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Turbulent premixed combustion: Flamelet structure and its effect on turbulent burning velocities

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Abstract

This review paper addresses the following question: what is the structure of flamelets within premixed turbulent combustion and how does this structure affect the turbulent burning velocity? We also ask: how accurately can new models predict the flamelet structure as well as the values of turbulent burning velocity? Flamelet structure is defined to include the following quantities: reaction layer surface area per unit volume (Σ), the brush thickness (δ_T) and the stretch factor (I_0). One equation that is commonly used to relate these flamelet structure parameters to the burning velocity S_T is

$$\frac{S_T}{S_{L0}} = I_0 \int_{-\infty}^{\infty} \Sigma \, d\eta = I_0 \Sigma_{max} \delta_T.$$

Recent results obtained using laser imaging methods and direct numerical simulation (DNS) are reviewed in order to demonstrate the relationships between S_T, Σ, I_0 and δ_T. η is the direction normal to the brush. Measurements of Σ show that the wrinkling process is not local but has a "memory" of wrinkling that occurs elsewhere. The stretch factor I_0 depends on differential diffusion (Markstein number) even at large turbulence intensities. Thus the concepts associated with the theory of flame stretch have been found to be valid even for highly turbulent flames. Thin flamelets exist for nearly all cases for which images of the reaction zone have been obtained. Evidence of "non-flamelet" behavior is sparse. DNS now can successfully predict realistic values of turbulent burning velocity for laboratory-scale Reynolds numbers and for the realistic geometries of Bunsen and V-flames using complex chemistry and no empirical constants. Large eddy simulations (LES) also have predicted reasonable values of S_T, but some empirical constants are required. A number of current research issues are discussed.

Keywords: Turbulent; Premixed; Combustion; Burning velocity; Flamelet

Contents

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1. Introduction: Why do we need to know the structure of premixed turbulent combustion?

We begin our discussion with the question: why do we need to know the structure of the flamelets that exist within turbulent premixed flames? The word "structure" here refers to quantities such as Σ, δ_T and I_0, which are defined to be the flamelet surface area per unit volume, the brush thickness, and a stretch factor that is defined below. The answer to our question is that we need to know the structure because the turbulent burning velocity S_T depends on the flamelet wrinkling process which is geometry-dependent. That is, in real flames the wrinkling is not some "universal" process that depends only on the local turbulence level. Instead wrinkling depends on the complex geometry of shear layers, walls, flame–flame interactions and the location where the flame is anchored. Wrinkling has a "memory" of any wrinkling that might have occurred upstream. Therefore, models must be able to use differential equations to relate the wrinkling process to the burner geometry. Measurements of Σ, δ_T and I_0 are needed to determine if direct numerical simulation (DNS) or large eddy simulation (LES) can accurately predict these quantities using no adjustable parameters or a few parameters, respectively. For a model to be considered to be robust is not sufficient to show that the predicted burning velocity matches an experiment by adjusting some parameters. A robust simulation must predict the correct intermediate parameters such as Σ and δ_T as well as S_T.

One may ask: is it possible for any model to correctly predict the complex wrinkling process that occurs a real burner that is operated at a realistic Reynolds number? Fortunately new advances in DNS and LES provide a positive answer to that question.

Fig. 1 illustrates DNS results of Bell et al. [1,2] and Sankaran et al. [3]. Also shown are LES computations of Pitsch and Duchamp de Lagenest [4]. The DNS studies used no adjustable parameters and were able to include complex methane–air chemistry with 20 species and 84 reactions, realistic burner dimensions (from 1 to 5 cm) and realistic Reynolds numbers that are associated with laboratory-scale burners operated at mean velocities of 3–60 m/s. Values of u'/S_{L0} varied between 0.69 and 10; this is sufficient to cause the extreme degree of wrinkling that is seen in Fig. 1. The DNS and LES results are discussed in Section 4.

An important equation that relates the turbulent burning velocity to the flamelet structure is one that has been discussed by Bray and Cant [5]:

$$\frac{S_T}{S_{L0}} = I_0 \int_{-\infty}^{\infty} \Sigma \, d\eta. \tag{1}$$

The coordinate η is normal to the brush, and the integral in Eq. (1) is proportional to the product of the maximum value of Σ (which occurs near the center of the brush) and the brush thickness δ_T. This equation indicates that to achieve a rapidly propagating turbulent flame, it is desirable to have a large value of the product of the maximum surface density and the brush thickness.

Because of the importance of Eq. (1) its derivation is briefly reviewed. Damköhler [6] predicted that for one regime of conditions (which is now called the flamelet regime) the primary result of turbulence is to wrinkle the thin reaction layers, which retain the local characteristics of a laminar flame. For this regime he predicted that the ratio of turbulent to laminar burning velocity (S_T/S_{L0}) is equal to the area ratio (A_T/A_L). Fig. 2 illustrates the areas A_T and A_L of a wrinkled and an unwrinkled flamelet, respectively. In Fig. 2 each point along the wrinkled surface propagates at the flamelet consumption speed $S_{F,C}$ which has a time-averaged value of $\bar{S}_{F,C}$. The time-averaged volume per second of reactants that is traversed by a flamelet is $\bar{S}_{F,C}$ A_T. The reactants have the constant density ρ_R. Therefore, the mass per second of reactants traversed by the wrinkled surface inside the control volume is ρ_R $\bar{S}_{F,C}$ A_T. Now consider the dotted line in Fig. 2; it propagates at the turbulent burning velocity S_T. The volume of reactants traversed per second by the dotted line is S_T A_L and the mass/s of reactants traversed is ρ_R S_T A_L. Equating these two values yields

$$\frac{S_T}{S_{L0}} = \frac{A_T}{A_L}\frac{\bar{S}_{F,C}}{S_{L0}} = \frac{A_T}{A_L} I_0. \tag{2}$$

Bray and Cant defined the stretch factor I_0 and the flamelet consumption speed to be

$$I_0 = \bar{S}_{F,C}/S_{L0}, \quad S_{F,C} = \rho_R^{-1} \int \omega_R \, d\xi. \tag{3}$$

The instantaneous volumetric reaction rate is ω_R and ξ is the direction normal to each reaction layer. A slice of the