EXPERIMENTAL STUDY OF A TURBULENT V-SHAPED FLAME STABILIZED IN A STRATIFIED FLOW

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ABSTRACT

The experimental work presented in this paper deals with the analysis of a premixed flame propagating in a non-homogeneous concentration field. The purpose is to characterize the effect of the stratification on the topology, structure and propagation speed of the flame front. The arrangement consists in a stationnary V-shaped flame, stabilized on a rod and expanding in a lean premixed CH_4/air flow. The interaction between the oblique front and the stratified slice, which equivalence ratio is close to one and size is larger than the flame front thickness, is investigated in both the laminar and turbulent cases. Techniques such as PIV and CH* chemiluminescence are used in order to describe the instantaneous fields. Measurements by LDA, thermocouple and a concentration probe provide informations on the mean fields. Highlighted by a comparison with the homogeneous cases, the data point out numerous interesting results. First, concerning the laminar case, a particular shape of the flame front, called "pensinsula", has been observed. This behaviour is linked to a specific evolution of the burning velocity in the statified slice. Second, the turbulent analysis have emphasized a new evolution of the velocity field, strongly deflected in burned gases behind the stratified front. This global approach has been related to temperature and CH* emission results. Three peaks profiles, reveal that at least a "secondary" reaction zone is involved in the interaction process.

INTRODUCTION

Over the past few years, the most important concern of engine manufacturers was to reduce fuel consumption and toxic gas emissions. To satisfy these new constraints, one solution was to develop direct injection for gasoline engines (GDI). This solution generates a stratification charge near the spark plug with very lean global air-fuel ratio, but in this case, the phenomena occurring inside the cylinder are much more complex.

Up to now, the numerical (Fan and Reitz, 2000, Gill et al., 1996) or experimental (Zhou et al., 1998, Jeong et al., 1998, Plackmann et al., 1998) studies on stratified charge have been only devoted to industrial configurations where physical mechanisms could not be easily approached. Only a few of them, mainly dedicated to direct numerical simulations (Haworth et al., 1998, Hélie and Trouvé, 1998, Poinsot et al., 1996) have adopted a fundamental approach. Results have shown that partial premixing has negligible contribution to flame stretch and flame surface production, but leads to strong variations of the local flamelet structure and of the mass burning rate. They have also pointed out notable changes, both in the flame structure and propagation speed, which is increased compared to the homogeneous flow.

The experimental work presented in this paper is in keeping with this general pattern. The purpose is to analyse the propagation of a premixed flame in a stratified flow and to characterize the effect of stratification on the structure and propagation of the flame front. Although industrial applications are mainly interested in turbulent analysis, we have chosen here to first develop the laminar configuration, which is more appropriated to qualify the basic concepts, and then to study the influence of turbulence on the stratified case.

EXPERIMENTAL CONDITIONS

A schematic view of the two-dimensional experimental apparatus is shown in Figure 1. The flame is stabilized at

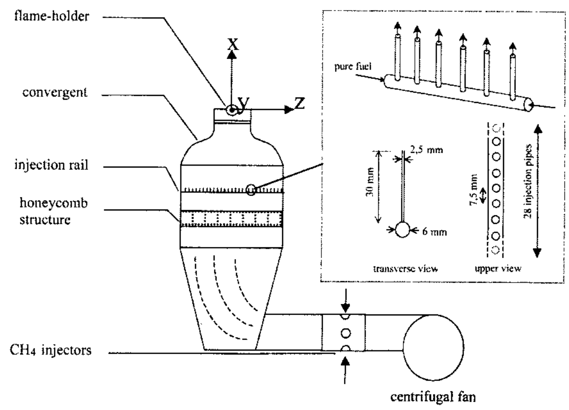

Figure 1: Experimental set-up.

the exit of the wind tunnel on a 2 mm diameter rod and V-expanding in a free flow which mean velocity is 5 $m.s^{-1}$. In the laminar case, the residual turbulence intensity is close to $I = 0.5$ %. For the turbulent flame study, a grid is set upstream in the flow in order to generate turbulence, whose characteristics are respectively $L = 5$ mm for the integral length scale and $I = 4$ % for the turbulence intensity at the exit station ($X = 0$ mm).

An injection rail, set within the settling chamber of the wind tunnel generates the stratified flow. Pure methane is injected by means of several small injection pipes in a homogeneous lean premixed methane-air flow (equivalence ratio = 0.58). In order to avoid aerodynamic disturbances due to the rail wake and to injection process, the arrangement is set just before a convergent and an isokinetic injection is achieved. Preliminary tests have confirmed the homogeneity of the stratification slice in the longitudinal direction Z (all along the injection pipes). The resulting transverse profiles of the equivalence ratio obtained at the station $X = 0$ mm

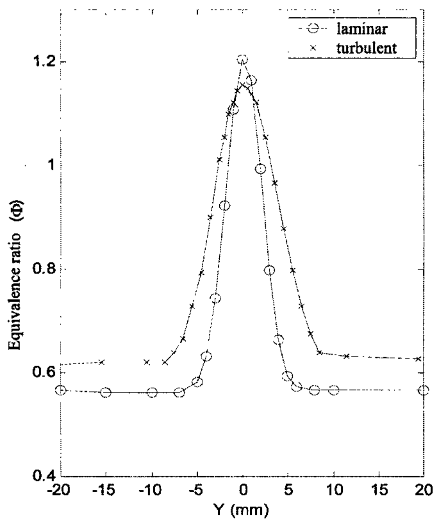

Figure 2: Equivalence ratio profile at the station $X = 0$ mm.

(in the flame stabilization zone) for laminar and turbulent cases are presented in Figure 2.

To characterize the stratification zone, four parameters are defined : the maximum value of the equivalence ratio (Φ_{max}) in comparison with the upstream mean value (Φ_0), the mean concentration gradient ($\frac{\partial \Phi}{\partial Y}$) and the stratification thickness (δ_S). In the frame of this study, at the initial station ($X = 0$ mm), the laminar (L) and turbulent (T) values are respectively $\Phi_{0L} = 0.58$, $\Phi_{maxL} = 1.2$, $\delta_{SL} = 12$ mm, $(\frac{\partial \Phi}{\partial Y})_L = 100$ m^{-1} and $\Phi_{0T} = 0.61$, $\Phi_{maxT} = 1.15$, $\delta_{ST} = 17$ mm, $(\frac{\partial \Phi}{\partial Y})_T = 60$ m^{-1}.

Different techniques have been used to detail the flame expanding in the stratified flow. A qualitative one, the tomography, provides information on the topology of the flame front. A laser sheet is then created by a 4 W argon ion laser associated to a rotating mirror and used to light incense particles seeding the flow. Images of the mean flame front position, corresponding to the interface between the bright (fresh gases) and dark areas (products), are recorded on a CCD camera (1528 x 1146 pixels^2).

To quantify the velocity field, Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) have been developed. For LDA, a two-colour, two-component Dantec system based on a 4 W argon ion laser and two burst spectrum analysers 57N20 Enhanced is used. For PIV, the laser source is a Nd:YAG (300 mJ) and measurements are based on a double-pulsed laser sheet (time delay: 50 μs). Photographs are recorded on a Dantec HiSense camera (1280 x 1024 pixels^2) and pairs of raw images were cross-correlated using 32 x 32 pixels^2 interrogation windows, with a 50 % overlap ratio between adjacent windows. Optical arrangements are such that the explored fields size is 41 x 51 mm^2 or 136 x 170 mm^2. In both cases, the premixed flow is seeded by particles of incense (only present in fresh gases) and zirconium oxide (ZrO_2) in order to allow measurements in burned gases.

Temperature measurements have been detailed by using Pt-Rh 30% / Pt-Rh 6% or Ni-Cr / Ni-Al thermocouples. The equivalence ratio fields have been obtained owing to a sampling probe linked to a gas analyzer based on the non-dispersive infrared absorption technique. In order to precise the reacting zone location, the CH* chemiluminescence fields have been also investigated with a cooled Intensified CCD camera Flame Star 2 (386 x 286 pixels^2).

RESULTS AND DISCUSSION

The purpose of this paper being to have a better understanding of the stratification influence on the flame front propagation, the laminar case is first studied. This configuration offers the opportunity to describe the topology of flamelets propagating in a non-homogeneous premixed flow, where the stratification scales are larger than the flame front thickness. In the second part of the work, the stratified flame expanding in a turbulent flow will be investigated.

The stratified laminar case

To highlight the non-homogeneous case, the laminar homogeneous case is first presented (Figure 3(a)). The laminar

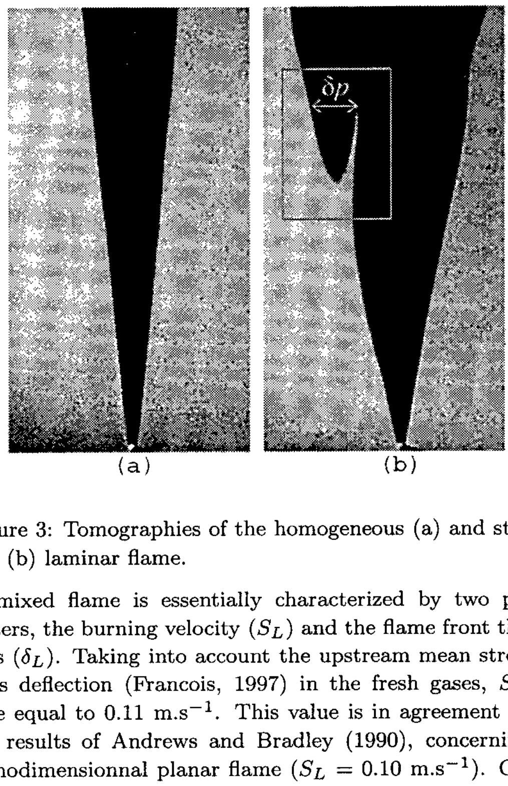

Figure 3: Tomographies of the homogeneous (a) and stratified (b) laminar flame.

premixed flame is essentially characterized by two parameters, the burning velocity (S_L) and the flame front thickness (δ_L). Taking into account the upstream mean streamlines deflection (Francois, 1997) in the fresh gases, S_L is here equal to 0.11 m.s^{-1}. This value is in agreement with the results of Andrews and Bradley (1990), concerning a monodimensionnal planar flame ($S_L = 0.10$ m.s^{-1}). Obviously, this effect should be considered for further analysis of the stratified case. Compare to the isothermal case, there is a deviation of the slice induced by the flame front. Visualizations, carried out by seeding the stratification slice with zirconium oxide particles, clearly show that the angle of slice deflection is in relation with the oblique flame front.

Concerning the flame thickness its value is defined by Jarosinski (1984):

$$\delta_L = \frac{T_b - T_0}{\left.\frac{dT}{dy}\right|_{max}} \quad (1)$$

δ_L is equal to 2.5 mm, which is lower than the stratification slice thickness ($\delta_S = 5\ \delta_L$).

Local analysis. A visualization of the V-shaped flame expanding in the stratified flow is presented in Figure 3(b). A particular pattern is obvious on the flame front, close to a regular oblique front. This bulging shape occurs in the stratified zone and its characteristic scale δ_P is in the same order of magnitude as the stratification slice thickness δ_S. This peninsula is separated from the oblique part by a vanishing strip of fresh gases. Thus, the first effect of the stratification is to induce a wrinkle of the flame front, and, as a consequence, to increase its length and the global mean reacting rate.

Figures 4 and 5 show the instantaneous velocity and CH* fields associated with this particular pattern occuring in the stratified zone. The detailed velocities description

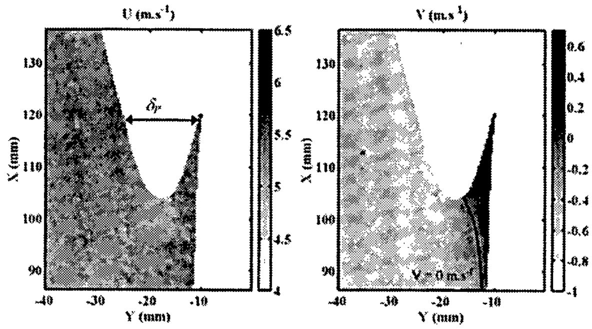

Figure 4: Axial and transverse velocity fields.

emphasizes the relationship between the bulging shape and its retroactive effect on the upstream flow. In particular, at the flame leading edge, the front curvature is associated to a strong deflection of the streamlines. This transverse evo-

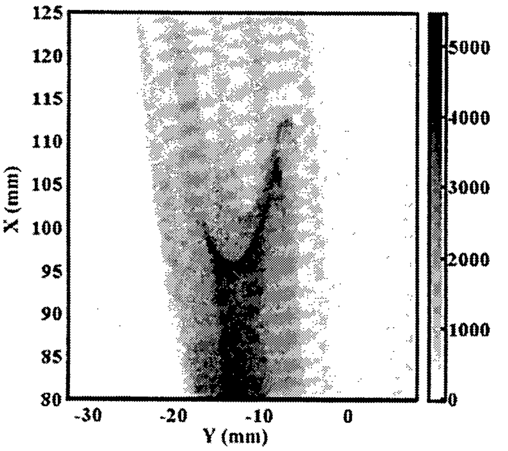

Figure 5: instantaneous CH* emission field.

lution can be related to a specific divergent line checked in Figure 4 (right). It is important to notice that this divergent line follows a different way from the vertical direction upstream of the leading edge front. This behaviour, which seems mainly controlled by the deflection of the stratified slice due to the oblique front, also reveals the retroactive effect of the stratified flame front. Moreover the most favorable direction for upstream propagation is approximately corresponding to the stoichiometric line.

Global analysis. The local analysis has emphasized a specific deflection of the mean streamlines in the fresh gases, which has to be discussed in the frame of an extended approach. The first aspect to be developed is the velocity evolution in the whole stratified flame, particulary in the burned gases. Figures 6 et 7 show the axial and transverse mean velocity profiles obtained for four axial stations, X = 30, 60, 90 and 120 mm. Compare to the classical laminar case, the effect of the stratification is first to induce a strong shift of the mean V-shaped flame. This deflection is here associated with higher transverse velocities in the stratified side due to the increased density step occuring in the stoichiometric stratification zone. This flame front evolution is also related

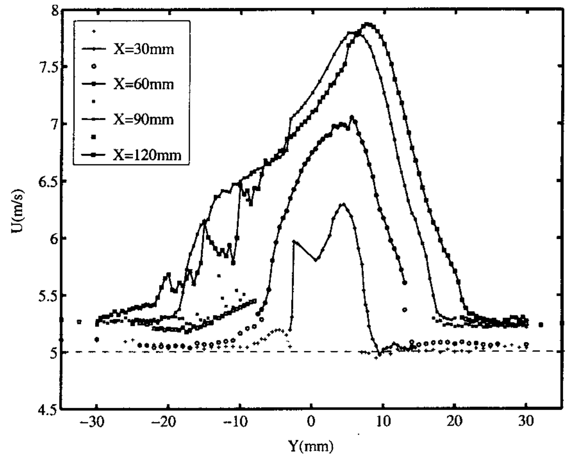

Figure 6: Axial velocity at different stations.

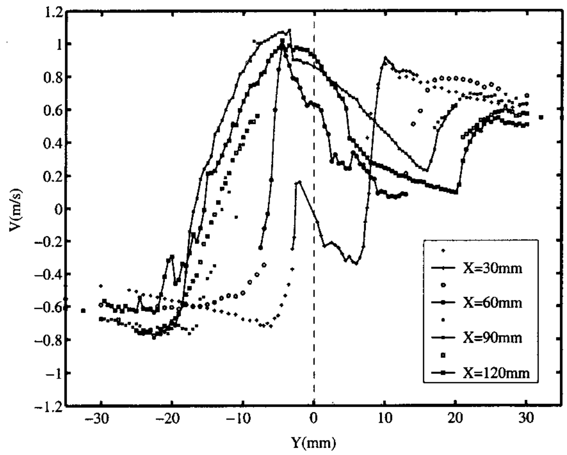

Figure 7: Transverse velocity at different stations.

to largest axial velocities. But this obvious process also involves a non classical phenomena, where the maximum of the mean axial velocity profiles is set far from the stratified part, in agreement with the mean streamlines deflection in burned gases. The normalized profiles of transverse temperatures and CH* emissions are plotted in Figure 8 for the two farthest stations X = 30 mm and X = 120 mm. Next

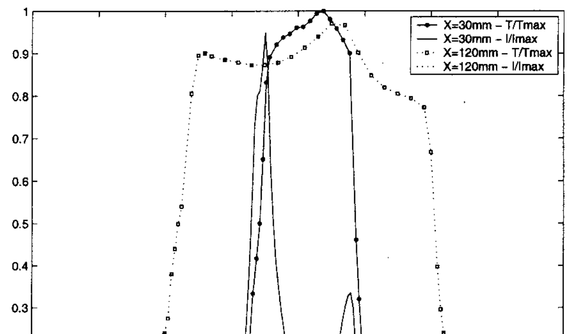

Figure 8: Normalized temperature and CH* emission profiles.

to the flame holder the two reaction zones, linked to each

V-branch, are visible on the CH* emission profile. This behaviour leads to a maximum temperature value in the centre part of the global flame. However, far downstream, three peaks stand out from the classical temperature shape. The oblique front expanding in the non stratified side reach a usual value, while the one on the stratified slice is clearly higher. But the most significant effect is pointed out by one more maximum in the V-flame center. These different temperature peaks are related to maximum values on the CH* profiles but this correlation needs improvements in order to explain a possible evolution of the chemical reaction.

Influence of turbulence on the stratified V-shaped flame

The knowledge of the influence of stratification on the turbulent flame is based on a first analysis of the homogeneous case. Figure 9(a) shows the classical wrinkle flame

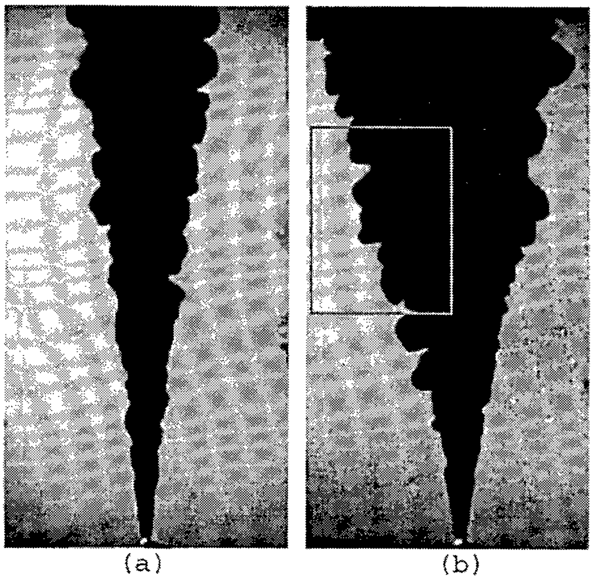

Figure 9: Visualisation of the turbulent homogeneous (a) and stratified (b) flame.

obtained according to the Borghi diagram (Borghi, 1984). As usual, the turbulent propagation velocity and the mean flame front angle are more larger than in the laminar case.

Local analysis. With the objective to have a better understanding of the effect of the non homogeneous flow on the wrinkle caracteristics, a local analysis has been developed. Results on the instantaneous topology and velocity field (PIV) are presented in Figure 9(b) and Figure 10. Due to the stoichiometric mixture encountered by the oblique flame front, its mean turbulent velocity is clearly increased, that leads to a larger value of the oblique front angle. Morever, the V-branch interacting with the stratification slice shows an increase of the characteristic scale of the wrinkle. Strangely, this influence is also significant on the other part of the flame, what probably results from a deflection of a part of the stratified slice upstream the stabilization zone.

The local flame front curvature and the scale of flame wrinkling are two important parameters for turbulent flames analysis. Curvature modifies the local burning velocity and the wrinkle scales are generally related to turbulence intensity. To detail this part, an image processing algorithm using Matlab software has been achieved. Flame contours are extracted from the tomographies thresholding and a cubic-

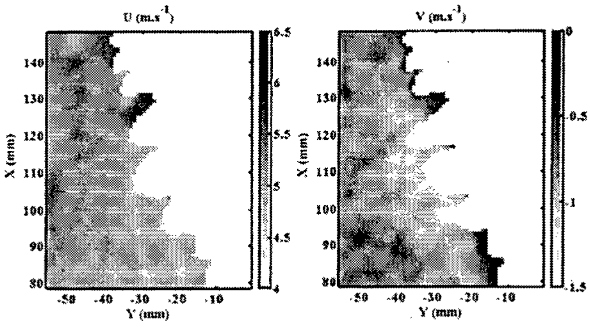

Figure 10: Axial and transverse velocity fields.

spline interpolation is used to calculate a smoothed function at each flame coordinate. The local flame front curvature (h) is then defined in curvilinear abscissa (s) by (Gray, 1993):

$$h(s) = \frac{\frac{dx}{ds}\frac{d^2y}{ds^2} - \frac{dy}{ds}\frac{d^2x}{ds^2}}{\left((\frac{dx}{ds})^2 + (\frac{dy}{ds})^2\right)^{\frac{3}{2}}} \quad (2)$$

With the sign convention adopted here, curvature is taken to be positive for convexity toward the burnt gas and negative for convexity toward the fresh mixture. The PDF of the curvature depends mainly on isothermal turbulent flow parameters and chemical flame characteristics (Lewis number). The distributions of curvature for the homogeneous

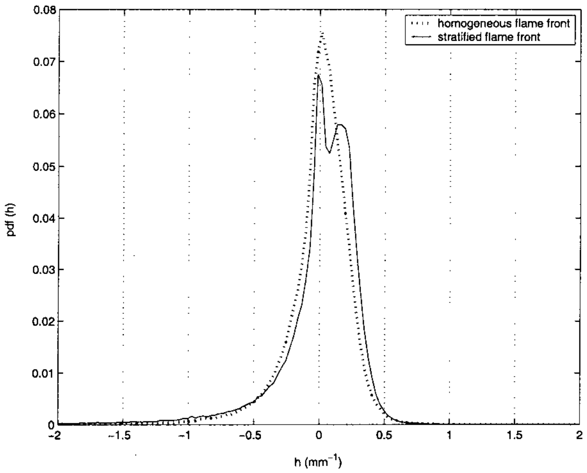

Figure 11: Distribution of flame curvature.

and stratified turbulent flame fronts are presented in Figure 11 over the whole domain ($0 < X < 160$ mm). PDFs values, calculated from 500 photographs, are presented without fitting. In both cases, the mean curvature is negative and very close to zero. For the homogeneous flame front, the curvature PDF can be approximated by a Gaussian distribution, as the results of several sudies (Shepherd and Ashurst, 1992), and the smallest radius of curvature is close to the half laminar flame thickness (Haworth and Poinsot, 1992). Results in the non-homogeneous case are significantly different. Two predominant values of curvature appear. The first one corresponds to a classical turbulent flame while the second one is specific to the stratified case. This variation of the local curvature has to be related to an evolution of the local burning velocity in the stratified slice. Even though such a particular behaviour needs to be corroborated by a local approach based on the curvature PDFs for different stations, this results are already very significant.

Global analysis. Compared to the turbulent homogeneous case, the main global effect of the stratification is to enlarge the mean angle (S_T is increased), a phenomenon associated with a stronger deflection of the mean streamlines. Figures 12 and 13 emphasize a specific behaviour of the turbulent stratified axial and transverse mean velocity fields, particularly in the burned gases. A great acceleration of burned gases (Figure 12) supports a very fast compensation of the flame-holder wake (approximately 20 mm compared to 70 mm in the homogeneous case). That results from a significant thermal expansion in the burned gases what is corroborated by temperatures measurements not presented here. Another interesting point is the level of the transverse velocities in burned gases (V_{max} = 1.5 m.s^{-1}) in the vicinity of the stoichiometric zone. The transverse positive velocities values indicate that, as in the laminar case, the effect of stratification is a shifting of the mean turbulent flame, which also explains the maximum axial velocities obtained towards the non-stratified front.

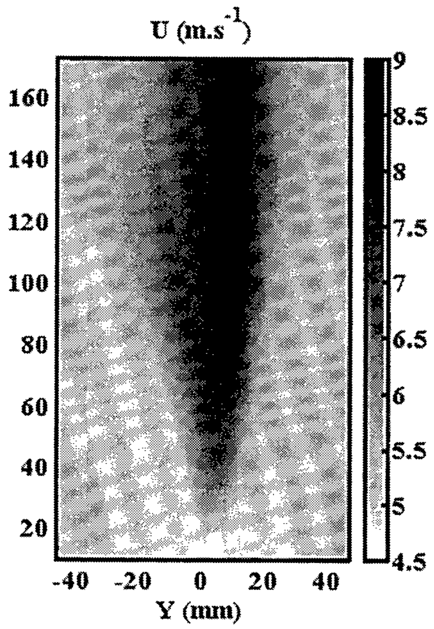

Figure 12: Mean axial velocity field.

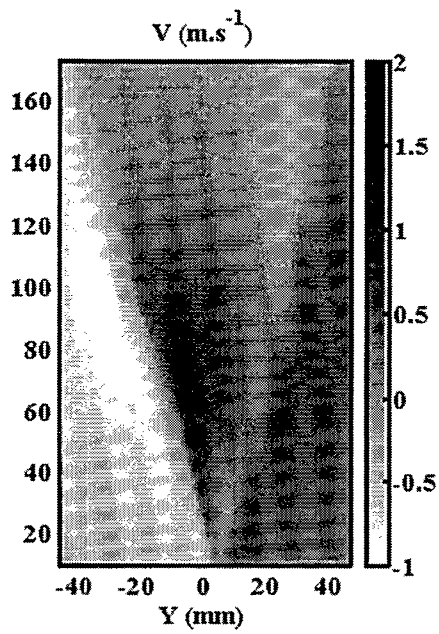

Figure 13: Mean transverse velocity field.

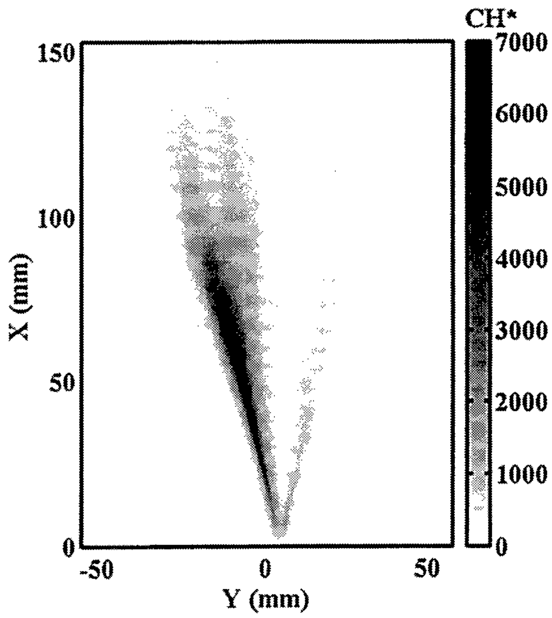

Figure 14: Mean CH* emission field.

The CH* emission field presented in Figure 14 for the whole turbulent flame, is also promoted in the stratification slice, slightly upstream the strong streamlines deflection zone. It is also noticeable that several branches of non-negligible intensity remain for stations higher than X = 100 mm. This phenomenon indicates that a particular chemical process is probably involved in the stratified V-shaped flame.

CONCLUSION

A new experimental arrangement has been characterized in order to study the propagation of a premixed flame in a stratified flow. Visualisations, CH*, PIV, LDA, temperature and concentration measurements are used to support the analysis on the flame front topology and to improve our knowledge of the effect of stratification on flame front propagation. The laminar stratified premixed flame is first studied as a reference case. The results emphasise a particular change in the flame front shape, associated with a retroactive effect of the stratified front on the upstream flow. A peninsula, whose scale is close to the stratification slice, appears revealing an increase of the flame front interface related to the mean reacting rate. The turbulence influences the expansion of the stratified V-shaped flame, first, by changing the mean flame front characteristics, as well as, the scale of the wrinkles. The analysis of stratified flame curvature PDF shows notable differences compare to the classical flamelet curvature distribution. Two values, one close to zero and another positive, seem to be predominant. The instantaneous velocity fields associated with CH* and temperature measurements give important information in order to explain the stratified turbulent flame. In particular, a specific behaviour leading to a three peaks profile both on the temperature and CH* profiles, needs new improvements in order to explain the chemical kinetic process involved.

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