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Turbulent consumption speed via local dilatation rate measurements in a premixed bunsen jet

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ABSTRACT

The mean local reaction rate related to the average expansion across the front and computed from the mean velocity divergence is evaluated in this work. Measurements are carried out in a air/methane premixed jet flame by combined PIV/LIF acquisitions. The procedure serves the purpose of obtaining values of a turbulent flame speed, namely the local turbulent consumption speed S_{LC}, as a function of the position along the bunsen flame. With the further position that the flamelet assumption provides a proportionality between turbulent burning speed normalized with the laminar unstretched one and the turbulent to average flame surface ratio, the proportionality constant, i.e., the stretching factor becomes available. The results achieved so far show the existence of a wide region along which the bunsen flame front has a constant stretching factor which apparently depends only on the ratio between turbulent fluctuations and laminar flame speed and on the jet Reynolds number.

1. Introduction

A common assumption in turbulent premixed combustion modeling is that of flamelet regime, where the thin reactive flame 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 $\dot{m}$ 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, 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.

First attempts to model dependencies for S_L began after Darrieus–Landau [2,3] studies on laminar flame front instabilities. In their original formulation they considered an inviscid initially flat surface of discontinuity separating two zones at different but constant densities mimicking a thin laminar flame front dividing reactants from combustion products. Boundary conditions at the interface are such to impose a normal burning velocity equal to laminar flame speed $S_{Lo} = S_L$ (function of thermo-chemical parameters only), a constant mass flux and no jump of tangential velocity across the flame. The results is a linear and unstable growth of disturbances at all wave-lengths k of the kind of $a = A\exp(\Omega t \pm i(k_y y + k_z z))$, where a is the front position, $\Omega \propto S_{Lo}k$ the inverse of the time constant of the harmonic perturbation applied to the front, y and z the transverse directions and x that normal to the unperturbed front. Since the system is considered inviscid and the only characteristic length is the flame front thickness, a simple dimensional prediction can directly lead to the above expression for Ω. This unconditional instability has been confuted by experiments that undoubtedly can reproduce stable flames, as in cellular flames, see e.g., [4]. In particular, shorter wavelengths are thought to initiate transport mechanisms inside the flame, influencing the flame structure and the normal burning velocity such that $S_{Lo} \neq S_L$. 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 $(1/R)$

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

where $\mathcal{L}$ is the Markstein length, function of diffusive properties of the reactive mixture and of the order of the flame front thickness. This new boundary condition adds to the dispersion relation of Ω a quadratic term (k^2) which stabilizes the small wavelengths in such a way that only a limited range of wavenumbers close to zero remains unstable.

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In a further step, Markstein [6] refined his previous position assuming that the relevant quantity controlling the flame velocity is the curvature of the front with respect to the curvature of the flow measured by the divergence of the velocity flow field,

$$S_L - S_{Lo} = S_{Lo}\mathcal{L}\left[\frac{1}{R} + \nabla\cdot\left(\frac{\hat{\mathbf{u}}}{|\hat{\mathbf{u}}|}\right)\right], \tag{2}$$

where $\hat{}$ denotes the perturbation from the plane solution.

This modeling is also consistent with Karlovitz concept of flame stretch [7], that is the relevant quantity controlling local flame speed S_L and flame quenching too. 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 $k = 1/\sigma(d\sigma/dt)$ caused either by curvature effects or tangential velocity gradients at the interface,

$$\left(\frac{S_L}{S_{Lo}} - 1\right) = -\frac{\mathcal{L}}{S_{Lo}}\left(\frac{1}{\sigma}\frac{d\sigma}{dt}\right), \tag{3}$$

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 Eq. (3) and aimed at the evaluation of S_{Lo} and $\mathcal{L}$ 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. Reasons for this choice are the relative simple tracking of the the flame radius $r(t)$ of the traveling front and an analytic expression for flame stretch $k = 2/r(dr/dt)$.

Coming back to turbulent combustion modeling 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., the turbulent consumption speed S_c [1]:

$$\dot{m} = \rho_u S_L A_T = \rho_u S_c A_o, \tag{4}$$

with ρ_u the unburned mixture density. Consequently,

$$\frac{S_c}{S_L} = \frac{A_T}{A_o}, \tag{5}$$

from which, by means of Eq. (3), it follows

$$\frac{S_c}{S_{Lo}} = I_o\frac{A_T}{A_o}, \tag{6}$$

with the stretching factor I_o 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–air mixture by combined PIV/LIF measurements. These measurements are instrumental in the evaluation of local and global turbulent consumption speeds. 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. (6) assumes constant values larger than unity. Such values may vary with experiments differing to each other from Reynolds number and equivalence ratio, that are global observables easily measurable and predictable. This could be of importance in numerical modeling where one of the major concerns is the definition of a stretched laminar flame speed.

2. Governing equations

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, e.g. a normalized temperature $c = (T - T_u)/(T_b - T_u)$ with subscript u/b indicating unburned/burned mixture [16]. Given the density of the mixture ρ and a molecular diffusion D an advection/diffusion equation ruling the conservation of c reads

$$\frac{\partial(\rho c)}{\partial t} + \nabla\cdot(\rho\mathbf{u}c) = \dot{\omega} + \nabla\cdot(\rho D\nabla c). \tag{7}$$

Its integration over a control volume $\mathcal{V}$, embedding the whole turbulent flame brush, leads to the determination of the average mass burning rate introduced in Eq. (4), [13]

$$\dot{m} = \int_{\mathcal{V}}\overline{\dot{\omega}}dV = \rho_u S_c A_o. \tag{8}$$

From the experimental point of view, two problems arise when dealing with this definition. First, the reaction rate ($\dot{\omega}$) cannot be measured directly; second, the consumption speed S_c depends from the choice of the reference area A_o. Attempts to measure $\dot{\omega}$ 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].

More specifically, continuity equation can be written in the form:

$$\nabla\cdot\mathbf{u} = \rho\frac{\partial(1/\rho)}{\partial t} + \rho\mathbf{u}\cdot\nabla\frac{1}{\rho}. \tag{9}$$

Now, defining the heat release parameter as

$$\tau = (T_b - T_u)/T_u = (\rho_u - \rho_b)/\rho_b, \tag{10}$$

it can be re-casted in terms of the progress variable c and unburned density in order to obtain [19–23] and [24].

$$\nabla\cdot\mathbf{u} = \frac{\tau}{\rho_u}\left(\frac{\partial(\rho c)}{\partial t} + \nabla\cdot(\rho\mathbf{u}c)\right), \tag{11}$$

which is the LHS of Eq. (7) [25,26]. In principle, the coupling of Eqs. (7) and (11) could lead to the evaluation of the reaction rate $\dot{\omega}$ provided that the molecular diffusion term is properly defined. From the experimental point of view this is not obvious when the flame front is an interface dividing reactants from products and the progress variable is known in its average distribution only. To overcome this difficulty it is considered the averaged form of Eq. (7)

$$\frac{\partial(\bar{\rho}\tilde{c})}{\partial t} + \nabla\cdot(\bar{\rho}\tilde{\mathbf{u}}\tilde{c} + \bar{\rho}\widetilde{\mathbf{u}''c''}) = \nabla\cdot(\overline{\rho D\nabla c}) + \bar{\dot{\omega}}, \tag{12}$$