Numerical Simulation of a Premixed Turbulent V-Flame[1]

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Turbulent premixed combustion is a major active research topic in combustion science. A number of computational studies have focused on idealized configurations to aid in interpreting flame dynamics observed in the laboratory, including one-dimensional strained flames, two-dimensional vortex/flame interactions and limited three-dimensional direct numerical simulations. In this paper, we present three-dimensional, time-dependent simulations of a full-size laboratory-scale rod-stabilized premixed turbulent V-flame. The computations use an adaptive projection method based on a low Mach number formulation that incorporates detailed chemical kinetics and transport. The simulations are performed without introducing models for turbulence or turbulence chemistry interaction. We outline the numerical procedure and experimental setup, and compare computed results to mean flame location and surface wrinkling statistics gathered from experiment.

Computational Model

We model a gaseous mixture, ignoring Soret and Dufour effects, and radiative heat transfer, and assume a mixture-averaged model for differential species diffusion. The chemical kinetics are modeled using the DRM-19 methane mechanism, containing 21 chemical species and 84 reactions. Our adaptive solution algorithm combines a symmetric operator-split coupling of chemistry and diffusion processes with a density-weighted approximate projection method for incorporating the velocity divergence constraint arising from the low Mach number formulation. Our approach to adaptive refinement is based on a block-structured hierarchical grid system composed of nested rectangular grid patches. The adaptive algorithm is second-order accurate in space and time, and discretely conserves species mass and enthalpy. The reader is referred to [1] for details of the model and its numerical implementation and to [2] for previous applications of this methodology to the simulation of premixed turbulent flames.

Burner configuration

In the experiment, premixed air and methane at equivalence ratio $\phi = 0.7$ exit a 5 cm diameter circular nozzle with a top-hat mean axial velocity profile of 3 m/s. Turbulence is introduced by a perforated plate

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that partially obstructs the axial flow 9 cm below the nozzle exit. The observed integral scale length of the turbulence at the nozzle exit is $\ell_t \sim 5$ mm. The fluctuation intensity is slightly anisotropic at $u' \sim 6.5\%$ and $\sim 5\%$ in the axial and radial directions respectively. A V-shaped flame is stabilized by the recirculation zone that develops just downstream of a 2 mm diameter rod spanning the width of the nozzle exit. The flame extends 20 cm or more downstream of the rod. Flow field and flame surface statistics are gathered from the experiment in a centered vertical plane normal to the rod up to 12 cm downstream of the nozzle exit using PIV imaging. Pointwise LDV measurements are used to characterize the turbulence.

The computational domain is a cube, 12 cm on a side, with the nozzle exit centered on the lower face. The sides of the domain are approximated as slip walls and the top is an outflow boundary. The fuel stream inflow profile is formed as the superposition of a mean flow and precomputed turbulent fluctuations that have been shaped to conform to experimental observation. Radial fluctuations are uniform across the fuel stream, but decrease rapidly to zero at the inside edge of the nozzle. Axial fluctuations are similar, but have a corresponding increase near the pipe wall. We specify a coflow of 1.5 m/s into the bottom of the domain outside the nozzle to control the shear layers that form around the outside of the fuel stream downstream of the inflow. The flame surface appears to be rather insensitive to the coflow velocity over the region of interest. Numerically, the flow is initialized with a steady laminar flame in a small circular region centered over the nozzle exit with the flame location near the inflow face. We then allow the system to evolve until the turbulent flame that forms appears to be statistically stationary.

Observations

In Figure 1, we compare computed and experimentally observed instantaneous flame profiles. The image on the left is a grey-scale representation of the simulated methane mole fraction, taken in a vertical plane normal to the flame-holding rod at its center. The dark V-shaped region in the center indicates fuel depletion by combustion; the outer boundary is perturbed by diffusion and convective interaction with the coflow stream. The corrugated surface of the flame indicates the level to which the turbulent inflow wrinkles the flame surface. The image on the right shows PIV data taken from an experiment with conditions similar to those of the computation. The premixed fuel is seeded with alumina particles that are illuminated by a vertical laser sheet. The darker V-shaped central region results from a decrease in fluid density, and a corresponding decrease in the density of flow markers as the reactants burn at the flame front. Clearly, the computations have reproduced qualitatively the experimentally observed flame shape and flame surface behavior for this case.

To construct statistical measures of the flame we define a progress variable $c = (T - T_u)/(T_b - T_u)$ where

$T_{u,b}$ are the temperatures of the unburned and burned gas. The mean flame position then may be visualized as the mean location of a contour in c. We observe that the V-flame appears to be statistically invariant to the coordinate parallel to the rod in the range (± 1.5 cm), and is essentially symmetric about the center. Thus, we define

$$\bar{c}\,(x,z) = \int_{-1.5}^{+1.5} \int_{0}^{\Delta t} 0.5\,[c(-x,y,z,t_0+\tau) + c(x,y,z,t_0+\tau)]\,d\tau\,dy$$

where t_0 and Δt are large enough to eliminate the influence of early time transients and provide a good statistical mean. Based on the $\bar{c} = 0.5$ contour, we deduce that the computed turbulent flame angle is roughly 10 degrees, which leads to an effective turbulent burning speed of 51.7 cm/s. This represents an increase by a factor of 2.3 from the laminar flame speed.

In Figure 2a, we overlay the $\bar{c} = 0.5$ (in red) contours and several representative instantaneous isosurface slices in planes normal to the rod at locations chosen randomly from the interval used to define $\bar{c}$. Similar information is presented from the corresponding experimental data in Figure 2b. Using such plots, experimentalists infer an effective flame area enhancement factor, i.e., ratio of areas of the actual flame surface to that of the mean flame. Early results suggest the computations predict an enhancement factor of 1.25, or a 25% increase in effective flame area due to turbulence.

Figure 3 displays computed information similar to that of Figure 2a, except that the isosurfaces are slices on horizontal planes at 1,3,5 cm above the burner. Qualitatively, flame surface perturbations appear to be isotropic and of constant wavelength as they convect upward along the flame. This is further illustrated in Figure 4 which shows a representative $\bar{c} = 0.5$ surface.

Conclusions

We have presented simulations of a laboratory-scale rod-stabilized turbulent V-flame burner without subgrid models for turbulence or turbulence/chemistry interactions. Initial comparisons of our results to experimentally measured flame statistics indicate that our methodology is sufficiently accurate to model this type of flame. In the presentation, we will present a more detailed comparison of the computed and measured flame.

References

[1] Day, M. S. and Bell, J. B., *Combust. Theory Modelling*, 4(4):535–556 (2000).

[2] Bell, J.B., Day, M.S., and Grcar, J.F., *Proc. Combust. Inst.*, 29 (2002).

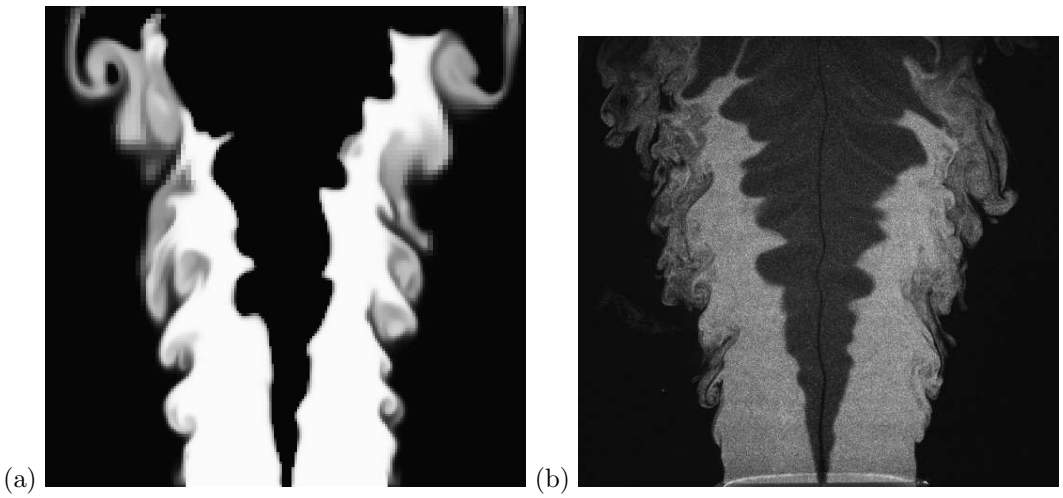

Figure 1. (a) Computed mole fraction of CH_4, (b) Photograph of illuminated particles seeded in fuel stream.

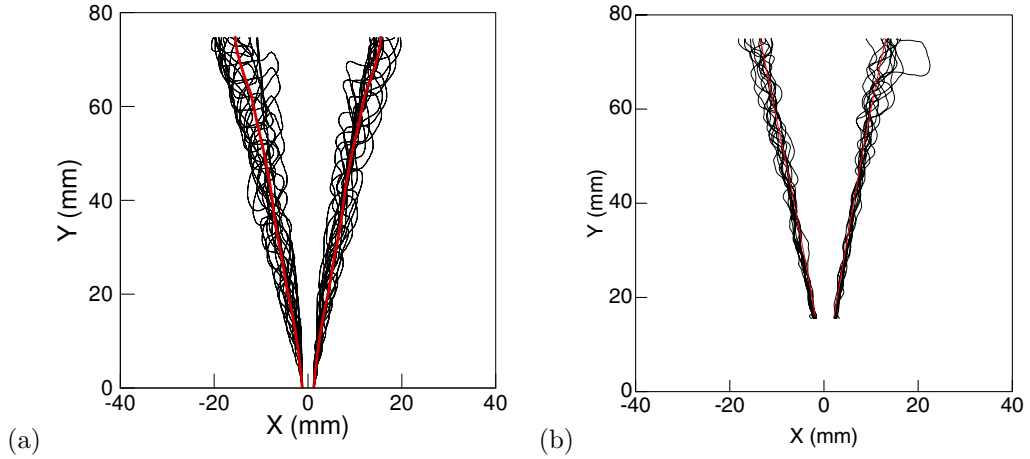

Figure 2: Instantaneous flame edges in a vertical plane, overlaid with computed mean, from (a) the simulation, and (b) experimental data

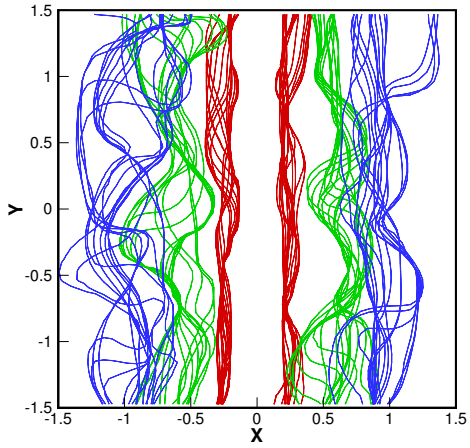

Figure 3: Computed flame edges in three horizontal planes at $z = 10$ (red), 30 (green) and 50 (blue) mm.

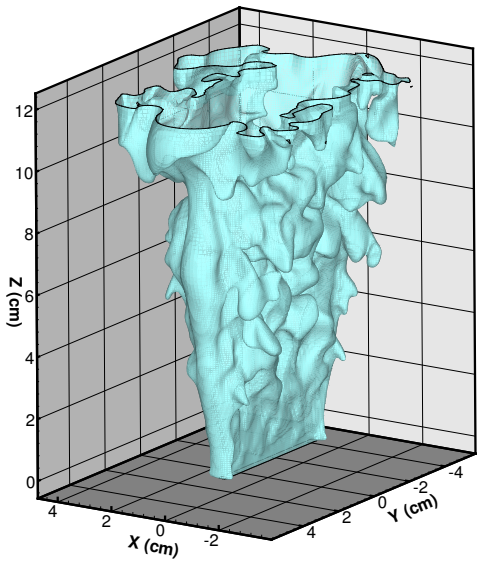

Figure 4: The computed $c = 0.5$ flame surface.