Direct simulation of turbulent combustion

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1. Previous work and objectives

Understanding and modeling of turbulent combustion are key problems in the computation of numerous practical systems. Because of the lack of analytical theories in this field and of the difficulty of performing precise experiments, direct simulation appears to be one of the most attractive tools to use in addressing this problem.

The first part of the present work (September 1988-September 1989) was split into two parts:

1. Development and validation of a direct simulation method for turbulent combustion.
2. Applications of the method to premixed turbulent combustion problems and especially to computations of flame/vortex interactions.

Results obtained during phase 1 were related to the choice of the equations to consider for turbulent reacting flows and the development of a new method to impose boundary conditions for the compressible Navier-Stokes equations. These results are summarized for the reacting case in Poinsot and Lele (1989) and for the non-reacting case in Poinsot and Lele (1990). Some of them have been presented at the 1989 APS meeting (Poinsot, Colonius & Lele 1989).

Results related to phase 2 describe the effects of isolated vortex pairs interacting with premixed flame fronts. An analytical study of the expression of flame stretch and curvature in a turbulent flow was first done during the visit of Prof. Candel at Berkeley in 1989 (Candel and Poinsot 1990). The definition of flamelet regimes and the applicability of flamelet models for turbulent combustion were reconsidered in view of the direct simulation results. These simulations were first used to predict the occurrence of flame quenching by isolated vortex pairs and the type of regime for which flamelet regimes may be obtained. Some of these results have been presented at the Symposium on Combustion in Orleans (Poinsot, Veynante & Candel 1990) and a complete description of this work has been submitted to the Journal of Fluid Mechanics (Poinsot, Veynante & Candel 1991). This study has received some interest among experimentalists: an experimental study on flame vortex interaction has already been published by Roberts and Driscoll (1990). In this work, the spectral diagram derived in (Poinsot *et al.* 1990) is re-constructed using experimental results.

From September 1989 to September 1990, new problems have been studied using direct simulation but also experiments and theoretical models:

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1. The influence of curvature on premixed flame fronts

Curvature is a parameter which has been neglected in many models of turbulent combustion but appears to be more important than expected. Its effects were investigated using direct simulation and experimental data of Bunsen burner tips. This study was performed in collaboration with T. Echekki and Prof. G. Mungal (Stanford Univ.)

2. The construction of a model for the flame stretch based on direct simulation and multifractal analysis

The stretch rate of flamelets in premixed turbulent combustion is of utmost importance in combustion models because it represents the source term of the flame surface. It was computed here using (1) detailed numerical simulations of vortex/flame interactions and (2) a model for intermittent turbulence taking into account all possible turbulence scales acting on the flame front (Meneveau and Poinsot 1990).

3. The simulation of the interaction between a random flow field and a flame front

Although much may be learned from computations of isolated vortices interacting with flames, certain problems require the simulation of a more complete case where a complete turbulent flow interacts with a flame front.

The general objective was to improve our knowledge of turbulent combustion but also to use this information for turbulent combustion models. The transfer of direct simulation results towards models is also in progress. A submodel to evaluate the flame stretch has been derived from the present study (Section 3) and incorporated in the Coherent Flame model used in France for piston and aircraft engines.

2. The influence of curvature on premixed flame fronts.

2.1 Introduction

The flamelet concept is a simple and widely used concept in turbulent combustion modeling. It is based on the assumption that combustion occurs in thin layers (called flamelets) which are convected and distorted by the turbulent flowfield (Marble and Broadwell 1977, Bray 1980, Williams 1985, Peters 1986). To first order, this requires chemical times to be smaller than the turbulence times. Diagrams proposed by Borghi (1984) or Peters (1986) give a qualitative description of the response of a given flame to a given turbulent flow field. Knowing the turbulence integral scale and the turbulent kinetic energy, these diagrams indicate if the flow will feature flamelets. However, because of the complexity of the mechanisms involved (Poinsot, Veynante and Candel 1990), the exact limits of the flamelet domain are still an open subject.

Even when the flamelet assumption is valid, modeling premixed turbulent combustion remains a challenging problem. This is due to strong flamelet/flow field interactions. On one hand, density changes through the flame front (typically an order of magnitude) result in vorticity generation and flow acceleration. On the other hand, the flow alters the flame structure through different mechanisms: curvature, strain, and unsteady effects. In computations of turbulent combustion, the flamelet assumption may be used in two different ways:

- If the flame is viewed as an infinitely thin interface between fresh and burned gases, its position may be tracked as a free boundary between the two phases (*flame front tracking*). This method does not solve for the internal structure of the flame but resolves all the flow turbulent motions. It may, therefore, be considered as a partial direct simulation method (Ghoniem *et al.* 1982, Ashurst 1987, Osher and Sethian 1987, Poinsot and Candel 1986). The concept of flame front tracking has also been used in fractal models of premixed turbulent combustion (Gouldin *et al.* 1989, Mantzaras *et al.* 1989).
- More global models (generally called *flamelet models*) are based on an average description of the turbulent reacting flow. The important quantity for modeling combustion is then the mean reaction rate (Bray 1980). Under the flamelet assumption, the mean reaction rate per unit volume is the product of the flame surface density (the mean flame surface per unit volume) and the mean local consumption rate per unit flame surface (Candel *et al.* 1988) or equivalently the product of the flamelet-crossing spatial frequency and the mean consumption rate per crossing (Bray and Libby 1986). In these models, the flow turbulence is not resolved. It is modeled, for example, through the turbulent kinetic energy and its dissipation rate. Similarly, the flame front topology is not resolved but modeled through the flame surface Σ.

Each of these two flamelet approaches makes use of a flame speed to characterize the local flame behavior. It is important to realize that these two flame speeds are fundamentally different.

- In flame front tracking models, the relevant flame speed is the normal flame front velocity with respect to the unburned gas. This is the only quantity required to describe the chemical process. We will call this speed *the displacement speed* S_d.
- In global flamelet models, the characteristic speed is a measure of the reaction rate per unit area of the flame front. We will refer to this quantity as *the consumption speed* S_c defined as:

$$S_c \equiv \frac{\int_{-\infty}^{+\infty} \dot{\omega}_R \, (\mathbf{n} \cdot d\mathbf{x})}{\rho_u Y_{R,u}}, \tag{1}$$

where $\dot{\omega}_R$ is the mass of reactant consumed per unit time per unit volume; ρ_u the density of the unburned gas; $\mathbf{x}$ the position vector of an infinitesimal amount of reactant; and $\mathbf{n}$ a unit vector normal to an isothermal surface at $\mathbf{x}$. Therefore, the integral in Eq. (1) is computed along the normal to the flame front. $Y_{R,u}$ is the mass fraction of the fuel in the fresh gases.

In the case of a one-dimensional, planar flame placed in a uniform flow of fresh gases, the displacement and consumption speeds reduce to the usual laminar flame speed S° ($S_d = S_c = S^\circ$).

When the flame front is curved or when the flow is non uniform, the displacement speed and the consumption speed may differ by orders of magnitude. In the case of a flame tip at unity Lewis number, the consumption speed S_c at the tip (on the symmetry axis) is of the order of the laminar flame speed S°, while the displacement speed S_d can be one order of magnitude larger than S° and S_c.

An important problem for all models based on the flamelet assumption is the correlation of the flame speeds of individual flamelets with the local flow properties. Which parameters should be used in a flamelet model to correlate the variations of the displacement and consumption speeds with the flow characteristics and the flame geometry is still an open question.

One possible answer to this question is the relation between flame stretch and the displacement flame speed S_d obtained by Clavin and Williams (1982). The flame stretch is defined by the fractional rate of change of a Lagrangian flame surface element Σ (Williams 1985):

$$\kappa = \frac{1}{\Sigma}\frac{d\Sigma}{dt}. \tag{2}$$

Assuming that the characteristic scales of the flame wrinkles are large compared to the flame thickness d and using asymptotic analysis, Clavin and Joulin (1983) show that the displacement speed is a linear function of a single parameter, the flame stretch κ .

$$\frac{S_d}{S^o} = 1 - \frac{\mathcal{L}}{S^o}\,\kappa, \tag{3}$$

where $\mathcal{L}$ is a characteristic length that depends on the thermal and diffusive properties of the combustible mixture. This relation has been used in studies of premixed turbulent flame propagation to express the displacement speed of the reaction front (Ashurst 1987).

The flame stretch κ may be written in terms of the kinematic and geometrical properties of the flame and of the flow field. It is the sum of two terms: a flame curvature term and a strain term (Matalon 1983, Candel and Poinsot 1990). When $\kappa > 0$, the flame front is positively stretched (in most cases, we will simply call it 'stretched'). The simplest example of a positively stretched flame is the planar stagnation point flame. When $\kappa < 0$, the flame front is negatively stretched (we will call it 'compressed'). A typical example of a compressed flame is a flame front curved towards the fresh gases.

The asymptotic relation (3) shows that, at least for small stretch values, stretch alone can be used to describe the flamelet behavior. The fact that curvature and strain play similar roles in flame stretch then suggests an important simplification: the flamelet behavior may be studied by considering only planar strained flames (these are simpler to study than curved flames). In other words, according to asymptotic analysis, a curved flame and a planar flame will feature the same dynamics if their total stretch is the same. Therefore, studying planar flames should be sufficient, and this explains why the basic emphasis of flamelet modeling of premixed turbulent combustion has been on planar strained flamelets where curvature is absent. In this context, the flame front is viewed as a collection of positively stretched laminar stagnation point flames (see Fig.1a). This geometry has been extensively investigated in analytical studies based on large activation energy asymptotic methods (Libby and Williams 1982, 1987, Libby, Linan & Williams 1983) as well as in computational works (Darabiha *et al.* 1986, Giovangigli and Smooke 1987) and experimental studies (Ishizuka and Law 1982).

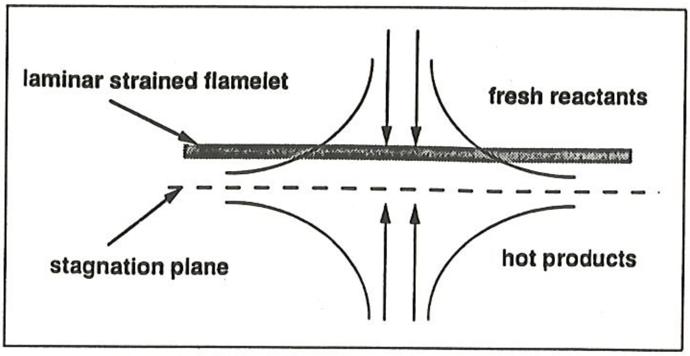


FIGURE 1A. The laminar stagnation point flame

Now, the first major difficulty in a description of turbulent flamelets based on planar stagnation point flames is that the asymptotic relation (3) (which is its first justification) has been established for low values of the flame stretch. Its extension to high stretch values (and strong curvature) has no rigorous basis. A second difficulty is that planar stagnation point flames are submitted to positive stretch and cannot really be expected to represent curved flamelets which are typically submitted to negative stretch. Since most turbulent flames involve high flame stretch and highly curved flame fronts, these questions have to be addressed to provide a satisfactory flamelet model. A simple examination of a turbulent flame (see Fig. 1.b) reveals that planar flamelets are not the only flamelets present along the flame front. Certain regions of the flame surface may be strongly curved towards the fresh gases and, therefore, negatively stretched (i.e. compressed). For example, a flame front embedded in a turbulent shear layer will be positively stretched at certain locations (typically in the braids) and strongly curved (and therefore negatively stretched or compressed) at locations where the flame is wrapped around the vortices. At this point it is worth mentioning that direct simulations of flames propagating in isotropic three-dimensional turbulence (Rutland 1989) show that flame fronts tend to align with the principal axis of strain and thereby suggest that in a statistical sense, the stagnation point flame picture is more probable than the curved flame. However, this does not mean that curved flames can be neglected. Although curved flamelets are not found in a turbulent flame brush as often as stagnation point flamelets, they might have a strong effect on the flame dynamics. Studying curved flames and more generally compressed flame fronts is clearly of interest.

Considering now strongly curved flames, we have first to wonder whether the dynamics of these flame fronts may be correlated with stretch only (in the same way that planar stagnation point flames are correlated with stretch). For example, the constant density analysis of Mikolaitis (1984) reveals significant effects of curvature on flame propagation. Mikolaitis claims that flame stretch alone is insufficient to explain the dynamical behavior of strongly curved flames (such as flame tips of Bunsen burners) and that curvature should also be included as an additional independent parameter in any model describing turbulent flamelets. Using similar

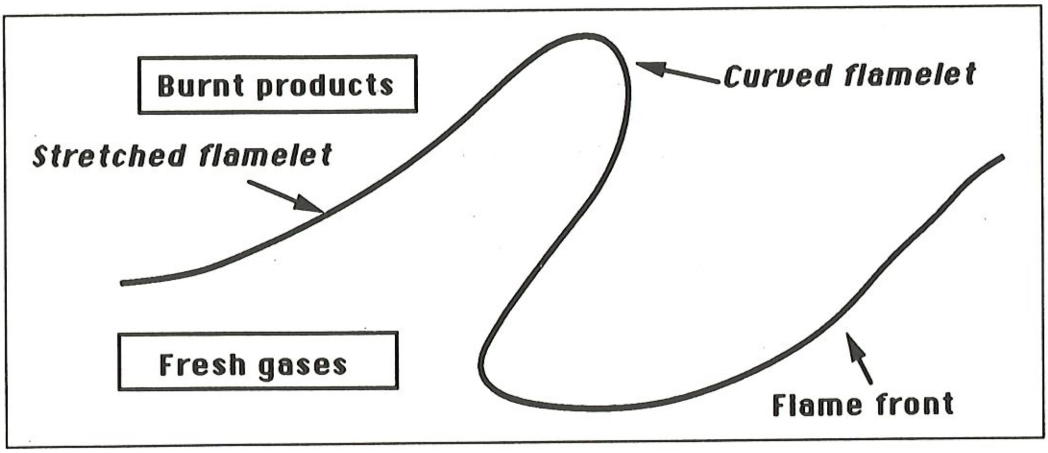


FIGURE 1B. A schematic of stretched and compressed flamelets in a turbulent flow.

ideas, the integral analysis of Chung and Law (1988) provides a relation for the displacement speed in terms of two parameters: the stretch κ and the curvature $\nabla_t \cdot \mathbf{n}$ (Law 1988):

$$\frac{S_d}{S^\circ} = 1 + \delta_T^\circ(\nabla_t \cdot \mathbf{n}) + (\frac{1}{Le} - 1)\,(\frac{\delta_T^\circ/S^\circ}{2T_{ad}/T_a})\,\kappa, \tag{4}$$

where δ_T° is the characteristic length of the preheat zone for the unstretched flame; T_{ad} the adiabatic flame temperature; T_a the activation temperature; $\mathbf{n}$ the unit vector normal to the flame pointing towards the burned gases; and Le the Lewis number. $\nabla_t \cdot \mathbf{n}$ is positive for a flame curved towards the unburned gases (convex flame) and may be written as $(\frac{1}{\mathcal{R}_1} + \frac{1}{\mathcal{R}_2})$ where $\mathcal{R}_1$ and $\mathcal{R}_2$ are the principal radii of curvature of the flame surface. $\nabla_t \cdot \mathbf{n}$ reduces to $\frac{1}{\mathcal{R}}$ in a two-dimensional geometry and to $\frac{2}{\mathcal{R}}$ in an axisymmetric geometry. According to Eq. (4), the displacement speed is a function of two geometrical parameters: flame stretch and flame curvature (and not only flame stretch). At unity Lewis number, Eq. (4) reduces to a form similar to the simple relation suggested by Markstein (1951) in his semi-phenomenological analysis. The relation suggests that the deviation of the displacement speed S_d from S° is proportional to the curvature parameter $\frac{1}{\mathcal{R}}$. We will refer to this relation as a Markstein type relation. The validity of Eqs. (3) and (4) may be checked later by comparing their predictions with numerical simulations and experimental results for unity Lewis number.

A convenient geometry to investigate the dependence of the characteristic flame speeds on strain and curvature is the flame tip of a Bunsen burner (Fig. 2). Flame tips are highly curved, steady flames. They may be viewed as a simple prototype of curved flamelets in a turbulent flow field. As indicated above, planar stagnation point flames are positively stretched ($\kappa > 0$) while flame tips are compressed ($\kappa < 0$). Since for most practical cases, the constant $\mathcal{L}$ in Eq. (3) is positive, Eq. (3)

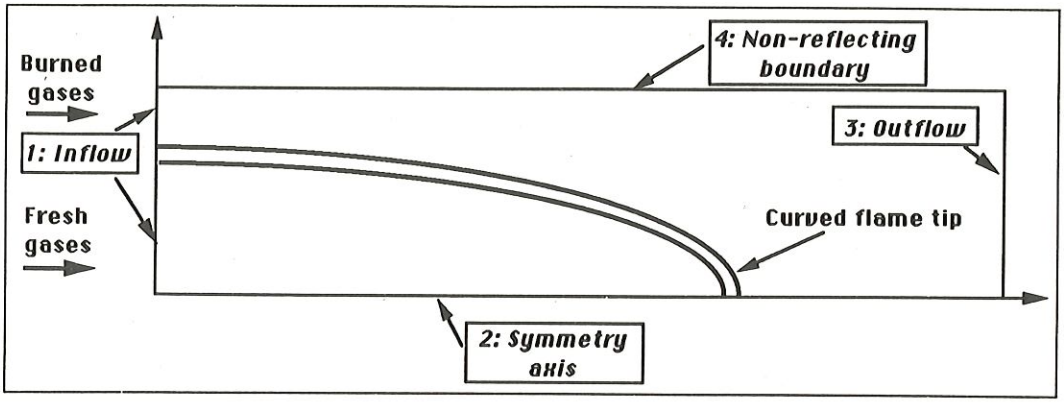


FIGURE 2. The flame tip as a prototype of curved flamelet.

shows that displacement speeds for a stagnation point flame will be lower than the unstretched flame speed while they will be higher for flame tips.

An advantage of the flame tip geometry is that both the displacement and consumption speeds can be unambiguously evaluated since the flow outside the flame region is almost uniform. In the case of a stagnation point flame, because the unburned gas flow is not uniform, the displacement speed cannot be measured directly. Moreover, the flame tip is less restrained by boundaries and is free to move in the flowfield to escape regions of intense strain, like flamelets in a turbulent flame brush. In terms of local flame structure, these properties suggest that the flame tip may be a good prototype of flamelets in premixed turbulent combustion.

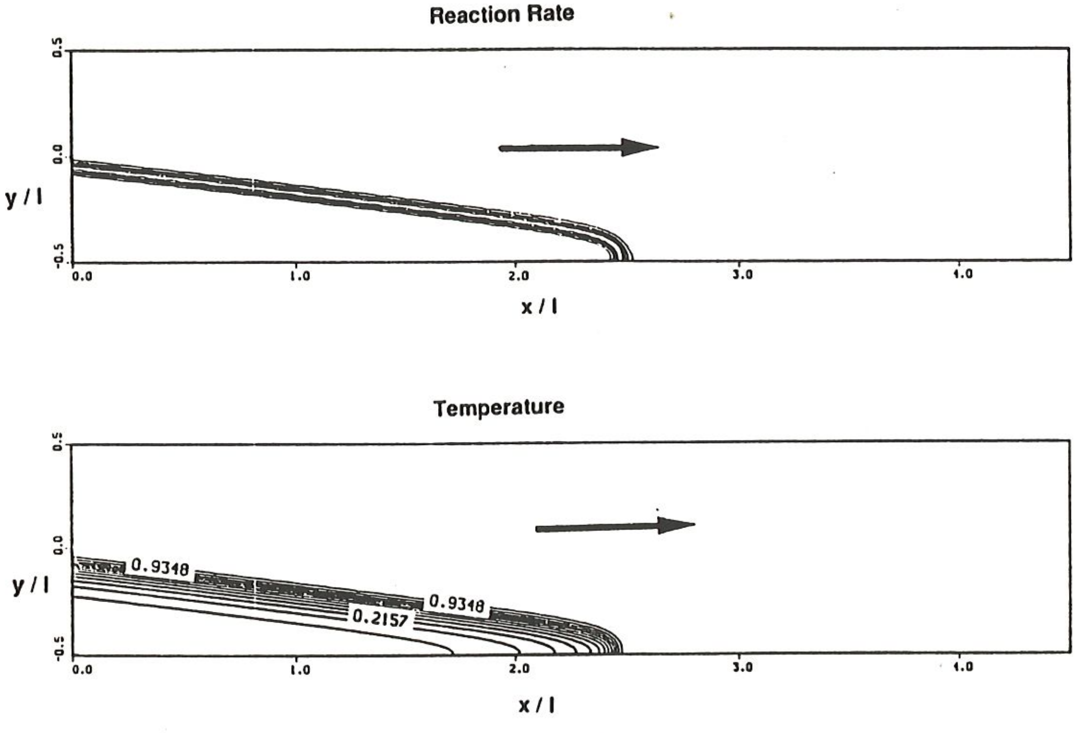
The objective of the study of Poinsot, Echekki & Mungal (1990) was to investigate the physical mechanisms controlling flame tips and more generally strongly curved laminar flamelets embedded in a turbulent flowfield. This was done using a new one-dimensional analysis of curved flame propagation in a non-uniform flow along with numerical simulations and experimental data describing the two-dimensional flame tip. The discussion was restricted to gas mixtures of neutral diffusion (the Lewis number is equal to unity). Details of the analysis may be found in Poinsot, Echekki & Mungal (1990). We will only summarize the main results here.

2.2 Results

The quasi-one dimensional model giving a balance equation of fuel mass in a streamtube was first applied to the flame tip of the Bunsen burner. Results show that while the consumption speed is uniquely related to the processes occurring in the reaction zone, the displacement speed is strongly dependent on the hydrodynamic and diffusive processes occurring upstream of the reaction layer. Three mechanisms affecting the displacement speed were identified: a chemical mechanism associated with the modification of the reaction zone structure, a hydrodynamic mechanism due to lateral flow divergence and flame curvature, and a diffusive mechanism due to the diffusion of reactants and heat being non-aligned with the mean flow direction.

Direct simulations were then used to investigate the structure of the two-dimensional flame tip (with a Lewis number of unity):

(1) the reaction zone structure and, thereby, *the consumption speed* are not modified by curvature. Within the accuracy limits of the computation, any element of the flame front is characterized by the same distribution of the reaction rate along the normal to the front and, therefore, features the same local consumption speed (Figure 3). It is interesting to recall here that planar stagnation point flames also exhibit a large insensitivity to stretch when $Le = 1$ (Williams 1985). This is even more true in a turbulent flow where flamelets are able to move freely to escape from regions of high strain. Therefore, we may conclude that at unity Lewis number, the consumption speed of flamelets is affected neither by strain, nor by curvature. In other words, stretch (positive or negative) has no effect on the consumption speed. This is a considerable simplification for global flamelet models because (when the Lewis number is unity) the consumption speed may be assumed to be unaffected by turbulence and equal to the unstretched laminar flame speed $S°$.


Reaction Rate

Temperature

FIGURE 3. Computation of a flame tip of a Bunsen burner, Lewis = 1. Contours of reaction rate and of temperature.

(2) *the displacement speed* may be an order of magnitude higher than the unstretched flame speed $S°$. This effect is not due to any chemical mechanism because, as discussed above, the reaction zone structure at the tip is not affected by curvature (see Figure 3). The hydrodynamic mechanism was investigated by studying the divergence of the streamlines at the tip. It was found that this mechanism

accounts for approximately one half of the total increase of the displacement speed at the tip. The diffusive mechanism accounts for the other half. It was investigated by observing the divergence of the reactant pathlines relative to the mean flow streamlines and by comparing the flame structure at the tip with the structure of a one-dimensional planar flame. The calculations show that the reactant pathlines diverge faster than the streamlines of the mean flow resulting in a net 'leakage' of reactants across the boundaries of the central streamtube.

Correlations of the displacement speed with flame stretch show that a single parameter (the flame stretch) may be used to predict the displacement speed and that the linear relationship predicted by asymptotic analysis holds for a wide range of stretch values. In the case of constant transport properties ($\rho\mathcal{D}$ = constant), the simulations results agree with the prediction of asymptotic analysis. In the case of variable transport properties, the dependence of the displacement speed is also linear but the slope of the result has to be modified to account for the large variations of the transport coefficients with temperature. The classical Markstein relation as well as its extension proposed by Chung and Law (1988) are found to be valid only at low stretch.

In the context of turbulent combustion, a first result of the analysis is the existence of a minimum radius of curvature of a curved flame convex towards the fresh gases. When applied to the turbulent motion of a flame front in a non-uniform flowfield, the formulation also predicts that curvature will induce very different propagation speeds at different locations of the front. Flamelets which are strongly curved towards the fresh gases have very high displacement speeds and come back to more planar shapes rapidly. This effect attenuates the level of flame surface corrugations and may explain why the inner cut-off scales (the size of the smallest corrugation of the flame front in fractal theories) measured in experiments are very large (Shepherd, Cheng & Goix 1989). As a result, at a given instant, strongly curved flamelets are less likely to be found than positively stretched flamelets which correspond to a more 'stable' flame configuration. This point confirms previous results obtained by direct simulation of flame propagation in three-dimensional turbulence (Rutland 1989). Whether this justifies the use of the planar stagnation point flame as the only flamelet prototype in models for premixed turbulent combustion remains an open question. Although curved flamelets will have short lifetimes, they might have a strong effect on the flame dynamics and on the flame surface variations.

Finally, it is worth emphasizing that this work presents correlations between flame stretch and flame speeds valid only for unity Lewis number. It is well known that non-unity Lewis number leads to more complex situations like flame tip opening. In these cases, the consumption speed will depend strongly on curvature, but one may expect the hydrodynamic and diffusive mechanisms to still be the main parameters to determine the displacement speed.

3. A model for flamelet stretching and quenching rates

3.1 Introduction

The main simplification used in the studies of Poinsot, Veynante & Candel (1990) was to neglect the effect of multiple vortices on the flame front and the structure of turbulence itself by considering the interaction of isolated vortices with a flame. The objective of the present work was to make some progress on these issues by combining the flame/vortex computations with the multifractal theory studied at CTR by C. Meneveau.

The starting point of this analysis is again the flamelet assumption (see Section 2.1) (Peters 1986, Williams 1985, Poinsot, Veynante & Candel 1990). This assumption was first extended to take partial quenching and non-laminar flamelet structures into account. In most flamelet models, one assumes that each flamelet behaves like a laminar flame. This is not a necessary assumption: the only important assumption in flamelet modeling is related to the topology of the flow and to the fact that fresh and burnt gases are separated by a relatively thin continuous region where chemical reactions take place. This region may have a laminar flame structure, but it may also be thickened by small scale turbulence without invalidating the flamelet assumption.

The flamelet assumption is not always satisfied. Knowing the turbulence integral scale and the turbulent kinetic energy, turbulent combustion diagrams indicate whether the flow will contain flamelets, pockets, or distributed reaction zones. This information is essential for building a model for turbulent combustion. A continuous flame front, without holes, will not be modeled in the same way than a flame which is broken into many small pockets and where combustion does not take place along a sheet but in a more distributed manner. Under the flamelet assumption, a central parameter for turbulent combustion modeling is flame stretch. Flame stretch is a measure of the variations of the flame surface A and is defined by (Candel and Poinsot 1990, Matalon 1983):

$$K = \frac{1}{A}\frac{dA}{dt}. \tag{5}$$

It is a local instantaneous characteristic of the flame front. Flame stretch controls the growth of the flame surface through two processes: (1) flame surface production and (2) flame quenching. Small to moderate flame stretch creates active flame surface, while high stretch might lead to flame quenching.

3.2 Flame surface production

When the flamelet assumption is valid, the modeling of turbulent combustion mainly reduces to the evaluation of the flame surface density Σ (defined as the flame surface per unit volume) (Darabiha *et al.* 1988, Marble and Broadwell 1977, Pope 1988) or the passage frequency of the flamelets (Bray and Libby 1986, Cant and Bray 1988, Cheng *et al.* 1988). For example, the formulation of the Coherent Flame model (Candel *et al.* 1988, Marble and Broadwell 1977) provides a conservation equation for Σ in a Lagrangian frame moving with the turbulent flame.

$$\frac{d\Sigma}{dt} = \bar{K}\Sigma - Q_c, \tag{6}$$

where $\bar{K}$ is the mean stretch rate averaged along the flame surface. The second term Q_c on the RHS of Eq. (6) corresponds to flame surface annihilation by mutual interaction of flame fronts (for example, the merging of two flame fronts together). The average stretch $\bar{K}$ is of utmost importance in Eq. (6) because it imposes the source term for the flame surface and ,therefore, the mean turbulent reaction rate $\overline{\dot{w}}$ given by

$$\overline{\dot{w}} = w_L \Sigma. \tag{7}$$

where w_L is the mean consumption rate per unit surface along the flame front (if one assumes that the flamelet has a laminar structure, w_L will be the laminar consumption rate for the same chemical parameters and the same stretch).

3.3 Flame quenching and definition of the flamelet regime

The most important mechanism controlling the validity of the flamelet assumption is the occurrence of flame quenching by turbulence. When no quenching occurs in a premixed turbulent flame, the flame zone is 'active' everywhere and may be treated as an interface separating fresh unburnt reactants from hot burnt products. This regime is called the 'flamelet' regime.

It is necessary to discuss here the definition of a flamelet regime. Poinsot *et al.* (1990) propose:

Definition 1: *A premixed turbulent reacting flow is in a flamelet regime if, at any given time, any line connecting one point in the fresh gases to another point in the burnt products crosses (at least) one active flame front, i.e. there are no holes in the active flame surface.*

Definition 1 is very restrictive. First, it is reasonable to assume that a hole which persists only for a short time will not force the flow to a 'non-flamelet' regime. Second, even if the flame surface contains locally quenched surfaces, as long as these holes spread more slowly than the active flame surface, the regime will correspond to partial quenching and the flamelet approach will still provide a reasonable estimate of the reaction rate if quenching is accounted for. As we are interested in developing models for engineering applications, it is convenient to relax Definition 1 and to introduce a broader definition of the flamelet regime:

Definition 2: *A premixed turbulent reacting flow is in a flamelet regime if holes (generated by local quenching of the flame front) do not inhibit the growth of the active flame surface.*

Definition 2 allows us to consider regimes of partially quenched flames as flamelet regimes. What happens when holes in the flame front grow fast enough to interfere with the active flame surface is an open question. Fresh and hot gases will diffuse before they react, and our definition of flamelets will break down. In this case, it is possible that the flow will still be able to sustain combustion in a regime called distributed reaction zones. However, it might also be driven to total quenching. This point cannot be asserted at the present time. We will call this limit global (or total) quenching although it might, in fact, be only a transition to another regime of combustion (without flamelets).

Local flame quenching occurs when the flame front is submitted to external perturbations like heat losses or aerodynamic stretch which are sufficiently strong to decrease the reaction rate to a negligible value or in some cases to completely suppress the combustion process.

Quenching in *laminar flames* has received considerable attention in the last years. Asymptotic studies of laminar stagnation point flames established by the counterflow of reactants and products reveal that a laminar flame can be quenched by stretch if the flow is non-adiabatic or if the Lewis number (defined as the ratio of the thermal diffusivity to the reactant diffusivity: $Le = \lambda/(\rho C_p \mathcal{D})$) is greater than unity. These results have been confirmed by numerical methods for simple or complex chemistry and by experiments.

The idea that quenching mechanisms evidenced in laminar flames may be responsible for partial or total quenching in premixed turbulent flames is an important ingredient of many models of turbulent combustion (Peters 1986, Darabiha *et al.* 1988). Experiments show that quenching can, indeed, occur in turbulent combustion (Abdel-Gayed and Bradley 1985, 1989). However, the prediction of quenching in *turbulent flames* is still an open question. The classical theoretical approach to predict quenching in turbulent flames is to assume that flamelets behave like laminar stagnation point flames (Bray 1980) and are quenched for similar critical values of stretch. This is a crude approximation. In laminar stagnation point flames, a constant steady stretch is imposed to a planar flame. In a turbulent reacting flow, flamelets are stretched by vortices. Therefore, the stretch they experience is changing with time because the vortices are convected by the mean flow and are dissipated by viscous effects. Flamelets are also free to move to escape from regions of high stretch (which is not the case for laminar stagnation point flames). Moreover, vortices curve the flame front, making the analogy between flamelets and planar stagnation point flames doubtful. These points suggest that information on quenching in laminar stagnation point flames are not relevant to predict quenching in turbulent flames. A central difficulty to improve on this classical approach is the estimation of the flame stretch K in a turbulent flow.

3.4 The Intermittent Turbulence Net Flame Stretch (ITNFS) model

From the previous discussion, it is clear that the mean value of the flame stretch $\overline{K}$ is an essential parameter in turbulent combustion. It controls flame quenching as well as flame surface creation. It is also clear that studies of laminar stagnation point flames cannot be used directly to study quenching or flame surface creation in a turbulent flow. Additional parameters like curvature, viscous dissipation, and thermodiffusive effects also have to be considered.

Different expressions may be found in the literature for the mean flame stretch $\overline{K}$. Bray (1980) and Cant and Bray (1987) propose

$$\overline{K} = \sqrt{\epsilon/\nu}, \tag{8}$$

where ϵ is the dissipation of turbulent kinetic energy and ν is the kinematic viscosity.

Candel *et al.* (1988) use

$$\overline{K} = \epsilon/k. \tag{9}$$

where k is the turbulent kinetic energy. We will give here a more precise estimate of the flame stretch by combining different approaches:

(1) Use of direct simulations of flame/vortex interactions to predict the effect of a given isolated structure on a laminar flame front. Using results on flame/vortex interaction allows us to take into account viscosity, curvature, and transient effects. The basis for these results is the work of Poinsot *et al.* (1990)

(2) Use detailed experimental data about intermittent turbulence to determine the distribution of stretch along the flame front (Meneveau and Sreenivasan 1987).

(3) Define a net stretch of the flame by subtracting the rate of destruction of existing flame surface by quenching from the rate of increase of surface due to hydrodynamic straining.

The idea behind the ITNFS model is to use a complex model to describe the interaction of one vortex with a flame front and to extend it to a complete turbulent flow by supposing that the total effect of all the turbulent fluctuations can be deduced from the behavior of each individual scale in the fresh gases. This is clearly an important approximation. First, the interaction of multiple scales with the flame front cannot, in the general case, be reduced to the sum of the interactions of each vortex with the flame. Non-linear effects are to be expected. Second, the flame is not affected only by the fluctuations present in the stream of fresh gases. Flame-generated turbulence can also play a role. Therefore, the present approach should be viewed only as a first step towards a more complete treatment of the turbulent reacting flow. However, it represents a substantial improvement on classical estimates of the flame stretch. The ITNFS model may be used in any flamelet model (Candel *et al.* 1988, Bray and Libby 1986).

3.5 Results

The details of the computation may be found in Meneveau and Poinsot (1990). The main results of this analysis are:

(1) the existence of an efficiency function which characterizes the effect of a vortex of given size and speed on a flame front. In particular, it is shown that small vortices have low efficiencies, i.e. that they do not create as much flame stretch as their own time scales would suggest,

(2) the fact that flame quenching of a flame front by a vortex proceeds on a time scale which is the flame time and not the vortex time. In other words, however strong a flame front is stretched, this stretch has to be maintained for a time which is at least l_F/S_0 before quenching occurs (l_F is the laminar flame thickness and S_0 is the flame speed),

(3) an expression for the actual flame stretch of a premixed front in a turbulent flow was derived. Figure 4 presents the variation of this parameter as a function of two quantities: the ratio of the RMS turbulent velocity to the laminar flame speed (u'/S_0) and the ratio of the integral scale to the flame thickness (l/l_F). The flame stretch is normalized by the characteristic strain at the Kolmogorov scale $\sqrt{\epsilon/\nu}$ which is a measure of the stretch of material surfaces (Yeung *et al.* 1990). It appears that only for very large turbulence scales ($l/l_F >> 1$) or very small turbulence intensities ($u'/S_0 << 1$) does the ratio $\overline{K}/\sqrt{\epsilon/\nu}$ reach a value of order

one (the limit of $\overline{K}/\sqrt{\epsilon/\nu}$ for material surfaces ($l/l_F >> 1$) is 0.28 as shown by Yeung *et al.* (1990)). Meneveau and Poinsot (1990) also show that the flame stretch is not simply related to the characteristic strain at the integral scale ϵ/k. These results contradict many of the approximations used in models (Bray and Libby 1986, Cant and Bray 1988, Candel *et al.* 1988) and provide a new basis for turbulent combustion models based on the flamelet concept.

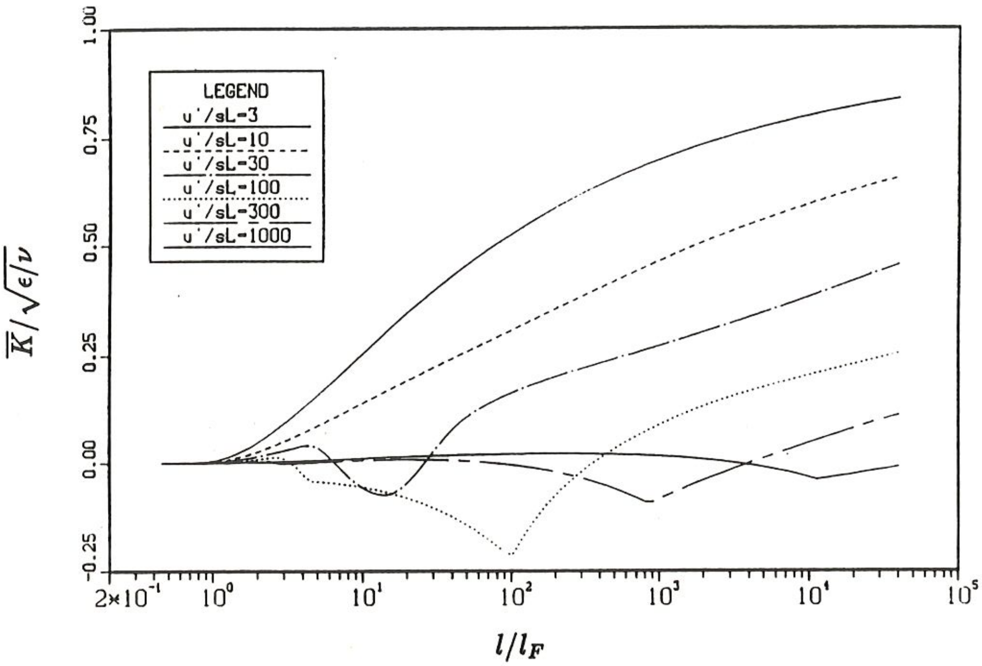


FIGURE 4. The total flame stretch in a turbulent flow.

(4) global quenching limits of premixed turbulent flames were obtained and compared to experimental and previous theoretical observations. Results show that, as assumed by Poinsot *et al.* (1990), quenching is quite difficult to generate in premixed flame fronts, and the flamelet domain is larger than expected from classical theories. Moreover, heat losses appear to have a large effect on the occurrence of quenching. These results agree with experimental studies.

4. The interaction of random flows with flame fronts

In the previous section, the interaction between a complete turbulent flow and a flame was studied using a theoretical description of the turbulent flow in the fresh gases (multifractal formulation). However, no simulation of such an interaction was actually performed. Starting in May 1990, such simulations were started in two dimensions and during the Summer Program in three dimensions. The main novelty in these studies is that we were able to compare two codes and evaluate their limits and common features:

(1) the first code was the one presented here: it uses a two-dimensional grid but solves for the compressible NS equations, with variable density, viscosity, and temperature.

(2) the second code was a three dimensional spectral code (Rutland 1989). This code solves for constant density flows and, therefore, ignores certain points which are clearly important for flames: dilatation, density and temperature changes, viscosity variations.

Similar runs were done using both codes. Results may be found in Haworth and Poinsot (1990) and Rutland and Trouve (1990). A general result was that many common conclusions were obtained. For example, the effect of the Lewis number on the structure of the reacting front appears to be exactly the same in 2 and 3 D cases. Higher Reynolds numbers, higher flow speed compared to the flame speed, and larger physical domains were obtained in two dimensions. However, many of the qualitative results were similar. An additional result provided by the two-dimensional code was the confirmation of the importance of vortex pairs (modons) in flame vortex interactions. Figure 5 shows a typical interaction between a premixed flame front and an initially isotropic turbulence.

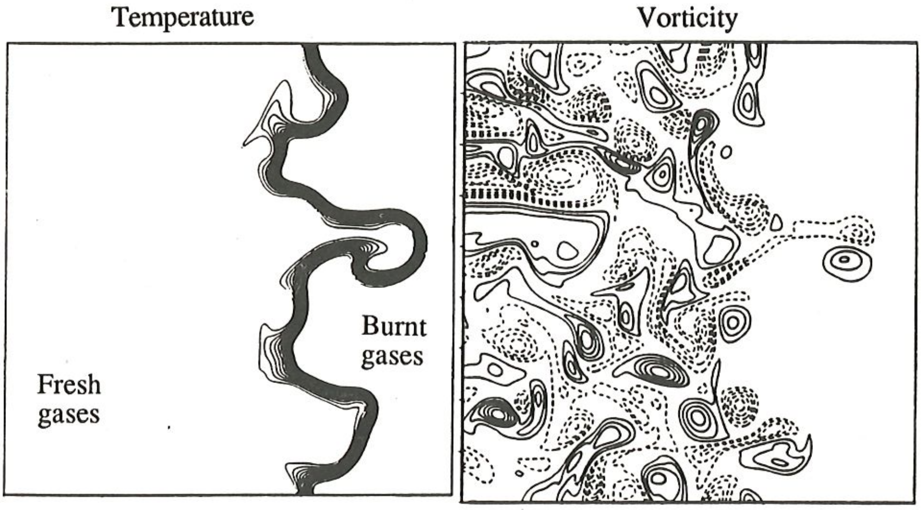


FIGURE 5. Temperature and vorticity contours in a two-dimensional direct simulation.

Vorticity and temperature contours are plotted. Pockets of fresh gases formed in the burnt gases (on the right side of the pictures) are created by vortex pairs originating in the cold gases and being convected at high speed through the flame front because of their self induced movement. The importance of vortex pairs in turbulent combustion was one of the main assumptions done in our two-dimensional studies of flame vortex interactions. That structures with self-induced velocities are quite important for turbulent combustion is clear. Which form these structures will have in a three-dimensional flow (vortex rings, pair of vortex filaments) is still an open question. These studies are being pursued and will be published in 1991.

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