Experimental study of freely-propagating premixed low-turbulent flame response to local stretch. Influence of Lewis numbers

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Abstract

An experimental investigation of the flame response to local stretch in the case of unsteady premixed low turbulent flames is presented. In order to point out the fundamental aspects of the interaction between combustion and turbulence, measurements of local flame properties (curvature, displacement speed) and tangential strain rate were performed under varying conditions of Lewis number and turbulence. An advanced field imaging technique coupling high speed laser tomography and cross-correlation Particle Image Velocimetry was used to measure the temporal evolution of local flame stretch exerted by the turbulent cold flow. A strong correlation between local flame displacement speed and local flame stretch rate was demonstrated, for several fuel/air mixtures. The influences of turbulence and Lewis number on these correlations were evaluated and compared with the linear relations obtained with mean flame speed and mean flame stretch.

Introduction

The aim of this work is to investigate the premixed turbulent flame response to local stretch by studying the temporal evolution of local properties of flame fronts and aerodynamical properties of the low turbulent cold flow at the entrance of the flame front. Combustion occurs in the flamelet regime where the interaction between turbulence and combustion are represented by flame surface area and local flame structure. For low positive values of flame stretch and for planar stagnation point flames, asymptotic analysis predict a linear relationship between the flame displacement speed S_d relative to the fresh gases of individual flamelets with the total flame stretch K [Clavin and Joulin, 1983] and [Williams, 1985], according the well-known relationship:

$$S_d = S_L° - £_d\ K \tag{1}$$

$S_L°$ is the unstretched laminar flame speed and $£_d$ is the Markstein length and changes signs for critical value of Lewis numbers Le_c, coming positive for $Le<Le_c<1$ and negative for $Le>Le_c$. An interesting feature is to extend this relation for high curved flamelets which are typically submitted to high negative and positive stretch. In this flame configuration, curvature effects are predominant in comparison with strain effects.

Experimental set-up and optical diagnostics

An experimental study has been realized to characterize both the spatial structure of the flame front and the dynamic of the turbulent cold flow in the case of freely-propagating premixed turbulent flames. The experimental set-up is described in details by Erard et al. (1996), and consists of a vertical wind tunnel where the different fuel/air mixtures are spark-ignited by thin wire electrodes. The flame kernels then propagate upstream in a decaying isotropic turbulent flow. The turbulent flow characteristics have been determined by LDV and the different turbulent conditions have been produced with a mean flow velocity of 4m/s. High speed laser tomography technique was adapted to visualize the instantaneous flame surfaces and the temporal evolution of the flame growth from the spark time to the fully developed flame in the combustion chamber [Renou et al., 1998]. A high copper vapor laser was used at 6.5mJ/pulse and 6kHz frequency with 50ns pulse duration. The flame surface images were recorded with a high speed CORDIN camera on photographic films. The contours of the different turbulent flames captured at several stages of flame development were extracted with an edge detection algorithm, using thresholding and smoothing procedures. The flame contours were centered and superimposed from the photographic film, for different stages of flame development. Local flame curvature h and flame displacement speed S_d^b relative to the burned gases can be determined for each stages of flame propagation [Renou et al., 1998] from the instantaneous flame front. Simultaneously, from the same tomographic recordings, and with an interval time of 166.7µs between each tomographic recordings, cross-correlation PIV was adapted to determine the turbulent flow field characteristics in the flow field [Lecordier, 1997]. From these instantaneous two-dimensional velocity fields, the velocity vectors can be determined in front of the flame fronts (Figure 1). The tangential strain rate defined by the derivative of the tangential velocity of the fresh gases is obtained by PIV along the flame contour according [Nye et al., 1996] and [Mueller et al., 1996]:

$$S_{tt} = \frac{f u_t}{f s} \tag{2}$$

where u_t is the tangential velocity of the fresh gas determined by PIV, associated to the flame contour.

Local flame stretch determination and analysis.

The local flame stretch can be calculated from the sum of a tangential strain rate S_{tt} with the product of local displacement speed and flame curvature [Candel and Poinsot, 1990]:

$$K = S_{tt} + 2S_d^b h \tag{3}$$

The local stretch K characterizes the instantaneous flame front during its propagation and controls the flame surface production. The application of stretch expression to the spherical expanding flames and averaged along the flame contour is generalized for turbulent cases by Law (1988), with the following relation:

$$< K >= \frac{2}{R_P}\frac{dR_P}{dt} \tag{4}$$

where R_P is the mean flame radius based on the flame perimeter.

• A comparison of these two mean flame stretch determination is exposed in figure 2, for an hydrogen/air flame (u'/U=4%, Φ=0.27) and indicates a good agreement between these two methods. This comparison can be considered as a validation for the local flame stretch determination from Eq. 3 in the case of low turbulence conditions and underlined the accuracy on this determination. For high turbulent hydrogen/air flames, the local flame stretch determination is not possible since large uncertainties can be observed between results from Eq. 3 and Eq.4.

• The local flame stretch is computed for several stages of flame propagation and experimental conditions and exposed in figures 4, 5 and 6 versus the local flame speed of the flame front relative to the unburned gases S_d, respectively for propane, methane and hydrogen/air flames. The slope of these linear correlations is always positive even for Lewis numbers more than unity. The flame speed behavior with local stretch is similar with local flame curvature [Renou, 1999]. Local strain effects can be neglected in comparison of curvature effects, and the local flame speed is always increased for an increasing of positive flame curvature. This phenomenon is enhanced for low Lewis numbers (hydrogen/air flames) where the flame fronts presents successively high negative and positive curvatures. Eq. 1 indicates an increasing (respectively decreasing) of displacement speed with flame stretch for $£_d<0$ (respectively $£_d>0$) whereas a positive linear dependence with K is experimentally observed for each fuel/air mixture (Figs. 4, 5 and 6).
These evolutions of experimental values of S_d with stretch present also an opposite trend with results obtained by numerical simulations [Chen and Im, 1998] in a case of turbulent planar flames. These differences may be principally explained by the difference between flame configuration geometry studied and probably by the choice of the isotherm for the flame speed determination. In a case of freely-propagating turbulent flames, mean and local values of strongly depend on flame development stages and thereby on the mean flame stretch as mentioned in [Renou, 1999]. These mean flame stretch effects are predominant in the first stages of flame propagation and must be take into account in Eq. 1 to predict the local flame speed.
One can notice that Deshaies and Cambray (1990) have also demonstrated in an experimental flame stagnation plane configuration that the choice of the isotherm is expected not only to influence the flame velocity value and also possibly to reverse its dependence on the flame stretch.
• Moreover, the temporal evolution of the mean flame characteristics can be obtained from tomographic recordings and may be correlated with the spatially averaged values of flame stretch, according the asymptotic spatially averaged relation:

$$< S_d >= S_L^{\upsilon} - £_d < K > \tag{5}$$

The experimental results obtained for a turbulence intensity of 4% and the three different fuel/air mixtures are reported in Fig. 3. The linear correlations indicate that for hydrogen/air flames (Le=0.33 < Le_c) the mean flame speed increases for an increasing mean flame stretch whereas, both for methane and propane/air mixtures (in the range of equivalence ratio) where the Lewis number is equal or more than unity, the mean flame speed decreases as the mean flame stretch increases. These evolutions of mean flame properties are in accordance with the expected trend suggested by asymptotic analysis, but differ strongly from the local flame properties correlation, thus indicating that the non-stationary effects have to be taken into account for such local correlations.

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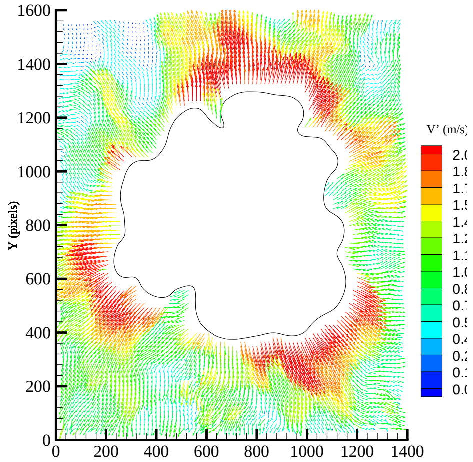

Figure 1 : Fluctuating velocity field obtained by PIV (64 pixels_, 75%) for propane/air mixture. u'/U=9%, Φ=1.0, t=7.0ms

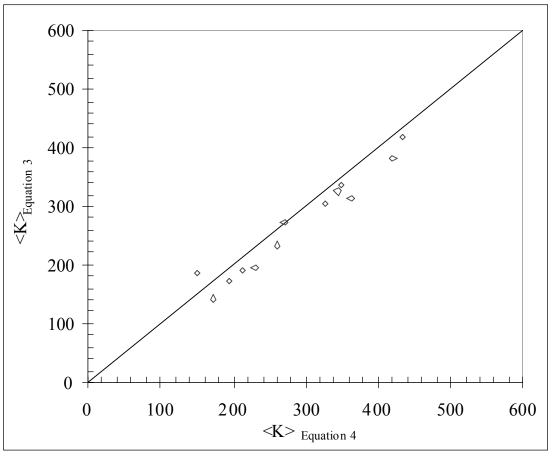

Figure 2 : Comparison of mean stretch values obtained by Equations 3 and 4 .

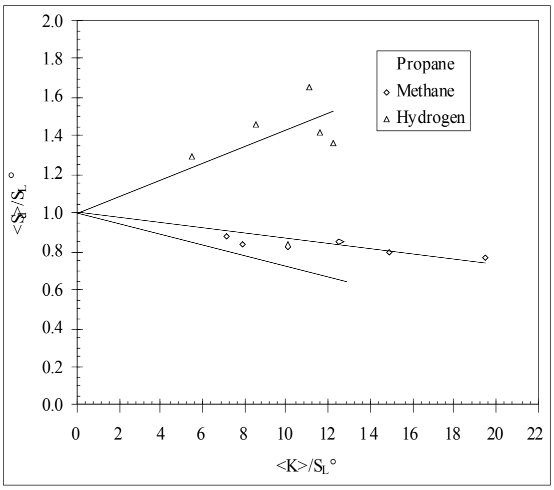

Figure 3 : Linear correlation between mean displacement speed and mean stretch for various fuel/air mixtures (u'/U=9%).

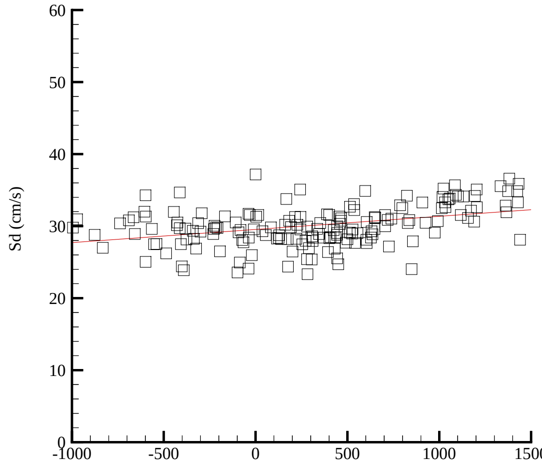

Figure 4 : Correlation between local flame speed and local stretch for propane/air flame. u'/U=4%, Φ=1.0, t=7.0ms

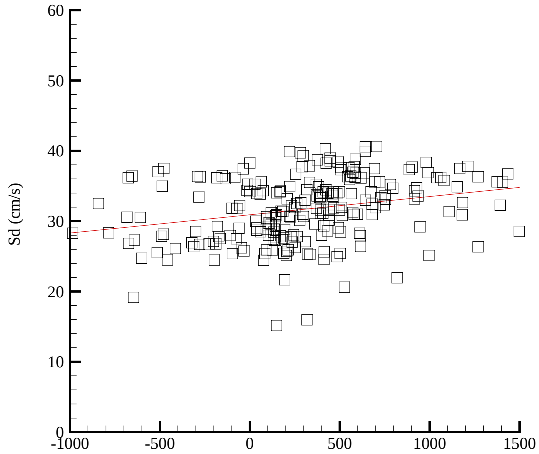

Figure 5 : Correlation between local flame speed and local stretch for methane/air flame. u'/U=4%, Φ=1.0, t=7.0ms

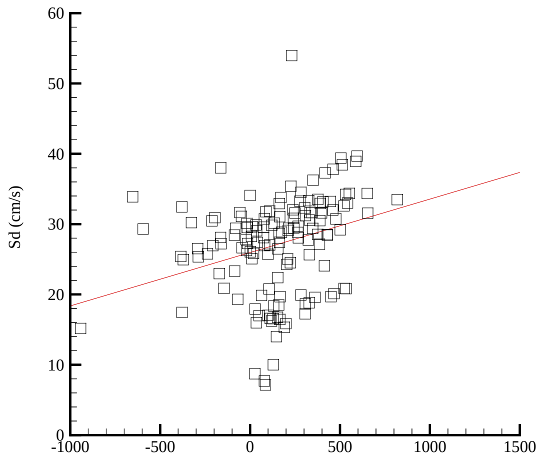

Figure 6 : Correlation between local flame speed and local stretch for hydrogen/air flame. u'/U=4%, Φ=0.27, t=7.0ms