of the rms velocity in the laminar and turbulent boundary layer cases (X=210 mm, d=7 mm).

Effect of the velocity ratio S_L/U.

The last phenomenon implemented in the interaction process results from the comparison between the flame front propagation and the local velocity in the boundary layer. Indeed when a flamelet sweeps across the boundary layer its own laminar velocity is slightly modified by curvature and strength, and can become larger than the velocity field encountered in this zone. Then, depending on the value of the velocity ratio, S_L (laminar propagation velocity) over U (local axial mean velocity), in the wall vicinity, the flame can move forward inside the boundary layer. Such a propagation in the upstream direction can lead to appearance of laminar tongues within the boundary layer.

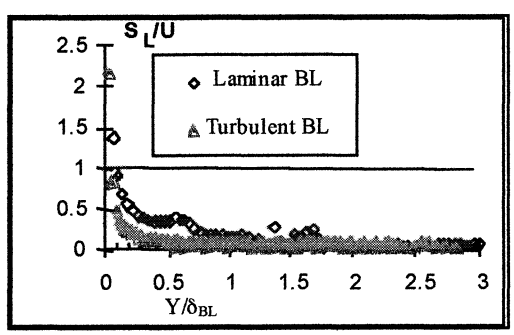


Figure 9. Evolution of the velocity ratio in the laminar and turbulent boundary layer cases (X=210 mm, d=7 mm).

Figure 9. shows the evolution of this ratio where S_L is defined as in Law et al. (1986):

$$S_L = S_L^0 \left[1 + (\frac{1}{Le} - 1) \frac{\delta_L^0}{S_L^0} K \right]$$

with S_L^0 and δ_L^0, the classical laminar flame speed and thickness, respectively, K = dU/dY and Le, the Lewis number.

Results emphasize the importance of this ratio in the laminar boundary layer which is consistent with the flame front shape visualized in Figure 5. (a). Inside the sublayer, in the nearest wall region, both cases generate values of the velocity ratio in the same order of magnitude ($S_L/U \sim 2$). As a consequence, even though this effect can be sensitive in the two cases studied, its efficiency on the length of the flame front interface is much clearer when interaction occurs between the laminar boundary layer and the flame.

To conclude this part, it is necessary to point out the three effects previously reported are all responsible for an increasing flame front length. By penetrating into the boundary layer, the flame is first submitted to the transverse velocity gradient which keeps burned gases. As it propagates within the boundary layer the turbulence intensity acts on the flame front and possibly may contribute to increase the wrinkle. Very close to the wall, the velocity ratio is preponderant and generates such peculiar structures described as laminar tongues. Then according to the boundary layer characteristic, results also emphasize that the relative importance of each event can be changed through the near wall region.

CONCLUSION

A new experimental study has been developed to improve our understanding of the physical processes occurring in the flame-wall interaction. The objective was to emphasize the aerodynamic point of view through the analysis of the influence of the boundary layer turbulence on the flame front topology.

First, results show a global deflection of the flame related to the boundary layer development and depending on its turbulent characteristic. When the flame is sufficiently close to the wall, an increase of the flame front interface is also noticed within the boundary layer. In that case a phenomenological approach has been developed in order to elucidate the physical processes involved. Three main effects have been investigated: the transverse velocity gradient, the turbulence level in the boundary layer and the effect of the velocity ratio S_L/U. Each of them contributes to the enlargement of the flame front interface and their relative contribution is depending on the boundary layer characteristics.

REFERENCES

Borghi R., 1985, "On the structure and morphology of turbulent premixed flame", *Recent Advances in the Aerospace Sciences*, pp. 117-138.

Bruneaux G., Akselvoll K., Poinsot T. and Ferziger J.H., 1996, "Flame-wall interaction simulation in a turbulent channel flow", *Combustion and Flame*, 107, pp. 27-44.

Chung S. H., Law C. K. , 1988, "An Integral Analysis of the structure and propagation of stretched premixed flames", *Comb. and Flame, n°*72, pp. 325-336.

Escudié D., 1988, "Stability of a premixed laminar V-shaped flame" Dynamics of Reactive Systems. Part I : Flames". Progress in Aeronautics and Astronautics, Vol. 113, pp. 215-239.

Escudié D., Haddar.E., 1993, "Experimental Study of a premixed turbulent stagnating flame". *Combustion and Flame*, vol. 95, n° 4, pp. 433-435.

Escudié D., Richard G., 1997, "Experimental Study of a Premixed Flame Interacting with a Wall", Turbulence, Heat and Mass Transfer 2, Delft the Netherlands, june 9-12, pp. 651-663.

Ezekoye O.A., Greif R. and Sawyer R.F.., 1992, "Increased surface temperature effecs on wall heat transfer during unsteady flame quenching", *Twenty-Fourth Symp. (Internat.) on Combustion, the Combustion Institute*, pp. 1465-1472.

François I., Larrauri D. and Escudié D., 1997, "Interaction between two premixed laminar V-shaped flame fronts at low Lewis number", *Combustion and Flame*, vol. 110, pp. 14-24.

Law C. K., Zhu D.L., Yu G., 1986, "Propagation and extinction of stretched Premixed flames", *Twenty-First Symp. (Inter.) on Comustion., the Combustion Institute*, pp. 1419-1426.

Lu J.H., Ezekoye O.A., Greif R. and Sawyer R.F., 1990, "Unsteady heat transfer during side wall quenching of laminar flame", *Twenty-Third Symp. (Internat.) on Combustion, the Combustion Institute*, pp. 441-446.

Yahagi Y., Ueda T. and Mizomoto M., 1992, "Extinction mechanism of lean methane/air turbulent premixed flame in a stagnation point flow", *Twenty-Fourth Symp. (Internat.) on Combustion*, the Combustion Institute, pp. 537-542.