Simulation of Flame Wrinkling in Turbulent Premixed Combustion

X.S. Bai and P. Wang
Division of Fluid mechanics
Lund Institute of Technology, 221 00 Lund, Sweden
Bai@mail.vok.lth.se

Abstract

Flame wrinkling increases the flame surface area and thus the burning rate of fuel/air mixture. The structure of local reaction zone changes as the wrinkled flame curvature and stretch change. In a recent numerical simulation [1], it was shown that intermediate species such as CO in a lean premixed turbulent flame are very sensitive to the modeling of flame wrinkling. Flame wrinkling has been taken account into numerical modeling in different ways. In models for the mean reaction rates, the wrinkled flamelet area was either modeled in terms of theory of fractals, in analog to the Mandelbrot's fractal surfaces of constant property in isotropic, homogeneous turbulence [2], or using a transport equation for the wrinkled flamelet area per unit volume [3]. In the flamelet library approach, wrinkling was modeled using a *G*-coordinate stretching [1,4], where *G* is a coordinate normal to the flame surface. The stretching factor was estimated to be in the order of the ratio between wrinkled flame surface area to the area of the mean turbulent flame brush.

This paper investigates a flame tracking method, the level-set *G*-equation method, for simulation of flame wrinkling. The *G*-equation was devised for tracking the motion of flame front. It has been used by several authors in different applications, such as studies of hydrodynamic instabilities (see [4] and references therein); simulations of turbulent premixed flames using Reynolds averaged Navier-Stokes equations (RANS) [1,4,5] and large eddy simulations (LES) [6]. In the statistically stationary RANS calculations, The wrinkling of the instantaneous flame front can not be simulated directly, rather, it has to be modeled. In LES, the unsteady motion of the large-scale eddies down to sub-range scales are calculated directly. The wrinkling of flame front (at least the large-scale wrinkling) may be captured in LES.

In this study, the following model G-equation is used

$$\frac{\partial G}{\partial t} + u_i^{gs} \frac{\partial G}{\partial x_i} = s_{sgs} \left(\frac{\partial G}{\partial x_i} \frac{\partial G}{\partial x_i} \right)^{1/2} \tag{1}$$

Here u_i^{gs} is the LES grid resolved velocity component in x_i direction; s_{sgs} is the sub-grid scale flame surface propagation speed, which depends on several factors: the thermal-chemical properties of the reactant mixture, the flame stretch, etc.. In the *G*-equation (1), the effect of flow convection by the three-dimensional eddies is taken into account in terms of u_i^{gs} and effect of differential diffusion (non-unity Lewis number) and flame stretch is taken into account in terms of s_{sgs}. It is modeled as the following [4]

$$s_{sgs} = s_L^0 (1 - \ell \kappa) - \ell S, \quad \kappa = -\nabla \cdot \vec{n}, \quad \vec{n} = \frac{\nabla G}{|\nabla G|}, \quad S = -n \cdot \nabla v^{gs} \cdot \vec{n} \tag{2}$$

Here ℓ is the Markstein length; $\vec{n}, v^{gs}, \kappa,$ and S are respectively the unit vector normal to the flame surface, the LES grid-resolved velocity vector, the flame curvature and the flame strain rate.

The above equations are numerically solved together with the space-filter Navier-Stokes equations in a bluff body stabilized premixed flame known as VR-1 test rig [7], as shown in Figure 1 below. The VR-1 test rig consists of a rectangular channel, 120mm high and 240mm wide. In the chosen test case, the propane/air lean premixed mixture, at equivalence ratio 0.6 and inlet temperature 600K is introduced to the combustor. A prismatic triangular flame holder, with the side length 40mm, is used to stabilize the combustion.

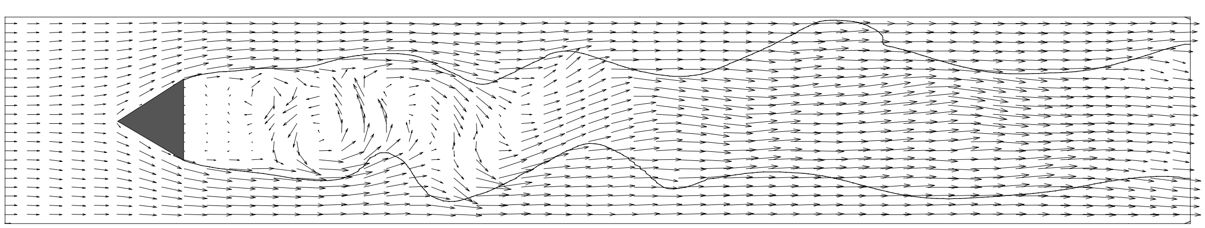

Figure 1. An instantaneous flame front (*G*=0) and velocity vectors plotted on a course grid (one fourth of grid points in each direction is shown).

Figure 1 shows an instantaneous flame front and the velocity vectors plotted on a cross section. Several grid sizes are tested. In the current figure, the grid sizes are respectively about 3mm, 1mm and 2mm in the axial, crossflow and spanwise directions. Only one fourth of the vectors in every direction are shown in Fig. 1. The recirculation zone after the prismatic triangular flame holder is captured. The flame front is shown in the figure by an iso-line (G = 0). As noted, the large scale wrinkling of flame is predicted. The wrinkle size is estimated to be close to the integral length. Smaller scale wrinkling that typically found in this type of flames is not captured. A possible cause of this failure may be the lack of resolution of small eddies or the lack of response of flame front to the smaller eddies.

A simple analysis is performed to examine the response of flame front to small disturbance. For a one-dimension flame moving following a sine wave as a function of time with a frequency ω and amplitude a, it can be shown that the G=0 front moves as a function of sine wave with the same frequency (with a phase delay of 90 degrees). The amplitude of the G=0 front fluctuation is however proportional to a/ω. This implies that the high frequency disturbance is not effective in perturbing the flame front. As a consequence, we may expect that in LES using G-equation, the small scale eddies with short time scales are not effective in wrinkling the flame front.

A measure for the flame front fluctuation in the flow field may be the time-averaged standard deviation of the G field. This quantity is related to the thickness of the time averaged mean flame brush. The standard deviation $\sigma = \sqrt{\overline{G'^2}}$ (time averaged) at $\overline{G} = 0$ (time averaged) is shown in Fig. 2 as a function of axial distance (x). Curve fitting expression $\sigma = 0.6\sqrt{x}$ and $\sigma = 0.11x$ are plotted as well. As seen, near the flame holder, the time averaged turbulent mean flame brush obtained by LES increases almost linearly with x. At far downstream the increase is slower (proportional to $\sqrt{x}$). This tendency is in good agreement with the Taylor theory of turbulent diffusion of passive surfaces in isotropic turbulence, as previously discussed in [8].

The G field obtained in LES has also been coupled with a stationary flamelet model [1] to calculate the time-averaged species of O_2, CO_2, CO and temperature. It is shown that because of the reasonable simulation of the thickness of the mean turbulent flame brush, the major species and temperature are in good agreement with measured data. The CO concentration is less well simulated since the small scale wrinkling is less well captured here.

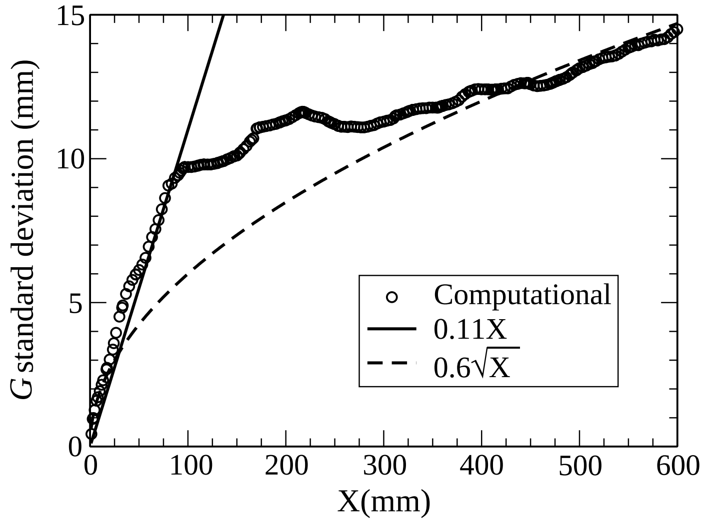

Figure 4. Time averaged standard deviation of $G, \sqrt{\overline{G'^2}}$, at the flame front ($\overline{G} = 0$) along axial direction.

Reference

[1] Nilsson, P., and Bai, X. S., *29th International Symposium on Combustion,* Sapporo, Japan, July 2002, in press.

[2] Gouldin, F.C., Bray, K.N.C. and Chen, J.-Y., *Combustion and Flame* 77 (1989) 241-257.

[3] Candel, S.M. and Poinsot, T.J., *Combustion Science and Technology* 70 (1990) 1-15.

[4] Peters, N., *Turbulent Combustion,* Cambridge University Press, 2000, p. 157.

[5] Nilsson, P., and Bai, X. S., *Experimental Thermal and Fluid Science*, 21, 87-98, (2000).

[6] Pitsch, H., Duchamp de Lageneste, L., *29th International Symposium on Combustion,* Sapporo, Japan, July 2002, in press.

[7] Sjunnesson, A, Olovsson, S., Sjöblom, B., *Internal Report VFA 9370-308*, Volvo Flygmotor (1991).

[8] Lipatnikov, A.N. and Chomiak, J., *Prog. Energy Comb Sci*., 28, 1-74, (2002).