Large Eddy Simulation of Supersonic Combustion using Eulerian Stochastic Fields

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Introduction

- Possible application of this work: scramjet - supersonic combustion ramjet - engine.

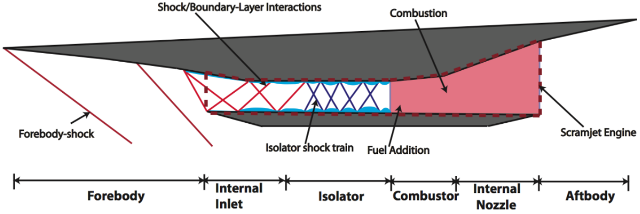


Figure Typical scramjet model - figure from Koo, PhD Thesis, 2011.

- Hypersonic planes, new rocket designs, detonations.
- Challenging modelling, as it includes shocks and turbulence/chemistry interaction.
- LES reduces computational effort, however important unclosed terms have to be modelled.

Large eddy simulation scalar PDF modelling

- Scalar LES-PDF modelling provides closure for reactive source term in low Mach number flows. In compressible flows, it is partially closed:

$$\frac{\partial \overline{\rho}\mathscr{Y}_\alpha^n}{\partial t} + \frac{\partial \overline{\rho}\widetilde{u}_i\mathscr{Y}_\alpha^n}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\Gamma' \frac{\partial \mathscr{Y}_\alpha^n}{\partial x_i}\right) + \overline{\rho} S_\alpha^n \left(\overline{p}, \mathbf{\Psi}\right)$$
$$- \frac{1}{2}\frac{C_{Y_\alpha}}{\tau_{sgs}}\overline{\rho}\left(\mathscr{Y}_\alpha^n - \widetilde{Y}_\alpha\right) + \left(2\overline{\rho}\Gamma'\right)^{1/2}\frac{\partial \mathscr{Y}_\alpha^n}{\partial x_i}\frac{\mathrm{d}W_i^n}{\mathrm{d}t}$$

$$\frac{\partial \overline{\rho}\mathscr{H}^n}{\partial t} + \frac{\partial \overline{\rho}\widetilde{u}_i\mathscr{H}^n}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\Gamma' \frac{\partial \mathscr{H}^n}{\partial x_i}\right) + \frac{D\overline{p}}{Dt} + \widetilde{\tau}_{ij}\frac{\partial \widetilde{u}_i}{\partial x_j}$$
$$- \frac{1}{2}\frac{C_H}{\tau_{sgs}}\overline{\rho}\left(\mathscr{H}^n - \widetilde{h}\right) + \left(2\overline{\rho}\Gamma'\right)^{1/2}\frac{\partial \mathscr{H}^n}{\partial x_i}\frac{\mathrm{d}W_i^n}{\mathrm{d}t}$$

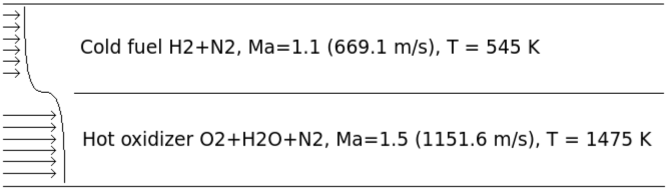
- Pressure can be exactly solved:

$$\overline{p} = \overline{\rho}\widetilde{RT} \approx \overline{\rho}R_u\left[\frac{1}{N_F}\sum_{n=1}^{N_F}\left(\sum_{\alpha=1}^{N_s}\frac{\mathscr{Y}_\alpha^n}{MW_\alpha}\right)T^n\right]$$

- Stochastic equations are coupled with compressible LES solver using the Smagorinsky model.

Three-dimensional compressible reacting mixing layer

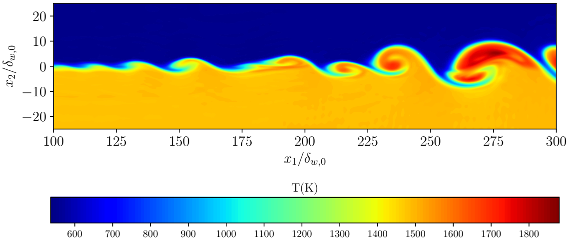
- Configuration used by Ferrer (2014):



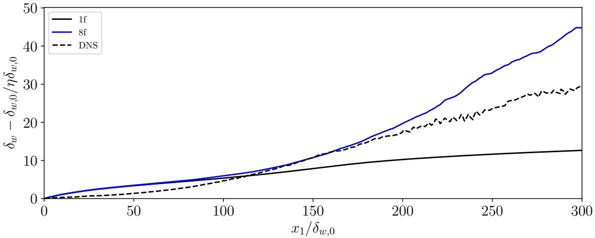
- Inlet and zero gradient boundary conditions. Periodic boundary conditions at z-coordinate.
- Convective Mach number of 0.35 ($M_c = \Delta U/(c_1 + c_2)$), resulting in weak compressible effects.
- Reaction mechanism of Yetter *et al.* (1991) to describe the combustion of hydrogen using 9 species and 19 reactions.
- Non uniform mesh size of 504$\times$132$\times$36.
- Hybrid spatial discretisation scheme (DRP + Riemann solver HLLC-TVD) and first order Euler-Maruyama temporal integration.

Results - 1 field, 8 fields x DNS

- Instantaneous temperature contour plot for 8 fields:

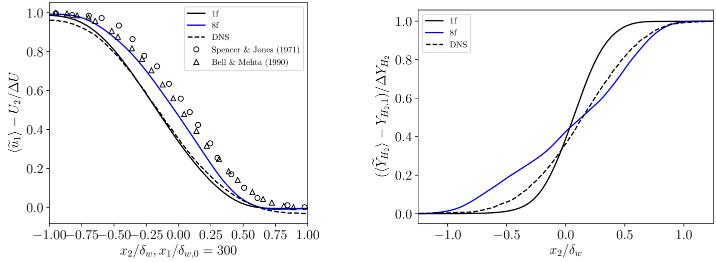


- Normalised vorticity thickness growth:



Results - 1 field, 8 fields x DNS

- Comparison at position $x_1/\delta_{w,0}$:



- Velocity profile has improved.
- Mixing level has increased, hydrogen profile is smoother.
- Simulation requires better z-resolution to diminish excessive thickness growth.

Conclusions

It is proposed a new scalar LES-PDF formulation:

- It is coupled with fully compressible equations.
- Filtered pressure is closed.
- Stochastic transport equations are developed within Eulerian framework.
- It can be applied to a wide range of combustion regimes and Mach numbers.

Future work:

- High-order temporal integration for the SPDEs.
- Adaptive Mesh Refinement (AMR).
- Experimental validation (supersonic burner).
- Scramjet study.

Thank you for your attention!

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