Time-resolved description of a flame front propagation toward an inclined wall - The effect of local stretch on flame speed

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Abstract Time-resolved PIV was used to analyse the propagation of a laminar flame front toward a wall in laminar flow conditions. Forced instabilities were applied to the flame so simple working conditions of Darrieus-Landau instabilities could be simulated in flames interacting with the wall in limited regions making possible to be captured time dependent processes that occur randomly in the wall. High speed PIV was used to acquire the flame propagation and all reactants velocities during the total process. Specific software was developed to determine flame speed in laboratory and flame coordinates. Combined with flow velocities at the same instant it was possible to separate flow transport effects in the determination of effective flame speed relative to reactants. Curvature and flow stretch for all instant positions acquired of the flame front are determined, being possible to identify various effects of the wall in the flame and direct influence of stretch on the flame. Results were analysed and show to be a direct influence of the wall on the flame behaviour. The change of flow patterns due to the wall are strongly affected and flame front is mainly influenced by it.

1 Introduction

The Turbulent premixed flame-wall interaction, which occurs in any industrial burning equipment, is a process controlled by a competition between thermo-diffusive and aerodynamic process. The presence of a wall creates a boundary condition for the flow ahead of the flame front. This flow pattern is likely to affect the flame front irregularities, conditioning ultimately the flow ahead of the flame (Foucher & Mounaim-Rousselle 2005, Bruneaux et al. 1997, Poinsot & Veinante 2001).

Although laminar cases of premixed flame-wall interaction are usually simplified into head-on and side-wall quenching, laminar flames are also known to have unstable characteristics being most willing to wrinkling (Bradley et al. 2001 in large scale explosions and in numerical stability analyses of Law & Sung 2000, and is worth to mention Helenbrook & Law 1997, Bradley et al. 1998 and Bradley et al. 2000). But the study of flow/flame/wall interactions in laminar flame propagations is still in very premature conditions. As has already presented by Foucher et al. 2003, in a wall presence a wrinkled flame has no longer a separated behaviour between head-on and side wall quenching or a mixed combination of both, effects derived from the reactants trapping between the flame and the wall increases the flame winkling and produces very elevated stretch that is responsible for variations in reaction rate and flame speed.

Foucher et al. 2003 shown that the unusual wrinkles appear in the flame front when the distance to the wall is reduced and that effect is in very high dependence of the equivalence ratio. The change of the equivalence ratio is a main process to modify the way how flame responds to curvature velocity gradients by thermo-diffusive effects, evaluated by the Markstein length (Bechtold & Matalon 2001), is also one of the main factors shown in Bradley et al. 1998, Bradley et al. 2000 and Bradley et al. 2001 for the development of cellular flames. Nevertheless, the equivalence ratio also affects the density change in the flame front (ρ_b/ρ_u) which is the promoter of the Landau-Darrieus instabilities. Both these effects have been widely analysed for a long time, but in the presence of a wall boundary heat release and flow are certainly affected, so as the flame approaches the wall the flame speed (S_u), perpendicular to the flame and defines the burning rate, might vary along the flame surface. As a consequence, in a wall vicinity, burning rate might increase or decrease leading ultimately to a premature extinction.

The appearance of unusual wrinkles presented by Foucher et al. 2003 brought us to the the main objective of this paper. It is our first intention to quantify the variation in flame speed (S_u) in regions of very high negative curvature based on the stretch relations with flame speed $S_u = S_l - Lk$, where L is the Markstein length, k the stretch factor and S_l the unstretched flame front velocity.

In this work a flame is artificially deformed as it approaches the wall to create a wrinkled flame front in the vicinity of the wall. In addition the wall is set to be oblique to the global flame propagation so asymmetries can be developed in the flow and promote the flame response. Using high speed PIV all flame front propagation is acquired, the reactants velocities $(\vec{U})$ determined and the instant flame front position is determined, so flame front displacement velocity $(\vec{W})$, defined in the lab coordinates, and flame curvature in each point can be calculated. Once determined all parameters, the flame front velocity can be obtained from the velocity triangle in the flame front, defined by $\vec{S}_u = \vec{W} \cdot \vec{n} - \vec{U} \cdot \vec{n}$ (see figure 1).

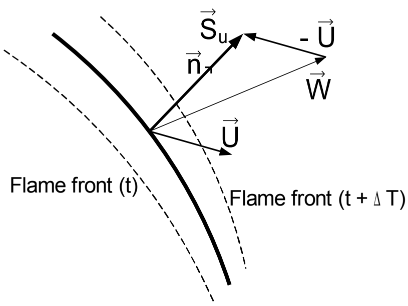

Fig. 1. Velocity triangle in the flame front

The total stretch factor is however a combination of effects of flame curvature and flow gradients on the flame front, defining respectively the curvature stretch (k_c) and the flow stretch (k_s), the total stretch is then the summation of both $(k = k_c + k_s)$. The definitions of curvature and flow stretch are as follows:

$$k_c = S_u(\vec{\nabla} \cdot \vec{n}) \qquad (1)$$

$$k_s = -\vec{n} \cdot (\vec{n} \cdot \vec{\nabla})\vec{u} + \vec{\nabla} \cdot \vec{u} \qquad (2)$$

The time resolved analyses of the propagating flame near the wall has the purpose to describe the flow patterns and its evolution during all propagation, correlate them with the evolution of stretch making identify the major contributions of the wall, or mechanisms, that affect the flame speed and stability of the flame front.

The experiments consider the laminar flame propagations in premixed propane/air conditions, considering mixtures with Lewis numbers $Le > 1$ and $Le < 1$, which are achieved with equivalence ratios $\Phi < 1$ and $\Phi > 1$ respectively.

In this paper will be following the description of the used experimental setup, PIV equipment, seeding and also the specific operating conditions that provided the achieved results. A demonstration of PIV processed results is provided and specific expressions used to determine stretch values. Further are presented results considering total stretch values and specific analysis that provide the separation between weakly and highly stretched flames. For ending is also analysed the importance of both sources of stretch and in which way these sources of stretch are influencing the flame front.

2 Experimental setup

Experiments of freely propagating flames in premixed propane/air mixtures in lean ($\Phi = 0{,}86$ and $Le = 1{,}6$) and rich ($\Phi = 1{,}52$ and $Le = 0{,}9$) conditions at ambient pressure and temperature were used in the experiments.

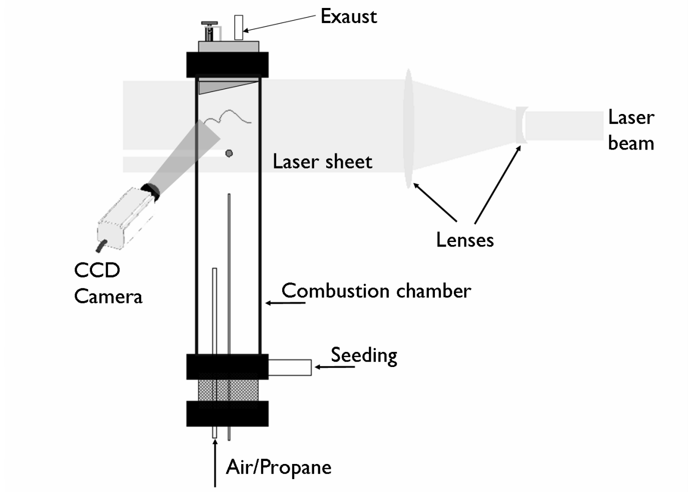

Fig. 2. Installation setup for image acquisition

The combustion chamber, presented schematically in figure 2, is made by a quartz cylinder (with 75mm diameter, 3mm wall thickness and 450mm height), a top wall with 15º inclination and a down window that is maintained closed during filling process, open only in each run to avoid pressurization of the chamber due to gas expansion. The filling is made by two separate inlets, one for propane and air and another for the seeding (DANTEC Safex Inside Nebelfluid), both positioned close the chambers bottom. As the seeding input requires additional air, that is taken into account and requires good mixing conditions at inside the chamber. For that matter the mixing process is made partially close the chambers bottom, where crossed flows provide a highly turbulent region, and pulled to fill the whole chamber by a suction pump also used to extract the exhaust gases after combustion, trough an exhaust valve at the chambers top wall. The exhaust system system is closed during each run.

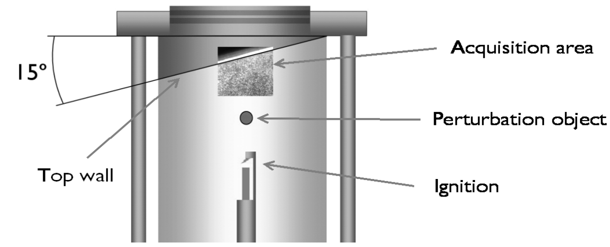

Fig. 3. Combustion chamber detail of flame wall interaction region

The used laser is a Spectra-Physics continuous Argon-Ion of 514nm and 2W maximum power output and the camera is a high speed CCD (KODAK Motion Corder Analyser, PS 220), capturing images with a resolution of 240×256 px^2, which in world coordinates are around 20×21,3mm^2. For all runs the whole flame propagation was completely captured, with a frame rate of 1000fps and a time exposure of 0.001s to each. It was used a 514nm light filter so only the reflected light from the laser could be captured by the CCD. The laser sheet passes through the combustion chamber axis perpendicular to the top wall.

To create a perturbation in the flame front was used a 10mm cylinder crossing the whole chambers diameter, positioned perpendicular to the acquisition plane and at a distance of 30mm to the top wall center. Ignition was always positioned at the chambers axis at a distance of 60mm from the top wall. Figure 3 shows the schematic arrangement of ignition, cylinder and top wall, showing also the acquisition area that is positioned above the cylinder capturing the near wall region.

For all runs the whole flame propagation was completely captured, with a frame rate of 1000fps and a time exposure of 0.001s to each.

3 Acquisition and processing

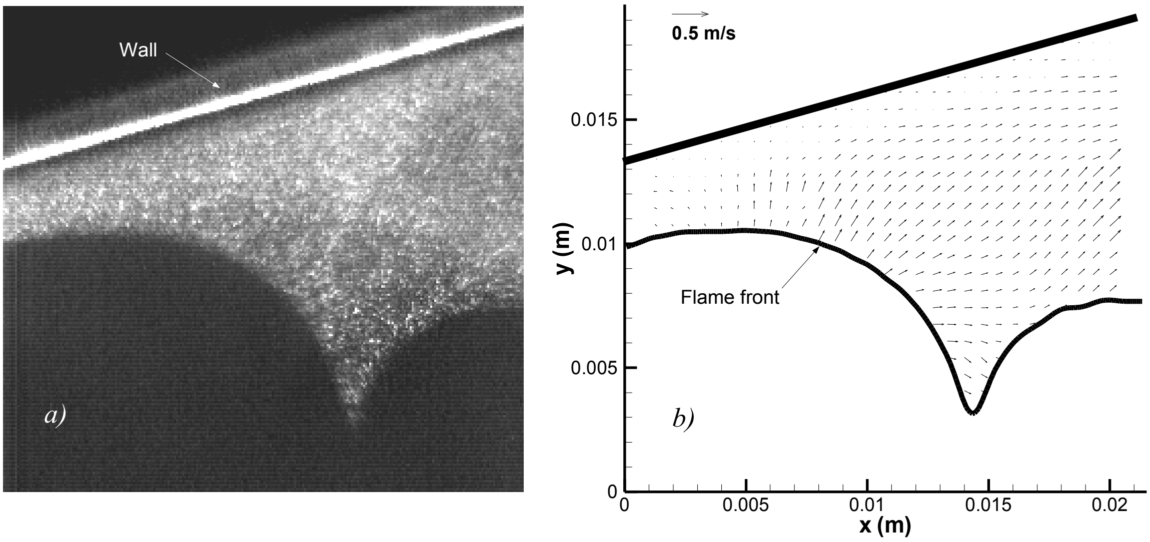

Fig. 4. Instant selection from propagation.

A sample image can be seen in figure 4a) where the top wall can be identified by the brighter line resulting from the incidence of the laser sheet, the reactants zone is found by the area where seeding can be seen, by opposite the burnt gases region where seeding no longer exists, and the flame front is identified by the the interface where the seeding disappears by evaporation resulting from the temperature increasing in the reaction zone. The reactants velocities were determined with PIV using interrogation windows of $32{\times}32\text{px}^2$ and 75% overlap. All regions where seeding was not available were masked so no pointless vectors could be determined. A software based on the procedures described by Foucher et al. 2000 was created to better estimate the flame speed in lab coordinates (Guerreiro, I. S. 2004). With this procedure the flame displacement speed is determined and the coupled with the reactants velocities to determine the local flame speed based on the velocity triangle presented in figure 1.

Given the flame front position and shape, the flame stretch is determined using equations 1 and 2. These equations are written for the 2D case and result are the following expressions for curvature and flow stretch respectively:

$$k_c = \frac{2\ S_u \dfrac{d^2 f}{d\,x^2}}{\left[\left(\dfrac{d\,f}{d\,x}\right)^2 + 1\right]^{3/2}} \tag{3}$$

$$k_s = \frac{\dfrac{\partial u_x}{\partial x} + \left(\dfrac{d f}{d x}\right)\left(\dfrac{\partial u_y}{\partial x}+\dfrac{\partial u_x}{\partial y}\right) + \left(\dfrac{d f}{d x}\right)^2 \dfrac{\partial u_y}{\partial y}}{\left(\dfrac{d f}{d x}\right)^2 + 1} \quad (4)$$

In equations 3 and 4 *u* means the flow velocity, where the subscript defines its direction, *f* represent the flame front coordinates in the *y* direction and S_u is the flame speed.

4 Results and discussion

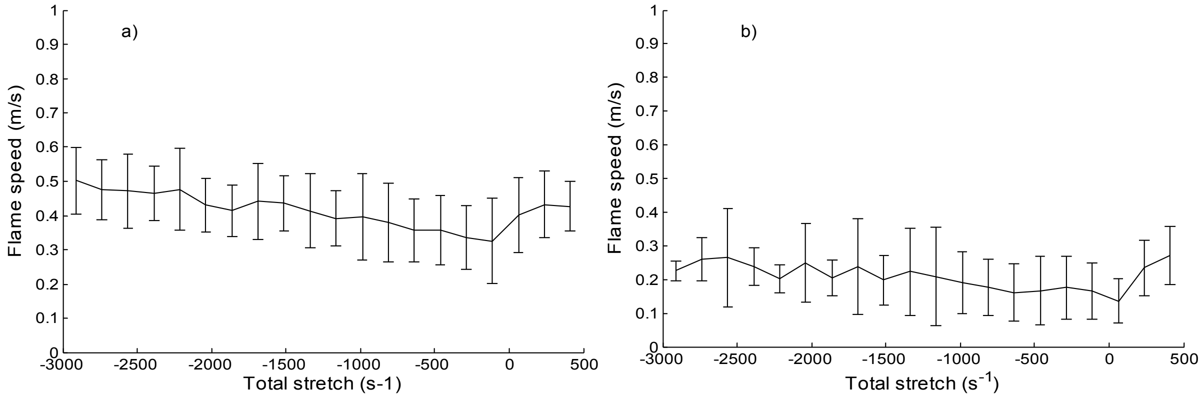

Fig. 5. Flame speed variation variation relative to total flame stretch. Premixed propane/Air with equivalence ration a) Φ=0,86 and b) Φ=1,52

The most important aspects that affect the flame front stability are the aerodynamic effects, which in freely propagating flames are known as the Landau-Darrieus instabilities, and the diffusion-thermal effects that promote the variations of flame flame speed due to stretch. For the last effect are presented in figure 5 the results of the experiments that show a very hight dependence of flame speed from total stretch, both for rich and lean flames.

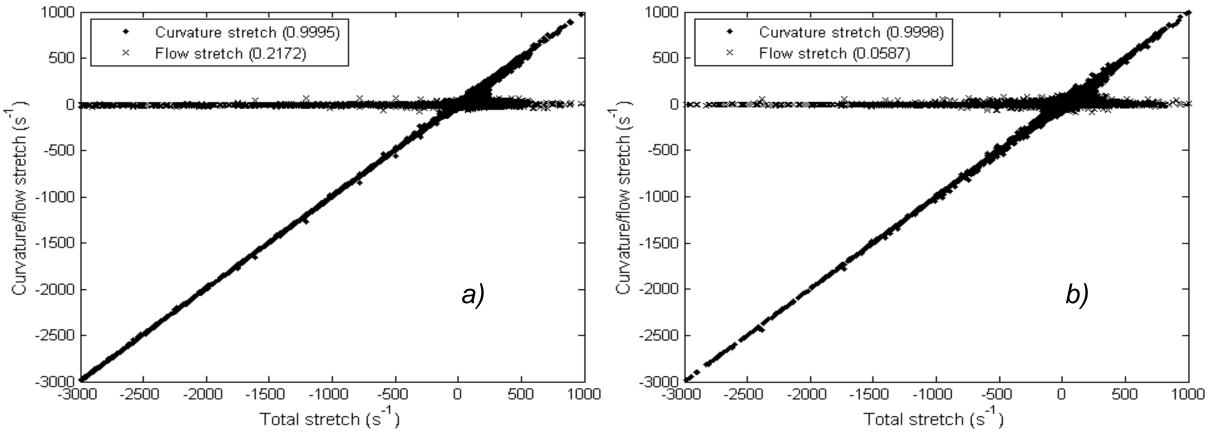

Fig. 6. Correlations from separated stretch sources with total stretch for a) lean flames and b) rich flames

According to results presented in Figure 6 the flame speed is strongly dependent on flame curvature stretch which dominates the total stretch factor. The total absence of correlation of flame speed from aerodynamic stretch is not a contradiction from previous studies that comply similar importance to curvature and flow stretch, but is a first evidence that its small importance in the study case, as can be shown in figure 6 the aerodynamic stretch represents a small part of the total stretch, which makes curvature what most influences flame speed. Considering the statistical quantities shown in table 1 is easily seen than the the relevance of curvature stretch is due to its very high dispersion relatively to the values of flow stretch.

	Lean (Φ=0,86)		*Rich (Φ=1,52)*	
Stretch:	*Curvature*	*Flow*	*Curvature*	*Flow*
Mean	9,3838	9,3073	3,2946	4,3162
RMS	451,85	15,017	386,30	8,6314
Correlation with total stretch	0,9995	0,2172	0,9998	0,0587

Table 1: Statistical properties of curvature and flow stretch

Given that curvature effects are the predominant source of stretch, our basis of comparison for the region of very high (negative) curvature must be with inwardly propagating flames. In this case, the results presented by Law & Sung 2000 for propane/air mixtures in equivalence ratios of *0,7* and *1,7* with Markstein lengths of $L=3{,}40\text{E-}4\,m$ and $L=1{,}38\text{E-}5\,m$ respectively, show behaviours similar with our achieved results. In figure 7 are presented the results for rich and lean flames in the region of negative stretch along with the achieved correlations, which for the the used equivalence ratios correspond to Markstein lengths between the ones presented by Law & Sung 2000.

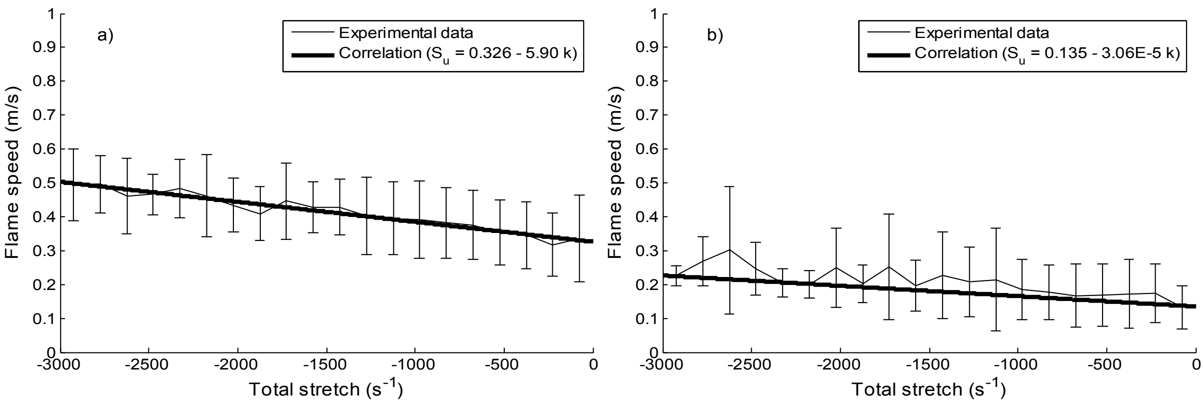

Fig. 7. Correlations of S_u/k for negative stretch values in a) lean and b) rich flames

The main difference from our results to the ones presented by Law & Sung 2000 is that the achieved stretch rates are very much higher in our case, but the consistent linearity shows that the thermo-diffusive effects are still acting in the same way as in low stretched flames.

Despite the strong dependencies of flame speed from curvature stretch, the main effect of the wall is to create a boundary for the flow, imposing stagnation points and redirecting the flow as mentioned by Foucher et al. 2003. In our case, the flame was intentionally disturbed to the wrinkles could be previously formed before the wall interaction, so we can now interpret the flow changes away in a isolated way.

It was not a single case during experiments that he occurrence of stagnation points were verified, but actually it occurred very often in the wall in the same way as described by Foucher et al. 2003. However, the trapped reactants didn't presented quite so often flow behaviour away of the wall, following different ways of flow behaviour that could lead to appearing stagnation points inside the flow or global flow reversion in parallel directions to the wall.

If the proximity of the wall interferes with the flow and that affects the flame front, then velocity gradients over the flame front must be affected. It can be sown in figure 8 by verifying that aerodynamic stretch, although it was not relevant for velocity variations, has higher probabilities to achieve values around -50 s^{-1} in distances of 4mm for lean flames and 5mm for rich flames. The flow stretch is a quantitative result that is dependent of flow velocity gradients in the flame front, then this result is a clear evidence that there are higher velocity gradients near wall.

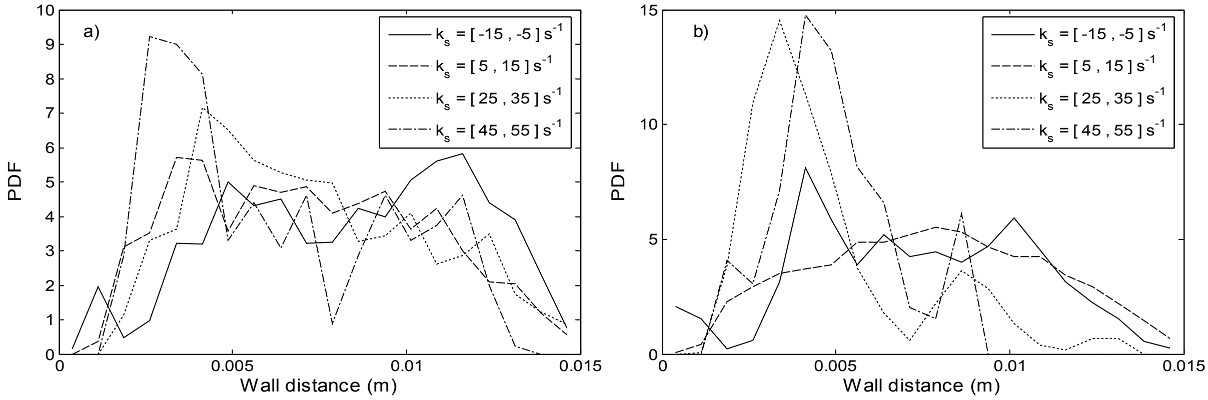

Fig. 8. Flow stretch variation vs wall distance

The results presented by Foucher et al. 2003 for methane also describe that small wrinkles are amplified between 0mm and 5mm, which is referred to be associated with the trapping of reactants between the flame and the wall. Can be seen in the work of Foucher et al. 2003 that maximum flow stretch is also increased in this region of 0mm to 5mm to values very close to what we obtained, clearly indicating a full accordance with our results. Is now evident that even if wrinkles have been previously formed in the flame front, is the influence of the wall to increase the velocity gradients within the reactants, which can be a way for destabilise the flame front.

5 Conclusions

The capability to acquire all propagation of a flame front with high speed camera made possible to resolve it completely during all flame progress and evaluate a high number of data. The chosen near wall region for acquisition of the propagating flame delivered data of the whole flow/flame/wall interaction from the reactants flow using 2D-PIV, the local flame speed and local stretch. The whole amount of data is still being analysed and already made possible to verify the correlations between the total stretch and flame speed, comparing them with theoretical results available.

High negatively stretched flames shown to have a behaviour similar to the ones predicted by Law & Sung 2000 in inwardly propagating flames, verifying that the linearity is still being verified for extremely high stretched flames.

It was verified that the curvature stretch is the dominant source that contributes to total stretch, specially because flow stretch, which is promoted by flow gradients within the flame front, doesn't achieve very high values until the flame doesn't approaches the wall and destabilise initial stagned flow of the reactants. Even in that case flow stretch is much smaller than curvature stretch. The effect of reactants trapping, as also suggested by Foucher et al. 2003, should be the mechanism for increasing the velocity gradients and flow stretch within the near wall region.

6 Acknowledgements

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