A Numerical Study of Premixed Turbulent Flame Dynamics

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Many experimental observations show that premixed turbulent flame speed and thickness grow in time (or with distance from flame-holder) in most flames. The goal of this work is to numerically study the effects of pressure-driven transport on the development of premixed turbulent flame structure, thickness, and speed by solving the following generalized flamelet closure

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{c}) + \frac{\partial}{\partial x}(\bar{\rho}\tilde{u}\tilde{c}) = \underbrace{\frac{\partial}{\partial x}\left(\bar{\rho}D_t\frac{\partial \tilde{c}}{\partial x}\right)}_{I} + \underbrace{\mathcal{U}\frac{\partial}{\partial x}\left[\bar{\rho}\tilde{c}(1-\tilde{c})\right]}_{II} + \underbrace{\frac{\rho_u}{\tau_f}\left(\frac{\bar{\rho}}{\rho_u}\right)^q \tilde{c}(1-\tilde{c})}_{III}, \qquad (1)$$

of the mean combustion progress variable balance equation

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{c}) + \frac{\partial}{\partial x}(\bar{\rho}\tilde{u}\tilde{c}) = -\underbrace{\frac{\partial}{\partial x}\left(\overline{\rho u'' c''}\right)}_{IV} + \bar{W}. \qquad (2)$$

Term III in Eq. 1 is a typical closure of the mean rate of product creation, $\bar{W}$, provided by various flamelet models [1,2]. Different models result in different expressions for the flame time scale, τ_f, but the specification of such an expression is not needed here, because a closure for τ_f does not affect the numerical results presented in a normalized form if τ_f is not varied in space and time.

Terms I and II in Eq. 1 model turbulent diffusion and pressure-driven transport [2], respectively, and together represent a generalized closure of the transport term IV in Eq. 2. Here, D_t is the turbulent diffusivity and $\mathcal{U}$ is a velocity scale. Term II may be associated with the submodel of pressure-driven transport, $\gamma S_L \bar{\rho}\tilde{c}(1-\tilde{c})/2$, developed by Bray et al. [3] for stagnating flames. Then, $\mathcal{U} = \gamma S_L/2$, where $\gamma = \rho_u/\rho_b - 1$ is the heat release factor, and S_L is the laminar flame speed.

We have kept the turbulent diffusion term I in Eq. 1; despite the fact that, in many laboratory flames, this term is much smaller than the pressure-driven transport term II almost in the whole flame brush ($0 < c_1 < \tilde{c} < c_2 \leq 1$, $c_1 \ll 1$, $1 - c_2 \ll 1$), for instance, term I was omitted by Bray et al. [3]

when modeling stagnating flames. One reason for keeping this term in simulations of a planar flame moving in a statistically stationary and uniform mixture is as follows. If one omits term I in this case, then the asymptotically steady solution of Eq. 1 should satisfy the following equation

$$S_t^o \frac{d\tilde{c}}{dx} = \mathcal{U}\frac{d}{dx}\left[\frac{\bar{\rho}}{\rho_u}\tilde{c}(1-\tilde{c})\right] + \frac{1}{\tau_f}\left(\frac{\bar{\rho}}{\rho_u}\right)^q \tilde{c}(1-\tilde{c}). \tag{3}$$

However, Eq. 3 includes only three dimensional parameters, S_t^o, $\mathcal{U}$, and τ_f, and, due to dimensional reasons, $S_t^o = \mathcal{U} f(\gamma)$ for an arbitrary τ_f, i.e., the fully-developed turbulent flame speed, S_t^o, does not depend on the mean rate of product creation. The absurdity of this conclusion[1] justifies keeping of term I in Eq. 2 even if this term is much less than term II at $c_1 < \tilde{c} < c_2$.

To simulate the propagation of a statistically planar 1D flame in statistically stationary and uniform mixture from the left to the right, Eq. 1 has been normalized

$$\frac{\partial}{\partial t'}(\bar{\varrho}\tilde{c}) + \frac{\partial}{\partial z}(\bar{\varrho}\tilde{v}\tilde{c}) = \frac{\partial}{\partial z}\left(\bar{\varrho}\frac{\partial \tilde{c}}{\partial z}\right) + P\frac{\partial}{\partial z}\left[\bar{\varrho}\tilde{c}(1-\tilde{c})\right] + \frac{\bar{\varrho}^q}{4}\tilde{c}(1-\tilde{c}) \tag{4}$$

by invoking the following velocity, $u_o = 2(D_t/\tau_f)^{1/2}$, length, $l_o = (D_t\tau_f)^{1/2}$, time, $t_o = l_o/u_o$, and density, ρ_u, scales and, then, solved together with the normalized mass balance equation and with the following state equation, $\bar{\varrho} = (1+\gamma\tilde{c})^{-1}$ [1,2]. The focus of this work is placed on the effects of P on the unsteady solution of Eq. 4, or, in other words, on the role played by pressure-driven transport, since we have already studied the dynamic behavior of the solution of Eq. 4 with $P = 0$ [4,5].

Shown in Fig. 1 are the effects of P on the self-similarity of the structure of developing flames. Numerous experimental data discussed elsewhere [4,5] show that the structure of various premixed turbulent flames is self-similar, i.e., the spatial profiles of the progress variable, normal to the flame brush, are described by the same function at different instants t after ignition when using the developing flame brush thickness, $\delta_t(t)$, in order to normalize the spatial coordinate. Our previous simulations [4,5] have shown that combustion models associated with $q = 0$ in Eq. 4 predict this property if $P = 0$, whereas the models associated with $q = 1$ are not capable for doing so (Fig. 1b). An increase in P makes the self-similarity of the profiles more pronounced if $q = 0$ (Fig. 1a) and almost self-similar

[1] The comment cannot be applied to stagnating flames studied by Bray et al. [3], because one more dimensional parameter, the flame strain rate, should be taken into account in the latter case.

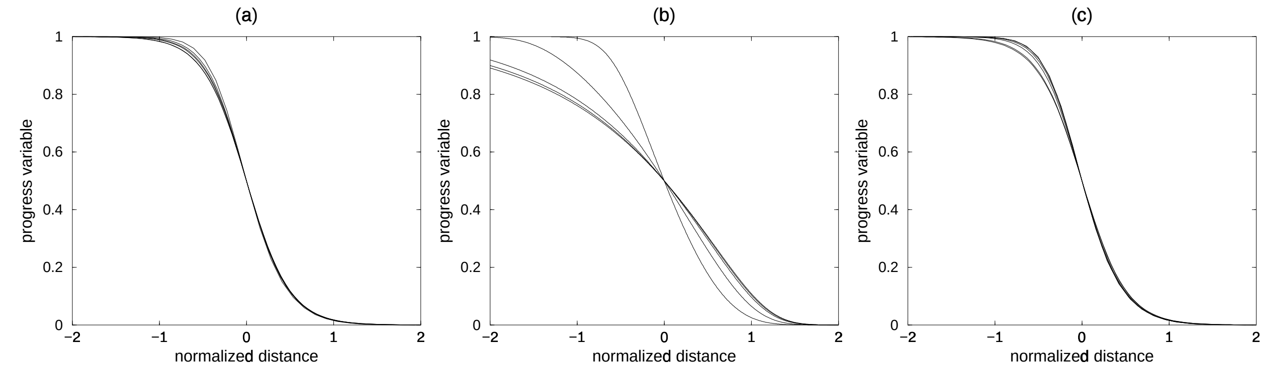

Figure 1: Progress variable profiles, computed at different instants and normalized with $\delta_t^{-1}(t) = \max|d\bar{c}/dz|$. a - $q = 0$ and $P = 2$; b - $q = 1$ and $P = 0$; c - $q = 1$ and $P = 2$.

solutions can be obtained even with $q = 1$ if P is sufficiently large (Fig. 1c). Thus, term II in Eq. 1, associated with the pressure-driven transport, enhances the trend to self-similarity.

Figure 2 shows that both normalized burning velocity, $u_t = \int_{-\infty}^{\infty} \bar{W} dx/(\rho_u u_0)$, and flame thickness, $\delta_t^{-1}(t) = \max|d\bar{c}/dz|$, are decreased by P. However, Fig. 3 indicates that the effects of P on the **development** of u_t and δ_t can be substantially reduced by re-normalizing the results using new velocity, $u_{t,\infty} \equiv u_t(t' \to \infty)$, length, $\delta_{t,\infty} \equiv \delta_t(t' \to \infty)$, and two time, $\delta_{t,\infty}/u_{t,\infty}$ or P^{-2}, scales. Indeed, curves drawn with the former time scale are close one to another if $P \leq 0.5$, whereas the curves computed at $P = 1$ differ substantially from the other curves (Fig. 3a); and curves drawn with the latter time scale are close one to another if $P \geq 0.5$, whereas the curves computed at $P = 0.2$ differ substantially from the other curves (Fig. 3b) Moreover, the obtained results show that $u_{t,\infty} \sim 1/P$

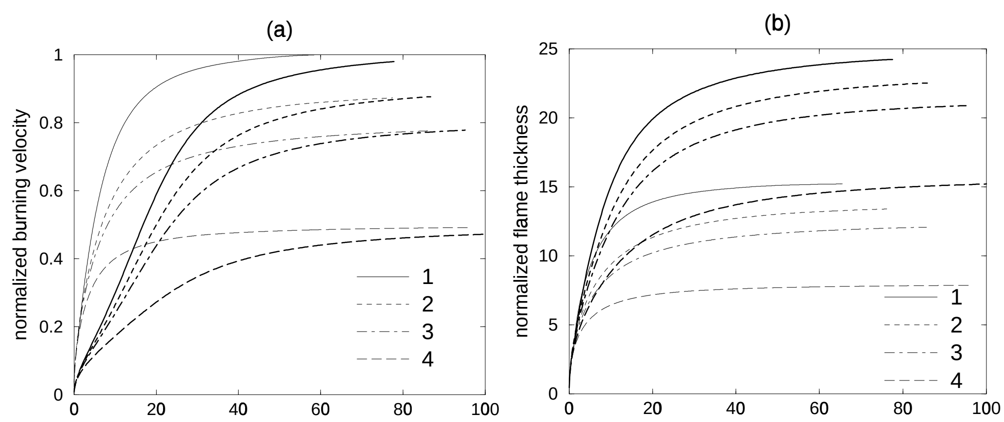

Figure 2: Development of normalized burning velocity (a) and flame thickness (b), computed with $q = 0$ (fine curves) and $q = 1$ (bold curves) at various P: 1 - $P = 0$; 2 - $P = 0.1$; 3 - $P = 0.2$; 4 - $P = 0.5$.

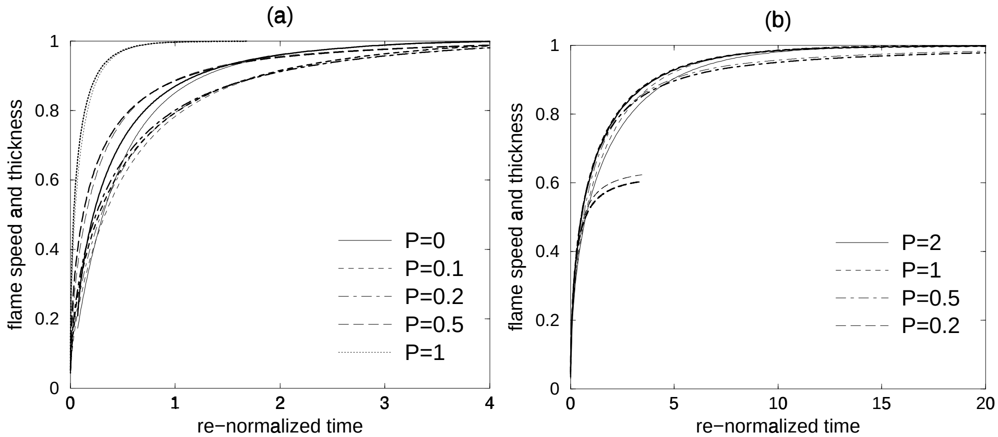

Figure 3: Development of burning velocity (fine curves) and flame thickness (bold curves), computed with $q = 0$ at various P, shown in legends, and re-normalized with the following velocity, $u_{t,\infty}$, length, $\delta_{t,\infty}$, and time scales, $\delta_{t,\infty}/u_{t,\infty}$ (a) or P^{-2} (b).

and $\delta_{t,\infty} \sim 1/P$ if $P \geq 0.5$. These observations imply that the flame dynamics changes substantially at $P \approx 0.5$ (or $\mathcal{U} \approx (D_t/\tau_f)^{1/2}$). We may note also that the development of re-normalized burning velocities and flame thicknesses is similar to one another in the whole range of P studied (cf. fine and bold curves in Fig. 3), in line with the results of a theoretical analysis of the self-similar solutions of Eq. 2, discussed in Refs. [5].

When considering the ranges of weak ($P < 0.5$) and strong ($P > 0.5$) pressure-driven transport separately, the role played by pressure-driven transport is mainly reduced to a decrease in $u_{t,\infty}$ and $\delta_{t,\infty}$ by P; whereas the **development of re-normalized** burning velocities and flame thicknesses is weakly affected by P. Moreover, if the submodel of $\bar{W}$ is able to yield a self-similar flame structure ($q = 0$), then, the structure is weakly affected by P. If the submodel of $\bar{W}$ is not capable for doing so ($q = 1$), then, the pressure-driven transport can make the structure self-similar (cf., Figs. 1b and 1c).

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