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Direct Numerical Simulation of the bending effect in turbulent premixed flames

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Abstract

In turbulent premixed flames, much experimental evidence points to a strong influence of pre-mixture turbulence intensity on the turbulent burning velocity. The linear enhancement of turbulent burning velocity in low-intensity turbulence is predicted accurately by current models. In contrast, the deviation from linearity in high-intensity turbulence, known as the "bending effect," remains to be explained. The present work has employed Direct Numerical Simulation (DNS) to investigate the bending effect. An initially laminar methane-air premixed flame was subjected to increasing levels of turbulence across five different simulations which maintained all parameters except the turbulence intensity constant. The bending effect was captured within these simulations. Subsequently, plausible explanations were investigated using the framework of the Flame Surface Density (FSD) approach. From the ensuing analysis, it is evident that flame surface area reflects distinctly the variation of turbulent burning velocity with turbulence intensity. Local flame quenching does not appear to be the primary mechanism behind the bending effect. Instead, the observed bending effect results from a shift in balance, under high-intensity turbulence, towards mechanisms that favour destruction of flame surface area. These mechanisms tend to preserve the reaction layer and, thereby, ensure the validity of Damköhler's hypothesis and flamelet models in conditions that cause the bending effect that is observed here to occur.

Keywords: Turbulent premixed flames; The bending effect; Direct Numerical Simulation; High-intensity turbulence

1. Motivation

Turbulent burning velocity s_T is a basic measure of how fast a turbulent fuel-air mixture burns. It is defined using the global transformation rate of reactants to products through the turbulent premixed flame brush:

$$s_T \equiv -\frac{1}{\rho_u Y_{u,F} A_0} \int_V \dot{\omega}_F \, dV, \qquad (1)$$

where ρ_u is the density of unburned gas, $Y_{u,F}$ is the fuel mass fraction in the unburned gas, A_0 is the flow cross-section area, and $\dot{\omega}_F$ is the fuel reaction rate. It is well known that s_T is sensitive to the oncoming turbulence as well as to the

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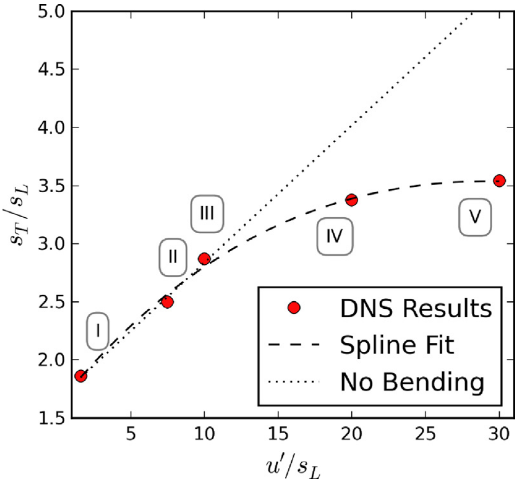

Fig. 1. Calculations from the present DNS cases (I–V) plotted to show the nonlinear "bending" curve of $s_T(u')$: turbulent burning velocity diminishes in high-intensity turbulence.

thermo-chemical properties of the mixture and to the flame configuration. Under increasing turbulence intensity u', with all other parameters held constant, the variation of s_T is found to be nonlinear [1]. This behaviour, known as the *bending effect*, has been reviewed in-depth [2,3], but it has not been explained as yet.

The present work has captured the classical bending effect (shown in Fig. 1 and discussed in Section 5.1) for the first time using Direct Numerical Simulation (DNS). In this article, we discuss the observed effect and seek an explanation for it in terms of the underlying turbulence-flame interactions as recorded in the DNS study.

2. Theoretical background

Damköhler's hypothesis [4] conjectured that, in low-intensity turbulence, s_T increases primarily because the turbulent flow field enhances the premixed flame surface area A_T as

$$s_T/s_L \sim A_T/A_L, \tag{2}$$

where s_L is the laminar flame consumption speed and A_L is the laminar flame area. The underlying assumption was that s_L remains valid locally on the flame surface in low-intensity turbulence. Subsequently, the applicability of Damköhler's hypothesis in moderate-intensity turbulence has been supported by 2D DNS [5], experimental measurements [6], and scaling analysis [7]. High-intensity turbulence – where the bending effect and its underlying processes occur – has remained elusive.

In recent years, the simultaneous advancement of laser diagnostics and supercomputing resources has opened high-intensity turbulent combustion to quantitative inquiry. A variety of physical scalings that characterize the bending effect have been investigated [8] and the limits of the $s_T(u')$ curve have been explored [9]. Some experimental studies have even questioned the validity of Damköhler's hypothesis in high-intensity turbulence [10]. At the same time, large-scale DNS is beginning to provide insights [11,12].

To date, it remains to be ascertained whether $s_T(u')$ indeed varies nonlinearly in the absence of heat losses. Given that $s_T(u')$ undergoes this bending effect, its governing mechanism has not been outlined either qualitatively or quantitatively and its consistency with the flamelet assumption is yet to be determined.

A common framework used in both experimental and computational analyses is the Flame Surface Density (FSD) approach [13]. Under the flamelet assumption, the mean flame surface-to-volume ratio Σ captures the turbulence-flame interactions which determine s_T [14]

$$s_T \sim s_L \int_{-\infty}^{\infty} \Sigma \, d\eta, \tag{3}$$

when integrated throughout the premixed flame brush. The quantity $\Sigma \equiv \langle \Sigma' \rangle$ is the mean of the local surface-to-volume ratio Σ' for a propagating flame surface and it evolves according to the transport equation [13]

$$\frac{\partial \Sigma}{\partial t} + \nabla \cdot (\langle \mathbf{u} + s_d \mathbf{n} \rangle_s) = \langle \dot{s} \rangle_s \Sigma, \tag{4}$$

where $\mathbf{n} = -[(\nabla c)/(|\nabla c|)]|_{c=c^*}$ is the local normal to the surface and $s_d = [(\dot{\omega} + \nabla \cdot \rho \mathcal{D} \nabla c)/\rho|\nabla c|]|_{c=c^*}$ is the local surface displacement speed. All of these quantities, including the surface averaging $\langle \phi \rangle_s \equiv \langle \phi \Sigma' \rangle / \Sigma$, are computed on iso-surfaces $c = c^*$ of the reaction progress variable $c \equiv (Y_u - Y)/(Y_u - Y_b)$. The generalised FSD $|\nabla c|$, defined in the context of LES [15], is closely related to the local flame surface-to-volume ratio Σ'. Since $\lim_{\Delta \to 0} \Sigma' = |\nabla c|$, we use the generalised FSD to calculate Σ' as, in DNS, the filter size $\Delta \to 0$.

The source term $\dot{s}$ represents local flame stretch rate on the iso-surface. It is more insightful to decompose $\dot{s}$ into the separate contributions from tangential strain rate a_t and mean curvature h_m according to

$$\dot{s} = a_t + s_d h_m, \tag{5}$$

where the components are given by

$$a_t = \nabla \cdot \mathbf{u} - \mathbf{nn} : \nabla \mathbf{u}, \text{ and} \tag{6}$$

$$h_m = \nabla \cdot \mathbf{n}. \tag{7}$$

The FSD approach links turbulent burning velocity s_T to local events such as flame surface wrinkling, flamelet-merging and intermittent quenching