TURBULENCE EFFECT ON THE STABILISATION REGIMES OF NON-PREMIXED FLAMES

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ABSTRACT
The aim of this experimental study is to point out the turbulence effect on the stabilisation mechanisms of a non-premixed flame. With this objective, a non-premixed methane-air flame stabilised on a tulip bluff-body is investigated. By means of direct visualisations and laser Doppler anemometry, an accurate description of the aerodynamic flow is provided. The influence of turbulence on the non-premixed stabilisation diagram is first described. Results point out an earlier transition of the five different regimes. Then the specific laminar ring flame region, where stabilisation is linked to the existence of a triple point, is particularly detailed. The main effect of turbulence is to modify the ring flame position and shape. A regular wave appears which analysis needs further development.

INTRODUCTION
Non-premixed flames obtained with double concentric jet burners are often industrially used. In such a configuration, flame stabilisation is generally ensured by a bluff-body generating high turbulence intensity and mixing rates. The complex flow patterns induced downstream the bluff-body need to be analysed according to the basic concepts governing the stabilisation process. Previous experimental studies have led to the identification of the main controlling parameters. The flame characteristic and topology are principally related to the fuel to air jet velocity ratio (Kimoto et al. (1981)). Depending on whether the fuel jet penetrates or stagnates in the recirculating zone, flames are then classified and called fuel jet or airflow dominant flames (Roquemore et al. (1986), Huang and Lin (1994)). Next to this classical velocity ratio, two other parameters have to be taken into account: the fuel characteristics (Dally and al (1998)) and the confinement (Scheffer et al. (1996)). In addition, recent studies have emphasised the part of the bluff-body shape (N'Guyen et al (1997), Esquiva and Escudié (2000)). Based on a detailed analysis of two different bluff-body geometries, the authors show that a profiled shape (Tulip) can induce an enlargement of the stabilisation domain. In particular, a specific zone called the "laminar blue ring flame" is significantly promoted. More precisely, results point out that for a fixed fuel to air velocity ratio the stabilisation process is clearly related to the aerodynamic of the annular flow, mainly controlled by the bluff-body shape. As a matter of fact, its influence on the recirculating zone leads to a change in the jet penetration and the mixing. Of course, if the mean flow is modified, the turbulence levels, principally linked to the mean velocity gradients, are modified too, what can act on the stabilisation process. Thus, if the aerodynamic of the annular airflow has such an importance on the behaviour of non-premixed flames, one may wonder about the influence of turbulence of this external flow. Up to now, only a few studies have been devoted to this problem (Favier and Vervisch (1998)).
In the frame of this work, we have chosen to look at the influence of turbulence on the stabilisation process of a non-premixed flame, anchored on a tulip bluff-body generating boundary layers expansion. The purpose is first to estimate the global evolution of the flame regimes as a function of turbulence swept by the annular airflow. Nevertheless, in order to value more precisely the importance of the turbulence parameter, the "blue ring flame" specific regime will be detailed. Owing to visualisations and aerodynamic field descriptions, the influence of the external turbulence on the ring characteristics and behaviour will be analysed.

EXPERIMENTAL CONDITIONS

Experiments are conducted in a non-confined device where natural gas (Dj= 5 mm) is supplied in the centre of an axisymmetric bluff-body (Tulip shape D_B=60 mm) surrounded by an annular (De=200 mm) co-flowing air (Figure 1). The exit velocity of the gas jet (Uj) and the mean axial velocity of the co-flow air (Ua) are variable (0<Uj<14 m/s, 0<Ua<20m/s), that allows investigation over a large domain of gas to air velocity ratio. To study the turbulent case, a square rod grid, which solidity and mesh size are equal to σ=0.36 and M_G=10mm, is set upstream the exit burner. Its geometry has been defined in order to generate scales and turbulence intensity levels comparable to the blue ring flame characteristics. At the axial blue ring station for an annular airflow velocity chosen equal to Ua=2.65 m/s, the turbulence intensity (u'/U) and integral scale (L) are 8% and 3mm respectively.

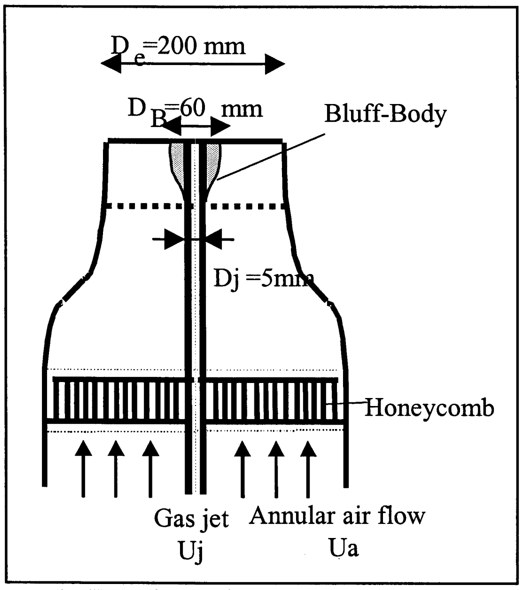

Figure 1 : Experimental set up.

Direct visualisations of the stabilised flames are recorded on a CCD camera. The aerodynamic description of the isothermal and reacting flows is performed by means of a two-component forward-scattering laser Doppler anemometry technique. The temperature and concentration fields are also detailed by using, respectively, a 6% Pt-Rh / 30% Pt-Rh thermocouple, and a sampling probe related to a gas analyser. In the frame of this paper, only velocity measurements will be presented.

RESULTS AND DISCUSSION

The analysis of the non-premixed flame is first conducted in the laminar case. The aim is to define the boundaries of the stabilisation diagram and to emphasise the specific laminar blue ring regime. The influence of turbulence will be then developed.

Characteristic mode and structure

A detailed description of the reacting flow in the "tulip" bluff-body's wake is performed over a wide range of annular flow to central jet velocity conditions. By fixing the central fuel jet velocity and by increasing the annular air flow velocity, five different stabilisation processes are observed before extinction (cf. Figure 2): laminar flame, transition I, laminar blue ring flame, transition II and recirculating flame. At low annular airflow velocity, a laminar axisymmetric diffusion flame is stabilised just behind the bluff-body. Increasing Ua leads to a first transition mode where the stabilising phenomenon is changing from a classical diffusion flame to a complex non-premixed flame stabilisation process. More precisely, this transition zone includes three specific flame features spreading out successively. First a wrinkle of the flame front appears. It grows and the flame reaches a particular behaviour called a "bulge flame", rich in soot. Second, the flame is lifted, "detached", and stabilised downstream in the wake. At the end of the transition zone, the flame moves upstream in the flow to stabilise again on the bluff-body surface, "reattached". This transition regime is followed by a "laminar ring flame", where a laminar blue ring is surrounding a laminar soot diffusion core. A further increase in the annular air velocity induces a new transition domain where the laminar blue ring flame becomes unstable and the central jet penetrates the reciculation zone of the bluff-body intermittently. This case corresponds to the transition between fuel jet and airflow dominant flames. Finally the "recirurlating mode" occurs and the flame is trapped inside the recirculation region (Esquiva and Escudié (2001)).

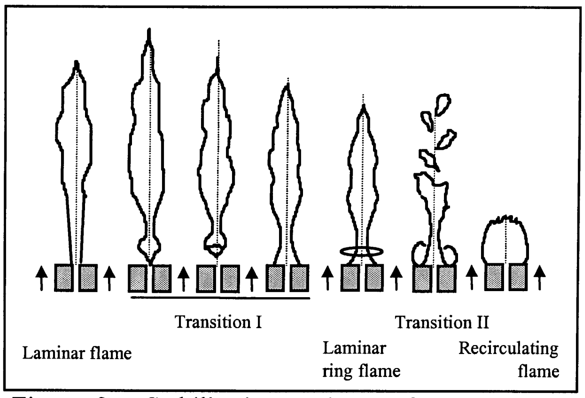

Figure 2 : Stabilisation regimes of non-premixed flames (Uj fixed, Ua increasing).

These different regimes are plotted on the stabilisation diagram presented in Figure 3. Results show that obviously the stabilisation process of a non-premixed flame in the wake of a bluff-body evolves as a function of the velocity ratio Uj/Ue. But they also put in advance that this development is linked to a regular evolution from a pure diffusion flame classically stabilised on the burner surface to a "partially-premixed" flame embedded in the bluff-body wake. Between these two extreme states, the intermediate case where the blue ring flame appears has now to be emphasised.

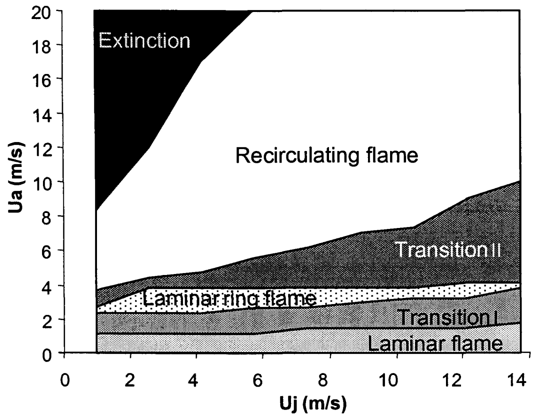

Figure 3 : Stabilisation diagram in the laminar case.

The laminar ring flame

The stabilisation process, called "laminar ring flame", and visualised in Figure 4, reveals a laminar blue ring (2) set far from the burner exit, and a blue cone (3) whose base corresponds to the ring. Both are broadly surrounding a laminar soot diffusion core (1).

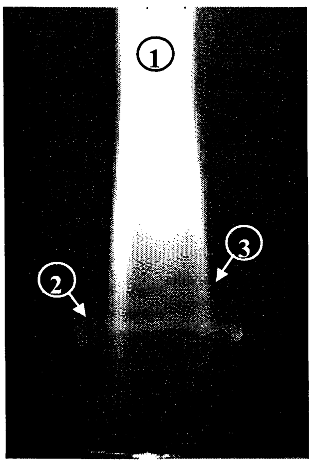

Figure 4 : Direct visualisation of the laminar ring flame.

Owing to a zoom set on the CCD camera, it is possible to enlarge a part of the ring visualisation. A tribrachial structure is clearly visible on the photograph presented in Fig. 5. It consists of three distinct branches corresponding to three different types of flames:

-a fuel-rich premixed flame, set along the inner part of the recirculation zone, towards the central fuel jet,

-a fuel-lean premixed flame, following the outer part of the recirculation zone, towards the annular air flow,

-a diffusion flame arising from excess fuel and oxidiser that survive through each branch of the premixed flames.

The intersection of these three branches at the leading edge of the blue ring is defined as the "triple point".

Such a flame, called "triple flame", was first observed by Phillips (1965) and its existence more recently confirmed by several studies (Kioni et al. (1993), Kioni et al. (1999), Azoni et al. (1999). All these works have shown that the triple flame structure has an intrinsic stabilisation mechanism, whereby the upstream flow velocity is reduced to the laminar flame speed by streamline divergence due to thermal expansion behind the curved triple flame front (Ruetsch et al. (1995)). Muniz and Mungal (1997) experimentally investigated the velocity profile at the base of a lifted jet flame and found it to be similar to the prediction of Ruetch et al. (1995). In particular, they observed that the flame stabilises itself in a region where the local gas velocity is near the premixed laminar flame speed.

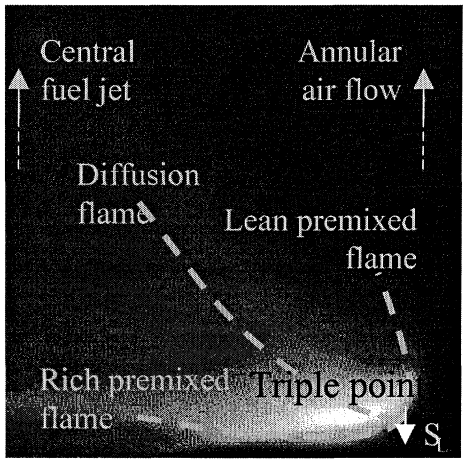

Figure 5 : Direct visualisation of the triple flame.

In the study presented in this paper the laminar ring flame domain is emphasised by the tulip bluff-body. As a consequence, the evolution of the triple flame can be investigated as a function fuel jet or annular air velocity variation. For this regime, due to the influence of these parameters (Uj, Ua) on velocity and mixing in the recirculation zone, the blue ring moves. For a fixed central fuel jet velocity, when the annular air flow velocity increases the gas jet is then constrained and its penetration reduced. That leads to larger mixture fraction gradients near the bluff-body's surface, and hence the laminar blue ring is shifted downstream.

Turbulence effect

The first effect of turbulence on the stabilisation process has been investigated by looking at the evolution of the non-premixed flame diagram. The same classification in five regimes previously observed can also be done. For the turbulent grid used, the evolution of the diagram boundaries as a function of the upstream airflow turbulence is not very noticeable (cf. Figure 6). Compare to the laminar case, when the annular airflow is turbulent the different stabilisation regimes are observed for smallest values of Ua. The main effect of turbulence is to generate earlier transitions.

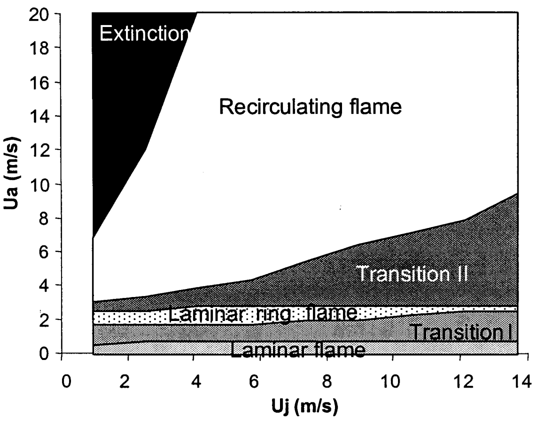

Figure 6 : Stabilisation diagram in the turbulent case.

In order to precise this point and to have a better understanding of the influence of turbulence on the stabilisation process, the particular case of the blue ring flame which lies between two transition modes (I and II) has been detailed. First of all, and to support the previous results on the diagram of non-premixed flames a quantitative description of the aerodynamic field will be provided. Then a detailed analysis of direct visualisations will be performed.

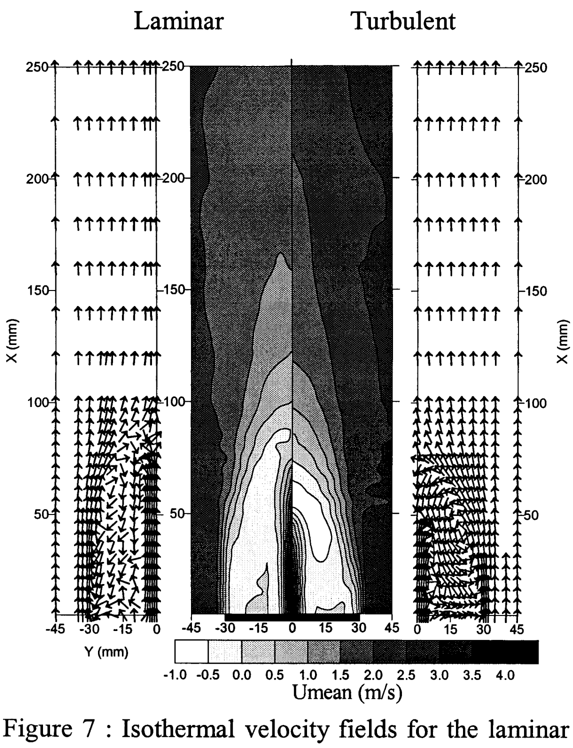

Figure 7 : Isothermal velocity fields for the laminar and turbulent cases Uj=4m/s and Ua=2.65m/s.

For a choosed experimental case in the laminar ring flame régime (Uj=4m/s and Ua=2.65m/s), a detailed description of the aerodynamic field is then achieved. The isothermal velocity field obtained for the laminar and turbulent cases is plotted in Fig. 7.

The turbulent case put in advance recirculating velocities greater than those obtained in the laminar one. This is linked to a shorter wake length, equal to 75mm in the turbulent case compare to 90mm in the laminar one. These results corroborate the evolution of the diagram boundaries as a function of turbulence. The mean wake being affected by turbulence, the laminar regions (both laminar and blue ring flames) are reduced and transitions occurs for lowest annular velocities.

The corresponding turbulent kinetic energy field $k=0.5(\overline{u'}^2+2\overline{v'}^2)$ is drawn in Figure 8. In the laminar case, large laminar zones and weak values of k stand at the interface between the recirculating flow and the jet penetration zone. Obviously, the turbulent case increases the whole turbulent kinetic energy fields, but these regions are also shifted close to the bluff-body surface, in accordance with the mean velocity profiles.

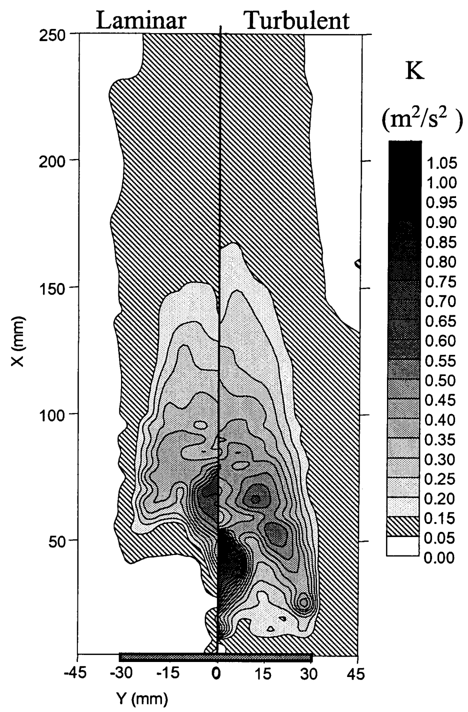

Figure 8 : Turbulent kinetic energy fields for the laminar and turbulent cases in the isothermal flow Uj=4m/s and Ua=2.65m/s.

The mean velocity field obtained for the reacting flow is presented in Fig. 9. Whatever the case, combustion induces a shifting of the recirculation zone apart from the central jet. However, as for the isothermal case, the main effect of the external turbulence is to change the recirculating velocities level and the length of the recirculation zone. Concerning the turbulent kinetic field, the classical relaminarisation effect due to heat release is here also demonstrated and most of the kinetic field displays small values.

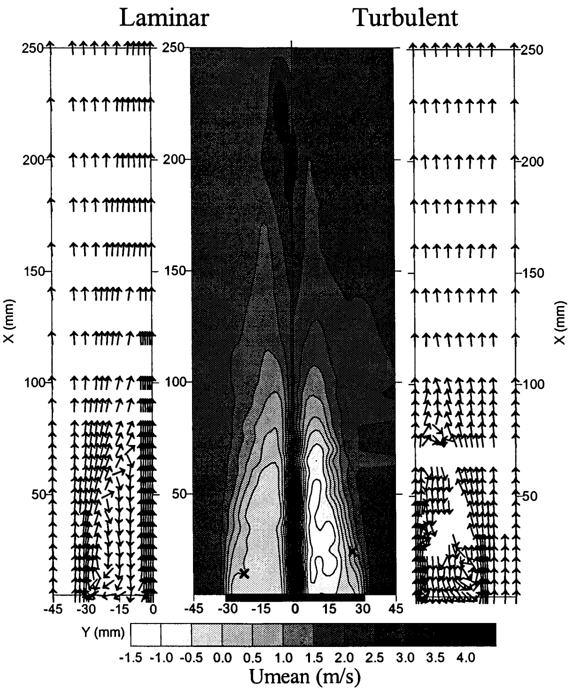

Figure 9 : Reacting velocity fields for the laminar and turbulent cases Uj=4m/s and Ua=2.65m/s.

In terms of the blue ring evolution, it is important to note that the mean position of the blue ring (marked with crosses) always lies in a vanishing turbulent kinetic energy region where the mean velocity is close to the laminar burning velocity of the stoechiometric methane-air flame S_L=0.4m/s.

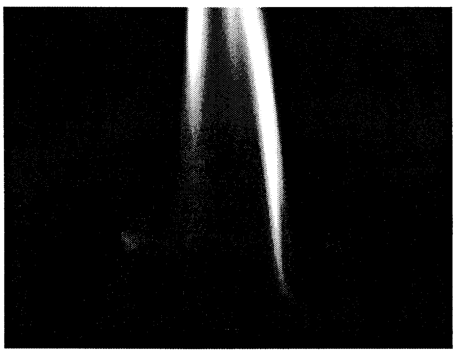

Figure 10 : The blue ring flame stabilised in a turbulent annular airflow.

A visualisation of the turbulent triple flame is presented in Fig. 10. Even though, as indicated before, the special blue ring case is still occurring when the annular airflow is turbulent, its shape is clearly modified. A regular wave is now disturbing the ring. The amplitude (a) and wavelength (λ) values of the wrinkle, issuing from image analysis, are equal to a=2mm and λ=20mm. In comparison, the longitudinal integral turbulent scale value measured at the same station in the isothermal flow is L=3mm. Even though a large continuum spectrum of turbulent scales is present in the external airflow, the blue ring stabilised at the frontier between the annular flow and the recirculation zone is characterised by well defined amplitude and wavelength.

To clear this phenomenon, we have looked at the evolution of the ring behaviour and characteristics when the annular air velocity is increased. To remain in the same regime previously described in the non-premixed diagram ("the laminar ring flame"), the annular air velocity range has to be small. For the laminar case, results have put in advance that an increasing annular air velocity is associated to a downstream shifting of the blue ring. As expected by considering the non-premixed diagram, the same evolution is found in the turbulent case. More over, due to the earlier transition, the mean ring position is higher for a same annular air velocity (cf. Fig. 11.) which is consistent with the previous analysis.

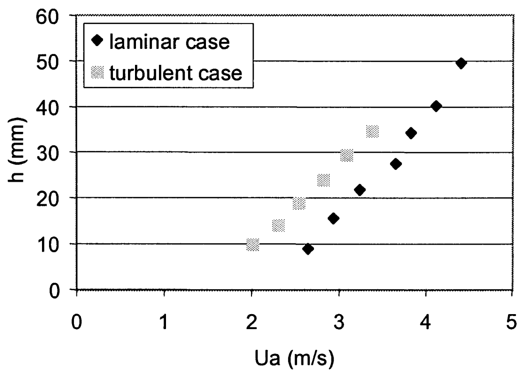

Figure 11 : Evolution of the blue ring height: comparison between the laminar and turbulent cases (Uj=4m/s).

Nevertheless, close to this evolution another factor has to be considered. In the turbulent configuration, a change in the external velocity alters the turbulence characteristics. If Ua increases, the turbulence intensity increases too, but the turbulent integral scale decreases. The corresponding effect on the wavelength and amplitude of the blue ring wrinkle is presented in Fig. 12.

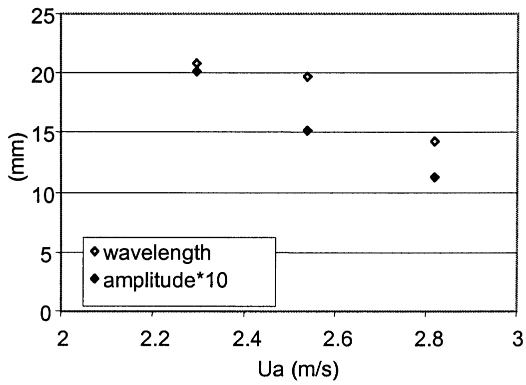

Figure 12 : Evolution of the wavelength and amplitude of the blue ring wrinkle as a function of the external velocity (Uj=4m/s).

A decrease is noted for rising annular airflow velocities (Uj fixed), but the connection with the turbulent characteristic of the external flow is not so clear. To approach this point, we have to recall that previous studies have pointed out the significant role of the bluff-body shape on the size of this particular regime. More precisely the stabilisation process seems highly controlled by the boundary layer expansion. As a consequence the specific blue ring topology should be linked to the effect of turbulence on the boundary layer development and stability. To understand this special event new investigations are required and work is now in progress.

CONCLUSION

Studies on flame stabilisation are still necessary in order to explain the fundamental physical phenomena involved in such a process. Previous studies have shown that the bluff-body shape is a significant parameter because it controls the aerodynamic of the annular airflow. As a consequence the influence of turbulence on the stabilisation process also needs to be investigated. With this aim, an experimental work has been conducted on the stabilisation of a non-premixed flame on a tulip bluff-body. First, the influence of turbulence on the stabilisation diagram has been detailed. Results show that the turbulent annular airflow induces modification of the bluff-body's wake such as greater recirculating velocities, shorter recirculation zone length, and a higher global level of turbulent kinetic energy. This evolution leads to a reduction of the laminar regions of the diagram. To support this analysis, the effect of turbulence on a specific regime which is significantly promoted by the tulip geometry (the laminar ring flame) has been investigated. Visualisations show that the blue ring is then disturbed by a regular wave which amplitude and wavelength are not directly linked to the turbulent scales. Further analysis are now necessary to give a better understanding of such a flame front topology.

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