LAMINAR FLAME-WALL INTERACTION STUDY: STRETCH EFFECT ANALYSIS

F. Foucher*, S. Burnel*, C. Mounaïm-Roussselle*
And
M. Boukhalfa, B. Renou**, M. Trinité****

**Laboratoire de Mécanique et d'Energétique*
Université d'Orleans, ESEM
8, rue Leonard de Vinci
45072 Orleans
e-mail : fabrice.foucher@univ-orleans.fr

***CORIA – UMR 6614*
INSA de Rouen
Technopôle du Madrillet
Av. de l'Université - BP 8
76801 Saint Etienne du Rouvray Cedex

1. Introduction.

In many industrial processes, the combustion is realized in closed chamber. Internal combustion engines have this specification which is involved an important energetic loss by heat transfer. Then, many studies were focused to quantify the effect of the flame-wall interaction on the wall heat transfer and on pollutants formation [1,2,3,4,5]. However, if many results concerning the quenching distance, the heat transfer intensity and the evolution of pollutants formation are available, few authors were studied the effect of the combustion chamber boundaries on the flame propagation speed, flame stretch or the variation of the consumption speed. Recently, Poinsot and al. [6] show by Direct Numerical Simulation that walls can affect the development of a turbulent, or laminar, flame even if the distance between the flame front and the wall is important.
Then, the aim of this work is to study experimentally the effect of a wall on the development of premixed laminar methane – air flame in the case where fresh gases are trapped between the wall and the flame front. To separate all phenomena encountered during the engine combustion process, an atmospheric pressure vessel has been developed. The particularity of this experimental setup is that we can generate different types of flame development (spherical, flatted, wrinkled…), as function of the ignition device location.
High speed Particle Imaging Velocimetry technique was applied to study the temporal evolution of different parameters. Here we present the temporal evolution of fresh gases velocity, flame displacement speed and stretch of the flame front as function of the local distance between the flame front and the wall in the case of the spherical configuration.

2. Experimental Setup

The experimental setup is an atmospheric pressure vessel (82x82x350 mm^3), fully described in [7]. At one of its extremity a wall is placed. Four windows allow the visualization of the interaction phenomenon. At the other extremity, a valve allows the closure of the vessel during the extraction of burned gases, the intake of fresh gases and the relax, then the open of it during the combustion to keep the pressure constant to the atmospheric one. Methane-air premixed mixture is used at three different equivalence ratios (0.6, 0.8 and 1). Different ignition device locations between the wall are possible to generate spherical or flatted propagation of the flame front.

3. Particle Imaging Velocimetry set-up and Images Processing

High Speed PIV measurement has been made by using the experimental setup realized at the CORIA, by Lecordier [8]. An Oxford copper vapor laser (512.6 nm and 478.2 nm wavelength, about 6.5 mJ energy per pulses, pulse duration equal to 50 ns) was used at a pulse frequency between 1 to 6 kHz. The 40 mm diameter laser beam passes through a semi-cylindrical lens (focal length 0.2 mm) and a semi-spherical lens (focal length 1 m) to form a sheet. The image acquisition is realized by a high-speed CORDIN camera on 35 mm Kodak TMax3200 photographic films. The size of the observed area is 30 x 35 mm^2. Films are digitized by a Kodak scanner at 2000dpi [7,8]. Then the magnification ratio is 22.5 µm/pixel. Images are binarised and the contour is extracted to get the flame front.

The fresh gases velocity is calculated with the Insight 3.3 TSI Software on a grid mesh of 64 x 64 pixels^2. Flame front velocity S_d and fresh gases velocity Vg near the flame are determined by using the binary images correlation and particles correlation on adaptive mesh grid (rotation and translation at each point of the contour of the instantaneous flame fronts) [7, 8].

With these measurements, it is possible to determine the local flame stretch defined by [9,10]:

$$K = S_{tt} + 2.S_d.h \qquad (1)$$

Where S_{tt} represents the tangential strain rate defined by the derivate of the tangential velocity of the fresh gases at each point of the contour, h, the local curvature of the flame front and S_d the flame velocity defined by:

$$S_d = \frac{\Delta x}{\Delta t}.\vec{h} \qquad (2)$$

4 Experimental results

In Figure1 an example of the spherical flame evolution at different timing steps and during 4.8 ms, is represented by superimposing flame front contour and velocity vectors. We can observe that fresh gases velocity decreases rapidly when the flame-wall distance is less than 5 mm. One must keep in mind that the fresh gases motion is induced by the thermal expansion of the reactive zone and by its confinement between the wall and the flame front. The wall creates a stagnation point involving an increase of the flame front radius and the tangential fresh gases velocity. Therefore, the tangential strain rate becomes as important as the stretch due to the curvature.

If we focus the analysis on the flame front orientated to the wall, it is possible to plot the different characteristics as function of the flame-wall distance. But due to the size of the mesh to calculate the cross-correlation (~1mm^2), no local properties can be determined between the wall and the flame front when the distance is less than 0.5 mm. In Figures 2 and 3 are

represented the flame front displacement and the fresh gases velocity associated to the contour for the different equivalent ratios. S_d and U_n decrease linearly as function of the flame front distance. The fresh gases velocity seems to tend toward zero and the flame front displacement toward a value lightly lower than the laminar combustion speed S_{L0} for each equivalent ratio (respectively $S_{L0} = 0.42$, 0.26 and 0.09 ms^{-1} for ϕ=1, 0.8, 0.6). The flame front is then globally modified by the wall which stops the motion of the fresh gases and decreases the displacement speed S_d. In Figure 4 the local flame stretch term K is presented for different equivalence ratios as function of the flame-wall distance. We show that K decreases linearly toward zero for the three equivalent ratios. If we decompose the different terms of the Equation 1, , we can note thatthe tangential strain rate S_{tt}, plotted in Figure 5, tends toward zeros when the flame-wall distance is greater than 5 mm and has a evolution as for a non-disturbed spherical flame development, reaches a maximum value and so becomes non negligible at the distance equal to 1.5 to 2 mm and for all equivalence ratios.Finally, when the flame front approaches the wall, the tangential strain rate decreases strongly. This tendency can be induce by the decrease of the flame displacement, affected by the wall, which decreases the motion of the fresh gases. The other term of the Equation 1, the local curvature stretch term $2.S_d.h$, represented in Figure 6, decreases rapidly as function of the flame-wall distance until it tends asymptotically to zero .
We could be distinguish three stretch evolution zones relevant for any equivalent ratio:

- The first one is characterized by the development of a non-perturbed spherical flame for distance d> mm. The stretch term K is then controlled mainly by the curvature effect and then by $2.S_d.h$ term.
- In the second domain, for a 2 mm< d < 3 mm, the stretch terms, $2.S_d.h$ and S_{tt} havesimilar values
- Finally, for d< 2 mm, $2.S_d.h$ tends asymptotically toward zero Stt decreases rapidly.

Due to the different evolution of $2.S_d.h$ and S_tt, the stretch effect K decreases linearly as function of the flame-wall distance d. Therefore, if the stretch K tends toward zero, we will measure the flame speed consumption (S_d-U_n), equal to the laminar flame speed S_{L0}. However, with the resolution of our experimental setup, we can not determine any velocity for distance d <0.5 mm and then verify this tendency.

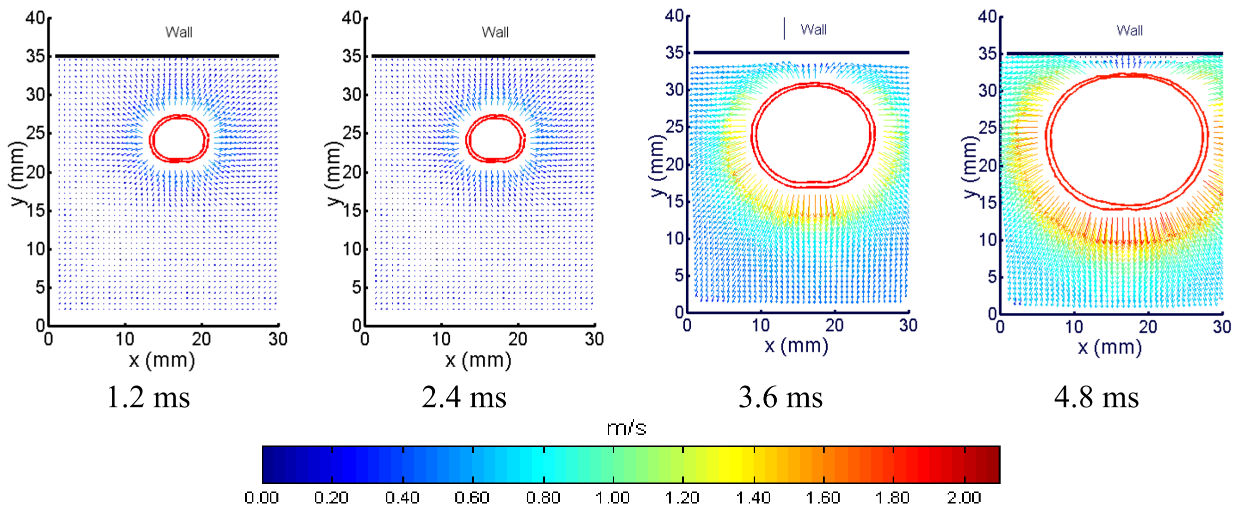

Figure 1 Temporal evolution of a spherical flame near a wall. Φ=1

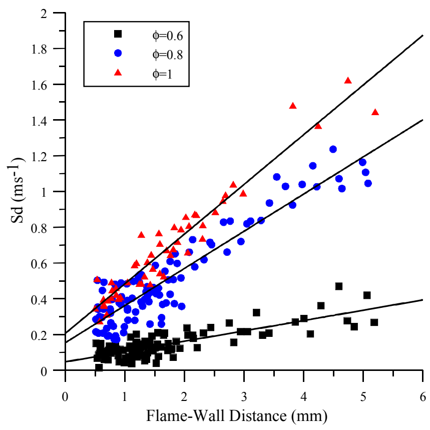

Figure 2 – Flame Front Velocity

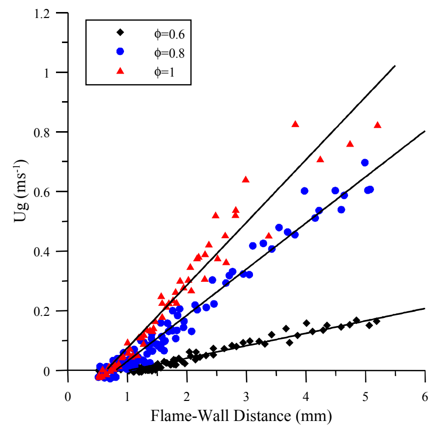

Figure 3 – Fresh gases velocity

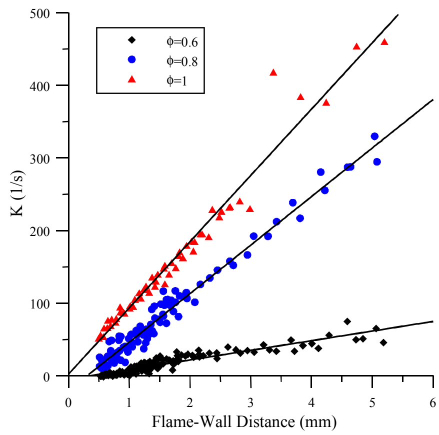

Figure 4 : Local flame stretch as function of the flame-wall distance.

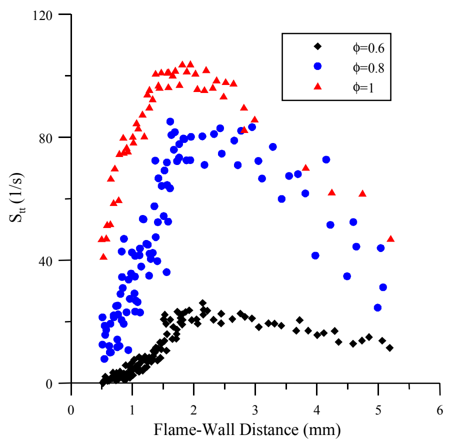

Figure 5: Tangential strain rate

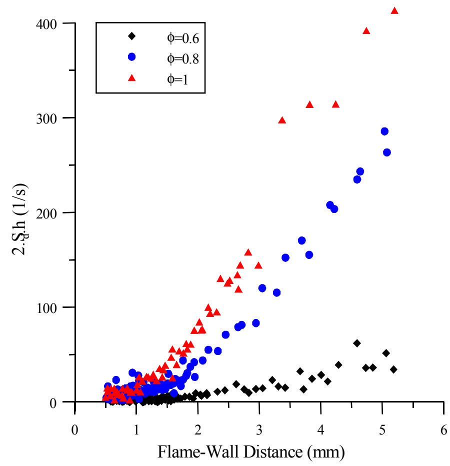

Figure 6 : Local curvature stretch

5. Conclusion

In this study, a high speed PIV system was used to study the temporal evolution of the flame-wall interaction. Associated with an appropriate image post-processing, we have determined local flame characteristics and particularly different terms of the flame stretch. The local stretch rate K decreases linearly as function of the distance d and at the approach of the wall it is governed by the tangential strain rate and not by the curvature one. This term is usually neglected in laminar flame studies. . In the case of spherical flame developmentconfiguration, the flame displacement speed is affected by the wall even if the distance between the front flame and the wall is fourty times greater to the flame thickness. This characteristic seems to be controlled by the velocity of the fresh gases.

References

1 **Angelberger, C**. “Contributions à la Modelisation de l’Interation Flamme-Paroi et des Flux Pariétaux dans les Moteurs à Allumage Command”é, Ph.D. Thesis, INPT, France, 1997.

2 **Blint, R.J. and Bechtel, J.H.** “Hydrocarbon Combustion near a Cooled Wall”, SAE paper 820063, 1982.

3 **Ezekoye, O.A., Greif, R. and Sawyer, R.F**. “Increased Surface Temperature Effects on Wall Heat Transfer During Unsteady Flame Quenching”, 20th Symposium (Int.) on Combustion, The Combustion Institute, pp.85-90, 1992.

4 **LoRusso, J.A., Lavoie, G.A., and Kaiser, E.W.,** “An electrohydraulic gas sampling valve with application emission studies”, SAE paper 80045, 1980.

5 **Lu, J.H., Ezekoye, O., Greif, R. and Sawyer, F.,** “Unsteady Heat Transfer During Side Wall Quenching of a Laminar Flame”, 23rd Symposium (Int.) on Combustion, The Combustion Institute pp.441-446, 1990.

6 **Poinsot, T. Haworth, D.C. and Bruneaux, G.**, “Direct Simulation and Modelling of Flame-Wall Interaction for Premixed Turbulent Combustion”, Combust. and Flame, 95 pp. 118-132, 1993

7 **Foucher,F, Burnel,S, Higelin,H, Mounaïm-Rousselle,C.** “Experimental study of flame-wall interaction by particle imaging velocimetry technique”. 10th Int. Symposium of Application of Laser Technique to Fluid Mechanics, Lisbon 2000

8 **Lecordier, B.**, “Etude de l’Interaction de la Propagation d’une Flamme Premelangée avec le Champ Aerodynamique, Par Association de la Tomographie Laser et de la Velocimetrie par Images de Particules”, Ph.D. Thesis, Université de Rouen, France, 1997.

9 **Renou B., Boukhalfa A., Puechberty D. and Trinité M.,** “ Effects of stretch on the local structure of freely-propagating premixed low turbulent flames with various Lewis number ”, 27th Symposium (Int.) on Combustion, The Combustion Institute, pp. 841-847, 1998.

10 **Bradley, D. Gaskell, P.H. and Gu, X.J.** “Burning Velocities, Markstein Lengths, and Flame Quenching for Spherical Methane-Air Flames: A Computational Study”, Combust. and Flame, 104, pp. 176-198; 1996

11**Sinibaldi, J.O. Mueller, C.J. and Driscoll, J.F.,** “Local Flame Propagation Speeds Along Wrinkled, Unsteady, Stretched Premixed Flames”, 27th Symposium (Int.) on Combustion, The Combustion Institute, pp. 827-832, 1998.