FRONT EVOLUTION AND FLAME STRETCH IN A TURBULENT PREMIXED BUNSEN FLAME

G. Troiani *, F. Battista **, F. Picano *, C. M. Casciola ****

guido.troiani@enea.it

* ENEA C.R. Casaccia, via Anguillarese 301 Rome, Italy.

** Dept. Mechanics and Aeronautics, Univ. "La Sapienza", Rome Italy.

*** Linnè Flow Center, KTH Mechanics, Stockholm, Sweden.

Abstract

The evolution of fame surfaces in turbulent premixed combustion is of crucial importance for the determination of consumption speed. Following the classical hypothesis of flamelets, the correlation between surface evolution and consumption speed S_c may be expressed as $S_c/S_{Lo} = I_o A_T/A_o$, with S_{Lo} the unstretched laminar combustion velocity, A_T and A_o the turbulent and average fame surface, respectively. The term I_o, namely the stretching factor, takes into account the influence of fame surface stretch $K=1/A(dA/dT)$ on the unstretched laminar combustion velocity. Depending on the chemistry of the reacting mixture S_{Lo} can raise or lower its value with the fame surface stretch, $S_L=S_{Lo}-LK$.

The fame surface is then stretched under the influence of the unburned front tangential and normal flow velocities and the curvature. By means of PIV velocity acquisitions and front position measurements in an air methane turbulent premixed jet flame at a relatively high Reynolds numbers (Re = 5000-15000), we examine the dependence of the evolution of turbulent flame front in term of turbulent to average flame surface ratio and I_o along the whole flame height.

Introduction

A common assumption in turbulent premixed combustion modeling is that of flamelet regime, where the thin reactive fame front is conveyed by the flow field. This front, being chemically reactive, propagates normal to itself towards the fresh reactants of a premixed mixture at a velocity usually referred to as laminar combustion velocity S_L. As a consequence, the combustion rate m can be thought as proportional to the product of the laminar combustion velocity with the reactive surface area. At a basic level of complexity, with S_L considered constant, i.e. $S_L = S_{lo}$, the combustion rate increases linearly with the flamelet surface. Actually, experimental measurements in turbulent flames [1] suggest a non-linear growth of combustion rates at increasing turbulence levels, implying a non-trivial behavior of the laminar combustion velocity.

In particular, shorter wavelengths are thought to initiate transport mechanisms inside the flame, influencing the flame structure and the normal burning velocity such that S_{Lo} is different from S_L. To take into account these phenomena, Markstein [5] prescribed different boundary conditions at the interface, introducing a dependence of front velocity S_L from its curvature (1/R)

$$S_L - S_{Lo} = S_{Lo}(\mathcal{L}/R) \ , \qquad (1)$$

where L is the Markstein length, function of diffusive properties of the reactive mixture and of the order of the flame front thickness.
A further step towards the definition of suitable dispersion relation of Ω is that of considering also the effects of flow inhomogeneities upstream the flame front [8,9]. The result now is that flame velocity depends on the flame stretch k = 1/σ (dσ/dt) caused either by curvature effects or tangential velocity gradients at the interface,

$$\left(\frac{S_L}{S_{Lo}} - 1\right) = -\frac{\mathcal{L}}{S_{Lo}}\left(\frac{1}{\sigma}\frac{d\sigma}{dt}\right) \ , \qquad (2)$$

with σ the elementary area defined on the flame front. Each point belonging to this area moves with a tangential velocity equal to that of the flow ahead the flame surface.
A number of experiments [1] mostly based on equation (2) and aimed at the evaluation of S_{Lo} and L have been performed in the past. The most common configuration adopted for this kind of measurements is that provided by laminar spherical flames expanding in a quiescent ambient.
Coming back to turbulent combustion modelling issues, the combustion rate $\dot{m}$ can be associated by means of the continuity equation not only to the laminar velocity S_L and to a fluctuating flame front surface A_T, but also to a reference (usually mean) front position (of extension A_o) and to an equivalent velocity, i.e.,

$$\dot{m} = \rho_u S_L A_T = \rho_u S_c A_o \ , \qquad (3)$$

the turbulent consumption speed S_c:
with $\boldsymbol{\rho}_u$ the unburned mixture density, from which by means of equation (2) it follows

$$\frac{S_c}{S_{Lo}} = I_o \frac{A_T}{A_o} \ , \qquad (4)$$

with the stretching factor Io grouping the dependencies of the ratio S_L=S_{Lo} [1].

As a matter of fact, estimates of I_o are typically performed by 2D-3D numerical simulations, where combustion rate and surface evolution are instantaneously available in the whole computational domain [10,11]. Concerning experimental measurements, results can be obtained with reasonable effort only for simple and highly symmetrical configurations, i.e. spherical or flat flames [12]. When geometries are only slightly more complicated, as for bunsen flames, the task

becomes a challenge, since the measurement of the local turbulent combustion rate is extremely difficult. This is the case of the present work aimed at estimating the time averaged local combustion rate in a turbulent premixed jet flame fed with a methane and air mixture by combined PIV/LIF measurements. These measurements are instrumental in the evaluation of local and global turbulent burning velocity. Comparison with global turbulent burning velocity data found in literature [13-15] provides confirmations that assumptions made for the present flames and discussed in details in next sections are appropriate.
Another key point addressed in this work is the investigation of the variability of the stretching factor I_o along the turbulent flame brush. In general, the degree of universality of the stretching factor I_o is not obvious and the geometry dependency/independency is still debated [1]. It is found that downstream a transitional zone at the exit nozzle, whose extension seems to depend on Reynolds number, local stretching factor evaluated by means of eq. (4) assumes constant values larger than unity. Such values may vary with experiments differing to each other from Reynolds number and equivalence ratio, which are global observables easily measurable and predictable. This could be of importance in numerical modelling where one of the major concerns is the definition of a stretched laminar flame speed.

Governing equations for the turbulent consumption speed
When a flamelet description of the problem is taken into account, the dynamics of propagating flame fronts at Low-Mach conditions and Lewis number unity can be defined in terms of a progress variable c [16]. Given the density of the mixture ρ and a molecular diffusion D an advection/diffusion equation ruling the conservation of c reads

$$\frac{\partial(\rho c)}{\partial t} + \nabla\cdot(\rho\mathbf{u}c) = \dot{\omega} + \nabla\cdot(\rho D\nabla c) \ . \tag{5}$$

Its integration over a control volume, embedding the flame front, leads to the determination of the average mass burning rate

$$\dot{m} = \int \bar{\dot{\omega}}\, dV = \rho_u\ S_c\ A_o \ . \tag{6}$$

From the experimental point of view, two problems arise when dealing with this definition. First, the reaction rate cannot be measured directly; second, the consumption speed Sc depends from the choice of the reference area A_o. Attempts to measure ω indirectly through the determination of the mass of reactants flowing by a control volume [17], have been performed in the past. Another method

consists in computing the divergence of the unconditioned average velocity field, as a measure of the dilatation effects of temperature increase. In particular, the latter technique has been applied to a flame flowing towards a stagnation plate, so to have an almost statistical flat flame front [18].
The final expression of the local turbulent consumption speed is,

$$S_c = \frac{\dot{m}}{\rho_u \int_V \nabla \cdot \overline{\mathbf{u}}\, dV} \frac{s_1 - s_0}{\int_{s_0}^{s_1} A(\xi) d\xi} \int_{s_0}^{s_1} \nabla \cdot \overline{\mathbf{u}}\, A(\xi) d\xi \ . \qquad (7)$$

Results and discussion

In this section results for turbulent consumption speed are presented. A compilation of flames at different values of the ratio U_{RMS}/S_{Lo} are realized by varying methane-air mass flow rate m and equivalence ratio Φ.
As a first verification of the consistency of the results, the S_c distribution along the flame brush has been averaged and results compared to those found in literature, usually obtained with global consumption speed measurements of mass flow rate and average flame surface, [13–15].

Figure (1) shows the result of this comparison with filled-diamond symbols referring to experiments carried out in the present work. Global turbulent consumption speed increases with the ratio U_{RMS}/S_{Lo} as also literature data do, and the associated error bars are within the dispersion of other results.

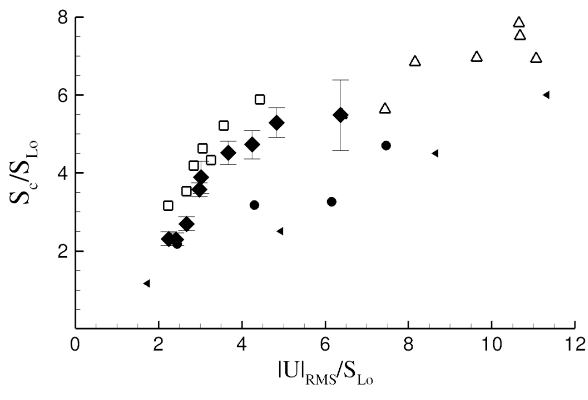

Fig. 1. Collection of average values of S_c/S_L. Symbols: (♦) present results; (•) Shepherd et al. 2001 [13]; (□, △) Gülder et al. 2000 [14]; (◄) Bedat et al. 1995 [15] ($S_c = S_d/4$).

To better understand the effect of turbulence on the global consumption speed a more thorough analysis should take into account the reciprocal variation of consumption speed and the degree of wrinkling of flame front. To this end it is quite straightforward to recast the equation

$$\frac{S_c}{S_{Lo}} = I_o \frac{A_T}{A_o} = I_o \frac{\int \Sigma \ A(\xi) \ d\xi}{A_o} \ . \tag{8}$$

The mean flame surface density Σ is the ratio between turbulent flame surface area and its embedding volume and it is a relatively simple observable accessible from the experimental point of view. In fact, by means of instantaneous OH-LIF measurements, it is possible to compute the mean flame surface density Σ.
To unveil the local character of I_o a scatter plot of consumption speeds and turbulent areas is reported in figure (2).

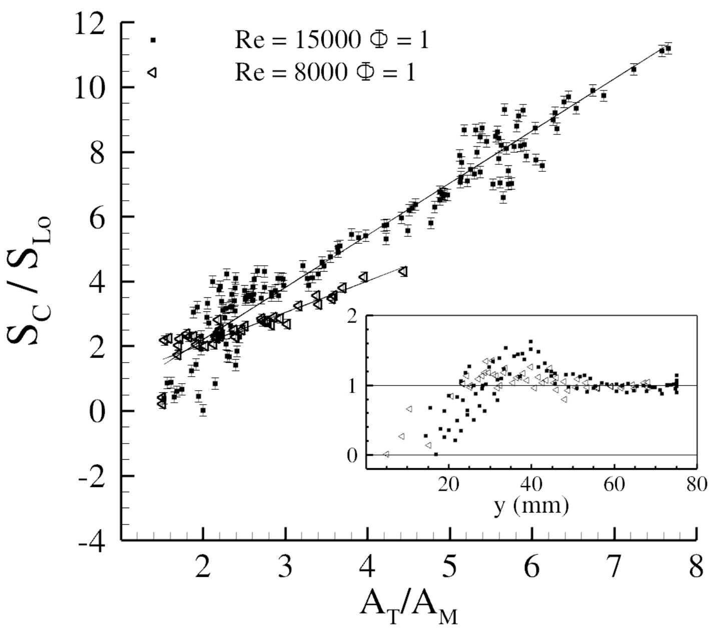

Fig. 2 Scatter plot of S_c/S_L vs A_T/A_M. Two best-fits represent values of $I_o = 0.97$ and $I_o = 1.61$. In the inset, compensated plot of $S_c/S_L/I_o$ vs axial coordinate y.

A linear regression has been applied for two representative cases, Re=15000 and Re=8000 both at Φ =1, giving slopes of 1.61±0.025 and 0.97±0.055 (shown in figure), respectively. It is evidenced that the stretching factor, i.e. the angular coefficient, has nearly constant values for each of the experiments carried out for a

wide range of turbulent. Reasons for the overestimation of global values of I_o are to be found in regions characterized by low surface wrinkling where the ratio A_T /A_M is closer to unity and deviations from linearity are present.
To give a physical meaning to this behavior it may be helpful to look at the development of I_o in the physical space. In the figure inset turbulent combustion velocities appear compensated with the corresponding linear fit underlining that low-wrinkled regions of the flame are close to the nozzle where turbulence is not yet fully developed. Just downstream the nozzle exit the flame front is corrugated by large scale velocity fluctuations induced by shear layer instabilities. Conversely, at flame tip turbulence developed and a wider spectrum of velocity scales is established and able to wrinkle the flame front at even finer scales.
This is an interesting result from the point of view of modeling, since it states that I_0 could be evaluated from global values such as turbulent velocity fluctuations at the nozzle exit, but it remains substantially constant along the flame height. This corroborates the flamelet hypothesis contained in the model of equation (8).

References

[1] J. F. Driscoll, Progr. in En. and Combust. Sc. 34 (1) (2008) 91 134.
[2] G. Darrieus, unpublished work presented at la technique moderne, and at le congrès de mécanique applique (1945) and (1938), unpublished work presented at La Technique Moderne (1938), and at Le Congrès de Mécanique Appliquée Paris.
[3] L. Landau, Acta Physicochim. URSS 19 (77).
[4] P. Clavin, Progress in Energy and Combustion Science 11 (1) (1985) 1–59.
[5] G. H. Markstein, J. Aero. Sci 18 (1951) 199.
[6] G. H. Markstein, Nonsteady flame propagation, No. 75, Pergamon, 1964.
[7] D. Karlowitz, D. W. Denniston Jr, F. E. Wells, J. Chem. Phys. 19 (1951) 541.
[8] P. Clavin, F. A. Williams, J. Fluid Mech. 116 (1982) 251–282.
[9] M. Matalon, B. J. Matkowsky, J. of Fluid Mech. 124(1) (1982) 239– 259.
[10] S. Candel, T. J. Poinsot, Combustion Science and Technology 70 (1) (1990) 1–15.
[11] A. Y. Poludnenko, E. S. Oran, Combust. and Flame 157 (5) (2010) 995–1011.
[12] T. Tahtouh, F. Halter, C. Mounaım-Rousselle, Combust. and Flame 156 (9) (2009) 1735–1743.
[13] I. G. Shepherd, R. K. Cheng, Combust. and Flame 127 (3) (2001) 2066–2075.
[14] O. L. Gulder, G. J. Smallwood, R. Wong, D. R. Snelling, R. Smith, B. M. Deschamps, J. C. Sautet, Combustion and Flame 120 (4) (2000) 407–416.
[15] B. Bedat, R. K. Cheng, Combustion and Flame 100 (3) (1995) 485–494.
[16] N. Peters, Turbulent combustion (1980).
[17] I. Shepherd, L. Kostiuk, Combustion and flame 96 (1994) 371–371.
[18] Y. C. Chen, M. Kim, J. Han, S. Yun, Y. Yoon, Combust. and Flame 154 (3) (2008) 434–447.