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Modeling of mean flame shape during premixed flame flashback in turbulent boundary layers

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Abstract

Direct numerical simulations of freely-propagating premixed flames in the turbulent boundary layer of fully-developed turbulent channel flows are used for *a priori* validation of a new model that aims to describe the mean shape of the turbulent flame brush during flashback. Comparison with the DNS datasets, for both fuel-lean and fuel-rich mixture conditions and for Damköhler numbers lower and larger than unity, shows that the model is able to capture the main features of the flame shape. Although further *a priori* and *a posteriori* validation is required, particularly at higher Reynolds numbers, this new simple model seems promising and can potentially have impact on the design process of industrial combustion equipment.

Keywords: Turbulent channel flow; Flame shape model; Turbulent premixed flame; Flame propagation

1. Introduction

Efforts aimed at the reduction in global emissions of greenhouse-gases and at the control of local emissions of pollutants are increasingly important for the energy sector. A considerable reduction in fuel consumption, due to increased efficiency, and in pollutant emissions, because of low flame temperature and without increase in the energy penalty intrinsic to dilution, can be achieved in stationary gas turbines utilizing lean-premixed (LPM) combustion technology [1]. Among the many challenges in enabling LPM combustion technology for gas turbine applications, accurate prediction of flame flashback, especially for non-conventional and highly reactive hydrogen-rich fuels [2], stands out as a key requirement for complete understanding of the complex physical processes that are of fundamental importance in burner design and optimization. Recent studies, involving high-resolution experimental measurements and direct numerical simulations (DNS) [3,4], focused on the characterization of flashback for premixed, preheated hydrogen-air flames in turbulent boundary layers, and have shown that one of the principal assumptions behind the widely-used flashback model of Lewis and Von Elbe [5] is flawed. Indeed, this

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pioneering model, dating back to 1943, in determining the critical velocity gradient for the onset of flashback erroneously assumes that the premixed flame, during its flashback in the wall boundary layer, has no effect on the approaching flow of the reactants while the recent investigations mentioned above have revealed the presence of flow reversals, induced by the flame in the viscous layer ($y^+ \lesssim 20$), located immediately upstream of the flame surface regions that are convex towards the reactants [4]. The implications of this finding range from a radically different picture about the mechanism of boundary layer flashback to the renewed need for a near-wall flame propagation model that correctly takes this new information into account. Other early studies, building on the methodology proposed in [5], have tried to chart the flashback behavior of premixed flames in the transition from laminar to the more interesting case of turbulent flows [6,7] and have reported empirical observation of considerable increases in the critical velocity gradients in the presence of turbulence; however, they have failed to clearly explain the reason for such increase in the context of a model that is ultimately based on a near-wall velocity balance within the quasi-laminar viscous layer. More recent studies [8,9] have taken into account local Lewis number and flame curvature effects on the onset of laminar boundary layer flashback but have not considered near-wall flame surface perturbation and curvature in the plane parallel to the wall that results from the interaction of the flame with the boundary layer streaks and that is instrumental to the creation of the flow reversals. Similarly to the classical work [5], the vast majority of theoretical models on turbulent combustion employs the limit of zero gas expansion, however a number of recent theoretical works take realistic gas expansion into account [10,11]. Following the latter approach in the attempt to fill existing gaps, we propose here a new model for the turbulent flame shape for premixed combustion in wall boundary layers that takes into account gas expansion and we provide *a priori* validation of the model based on the analysis of relevant DNS data. The remainder of this paper is organized as follows: Section 2 presents the new flashback model. Section 3 describes the DNS computations. Section 4 illustrates the *a priori* validation of the model. Finally, Section 5 summarizes the main findings and provides an outline of future planned work.

2. Flame shape model description

A model of the mean shape of a turbulent premixed flame in turbulent channel flow is formulated. In general, the mean location of the turbulent flame brush is represented as an interface that propagates, relative to the mean flow, following Huygens propagation picture and at the mean turbulent burning velocity S_T, whose parameterization is described in Section 4. In that parameterization, S_T depends on the laminar flame speed S_L, on the density ratio $D = \rho_u/\rho_b$, where the subscripts u and b denote unburnt and burnt conditions respectively, and on the rms velocity fluctuation u'. For the present anisotropic case, u' is interpreted as the square root of twice the mean turbulent kinetic energy per unit mass. u' is taken to be a known function of the wall-normal coordinate y based on a turbulent channel flow DNS database [12]. Steady state mean flame propagation is assumed. This implies a balance of the mean flow and the propagation of the interface toward the flow. The mean flow $U_m(y)$, which is streamwise and y dependent, is likewise obtained from the DNS database [12]. A sketch of the notional flame-in-channel configuration is given in Fig. 1. By symmetry, the interface normal at the center-plane $y = h$ (assuming walls at 0 and $2h$) is streamwise oriented, so the mean interface velocity at $y = h$ is $V_f = U_m(h) - S_T(h)$. This mean lab-frame *stabilization speed*, V_f, can also be expressed locally as $V_f(y) = (S_d(y) + U_n(y))_x$ where $S_d(y)$ and $U_n(y)$ are the local flame surface displacement speed relative to the fluid and the local (flame surface normal) fluid velocity respectively [13]. Here, the flame-normal direction is assumed to be a continuous function of y, which is not necessarily valid; see below. Steady state mean flame shape implies that the streamwise interface displacement rate V_f is, in the mean, independent of y. For $y \neq h$, the flame normal is not streamwise oriented. A relationship valid for all y is $V_f(y) = U_m(y) - S_{Tx}(y)$, where $S_{Tx}(y)$ is the upstream (opposing the mean flow) displacement rate of the interface resulting from propagation at speed $S_T(y)$ in the flame-normal direction. Denote the angle of the interface normal relative to the upstream direction as θ. Consider a locally planar interface for given θ. For $\theta \neq \pi/2$, displacement of this interface by a given distance D_n in the interface-normal direction results in interface upstream displacement $D_n/\cos\theta$ at given y. This corresponds to $S_{Tx}(y) = S_T(y)/\cos\theta$. Note that this gives the required behaviors

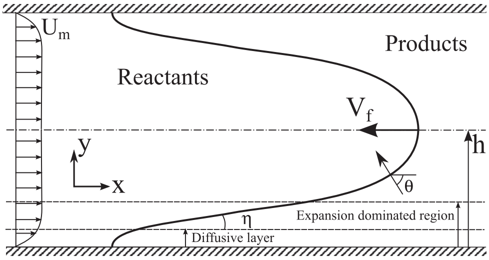

Fig. 1. A sketch of the notional flame in the channel.

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