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Introduction

The relationship between the turbulent premixed flame velocity and the turbulence parameters, namely turbulent intensities and turbulence scales, has been the subject of continuous interest mainly due to the immediate potential impact of the answer in the areas of practical importance [1,2]. Despite the continuing progress in the understanding of the turbulence and turbulent combustion mechanisms, we still lack a universal relationship or model, even for the wrinkled flame regime, that would satisfactorily explain the turbulent premixed flame data available in literature. One of the leading reasons for this is that turbulent premixed flames display phenomena which are not common in other turbulent flows. An interplay of turbulence, thermodynamics, and chemical kinetics leads to a highly complex situation, and it should be remembered that available turbulence models, as noted by Bray [3], are not uniformly successful in predicting complex flow fields even in the absence of combustion.

Turbulent flame propagation was first investigated by Damköhler [4], and he pointed out to two limiting cases based on the magnitude of the scale of turbulence as compared to the flame thickness. The identification of the turbulent premixed combustion regimes has been an integral part of the turbulent flame propagation problem.

Turbulent premixed combustion and combustion regimes have been discussed by several authors, e.g. [5-8]. To identify the different regimes several criteria have been discussed by Abraham et al.[1] and Gökalp [9]. The equivalency of the different criteria and form of the expression to be used to evaluate laminar flame thickness have been critically assessed in [9]. It is generally agreed that when the Reynolds number R_η based on the turbulence intensity and on the Kolmogorov length scale η is larger than the ratio of the turbulence intensity u' to the laminar flame speed u_l [10], turbulent premixed flames exhibit a wrinkled laminar flame structure. This regime, which can alternatively be described with the criterion $\delta_l < \eta$, where δ_l is the laminar flame thickness, is called the reaction sheets regime [5,11] or flame sheets regime [12].

In this paper, a conceptual model of turbulent premixed flame propagation in the wrinkled flame regime is presented. Resulting equation is tested against a large number of data sets obtained on a variety of experimental rigs.

Formulation

Following the analysis of Kerstein [13], our formulation starts with two alternative expressions for the thickness of the turbulent flame brush δ_t, which is the interval along the flow streamline where both burned and unburned gases exist. The turbulent flame brush moves with a mean velocity u_t relative to the mean fluid motion, as by the definition of the turbulent flame velocity. If the mean time required to consume an unburned fluid parcel entering the turbulent flame brush is τ, then the thickness of the flame brush can be expressed as [13]

$$\delta_t \approx u_t \tau \tag{1}$$

By analogy to the relationship between laminar flame thickness δ_l, laminar flame speed u_l, and the molecular diffusivity D, i.e. $\delta_l = D/u_l$, we can also express δ_t as follows

$$\delta_t \approx D_t/u_t \tag{2}$$

where $D_t = u'L$ is the turbulent diffusivity and L is the integral length scale of turbulence. Equations (1) and (2) yield

$$u_t \approx (u'L/\tau)^{1/2} \tag{3}$$

Adopting the suggestions of Tennekes [14] and Kuo and Corrsin [15] for non-reacting turbulence, that dissipative eddies are most probably consist of vortex tubes, with a diameter of the order of Kolmogorov length scale η and a spacing of the order of the Taylor length scale λ, Fig.1, it is possible to express the chemical lifetime of an eddy. Starting with this concept Abdel-Gayed and Bradley [16] proposed that the flame propagation across an eddy would originate at the dissipative vortex tubes. Then the mean distance the flame must cover to consume the mixture is of the order of $\lambda/\sqrt{2}$, which leads to a chemical lifetime expression

$$\tau \approx \lambda/(\sqrt{2} \cdot u_l) \tag{4}$$

The relationship for the isotropic turbulence [17], $\lambda/L = \sqrt{15}/\sqrt{Re_L}$, and Eq.(4) give

$$\tau \approx (L/u_l) \cdot \{15/(2Re_L)\}^{1/2} \tag{5}$$

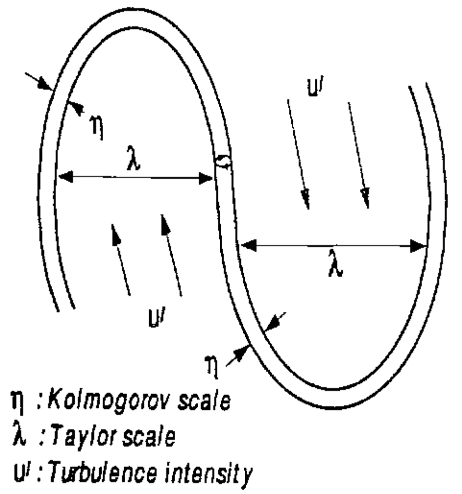

Fig.1 Micro-structure of isotropic turbulence [14].

Substituting Eq.(5) into Eq.(3), and noting that as $u' \rightarrow 0$, $u_t/u_l \rightarrow 1$, we get

$$(u_t/u_l) - 1 = 0.6\,(u'/u_l)^{1/2}\,Re_L^{1/4} \tag{6}$$

Equation (6) suggests a dependence of the turbulent premixed flame velocity on the turbulence Reynolds number as well as on $(u'/u_l)^{1/2}$.

Discussion and Conclusions

Wrinkled flame region is taken as the zone bounded by

$$R_\eta \geq 1.5(u'/u_l) \qquad and \qquad Re_L \leq 3200. \tag{7}$$

The first criterion is equivalent to $\eta \geq 1.5\delta_l$. R_η is the turbulent Reynolds number based on Kolmogorov length scale η, and δ_l is the laminar flame front thickness calculated as ν/u_l.

Turbulent premixed flame propagation data, which are within the wrinkled flame region defined by Eq.(7), are plotted as $(u_t - u_l)/u_l$ versus $(u'/u_l)^{0.5} Re_L^{1/4}$ in Fig.2 (note that $R_\eta \approx Re_L^{1/4}$). The agreement seen between many sets of experimental data is significant, especially when one considers the variety of rigs on which these data were obtained and sources of potential errors in the measured parameters.

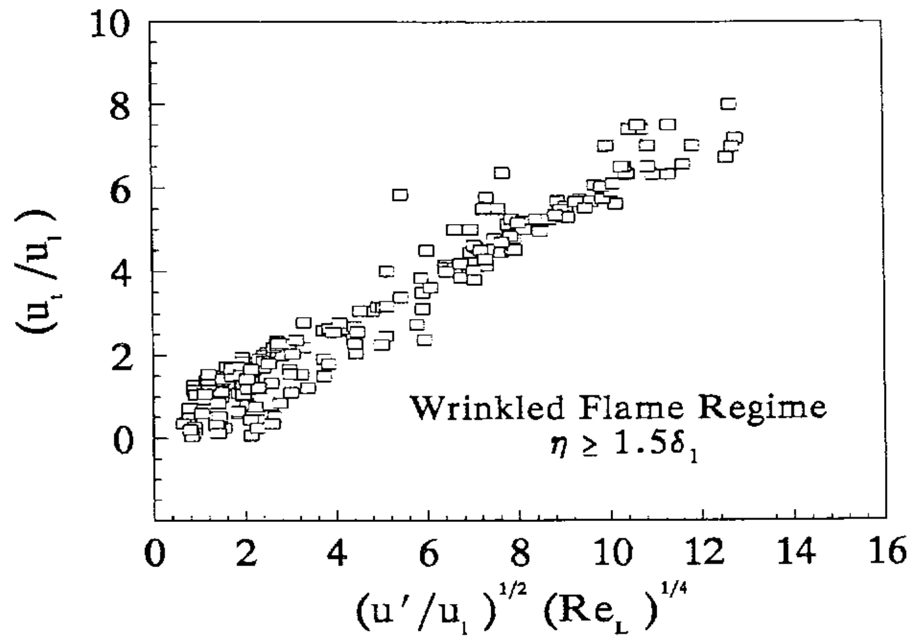

Fig.2 Comparison of the wrinkled flame model, Eq.(6), to experimental data. Experimental data sources are given in [19].

Figure 2 includes more than 200 data points for 15 mixtures reported by eight different research groups. The data in Fig.2 represents

$$(u_t/u_l) - 1 = 0.62\,(u'/u_l)^{1/2}\,Re_L^{1/4} \tag{8}$$

The slope 0.62 which resulted from experimental data is comparable to the value 0.6 in Eq.(6).

The model for the wrinkled flame regime is based on the concept of isotropic turbulence structure characterized by dissipative eddies consisting of vortex tubes with a diameter of the order of Kolmogorov length scale and a spacing of the order of the Taylor length scale. The model developed for the wrinkled flame regime suggests a wrinkled flame structure characterized by a turbulent length scale and the turbulence intensity. From a purely mechanistic point of view, the wrinkled flame surface distortions, namely the geometry of the wrinkles are controlled by the turbulent length scale as well as the turbulence intensity. It is interesting to note that the same conclusions can be reached by applying the fractal geometry concepts to the wrinkled flames [18]. Further details of this work and sources of turbulent flame data used in Fig.2 are given in [19].

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