Impact of bulk viscosity on the development of shocked shear layer

Radouan BOUKHARFANE* Pedro José MARTÍNEZ FERRER* Arnaud MURA* Vincent GIOVANGIGLI**

* Institut Pprime cnrs, France

** cmap cnrs, France

Contents

Problem description

- Constitutive model for a Newtonian fluid

$$\tau_{ij} = \underbrace{\kappa\Delta\delta_{ij}}_{\text{Volumetric changes}} + \underbrace{2\eta\mathcal{S}_{ij}^{d}}_{\text{Deviatoric part}}$$

  with $\Delta = \partial u_k / \partial x_k$ and $\mathcal{S}_{ij}^{d} = \mathcal{S}_{ij} - \Delta\delta_{ij}/3$

- Viscous dissipation rate

$$\Phi = \tau_{ij}\mathcal{S}_{ij} = \kappa\Delta^2 + 2\eta\mathcal{S}_{ij}^{d}\mathcal{S}_{ij}^{d}$$

- Stokes' assumption is justified if $\kappa = 0$ (y dilute monatomic gases) or/and $\Delta = 0$ (incompressible or weakly compressible flows)
- Stokes' assumption is not exact for:
  - ✓ most polyatomic gases, e.g., bulk to shear viscosity ratio is $\mathcal{O}(10^3)$ for CO_2 at room temperature
  - ✓ flows featuring high compressibility level where dilatational effects are not negligible

Problem description

- Few studies using DNS approach dedicated to the analysis of bulk viscosity effects
  - shock-hydrogen bubble interaction (Billet *et al.* 2008)[a]
  - turbulent premixed combustion (Fru *et al.* 2012)[b]

[a] Billet, G., Giovangigli, V., & De Gassowski, G. (2008). Impact of volume viscosity on a shock-hydrogen-bubble interaction. Combustion Theory and Modelling.

[b] Fru, G., Janiga, G., & Thévenin, D. (2012). Impact of volume viscosity on the structure of turbulent premixed flames in the thin reaction zone regime. Flow, turbulence and combustion.

Assessment of the present study

- Investigation of the bulk viscosity effects on shear layer (SL) development
- Direct numerical simulations: no turbulence models
- High-speed combustion regimes: Scramjet engines
- Multicomponent transport
- Gas mixtures: hydrogen, air . . .
- Influence of shock wave compression

CREAMS solver

- CREAMS: Compressible REActive Multi-Species solver (P' Institute)
  - ✓ Cartesian Navier-Stokes solver, three-dimensional, compressible, unsteady, viscous, multi-species, massively parallel (MPI, up to 100 000 cores)

Mass

$$\partial_t (\rho) + \nabla \cdot (\rho u) = 0$$

Momentum

$$\partial_t (\rho u) + \nabla \cdot (\rho u \otimes u + pI) = \nabla \cdot \tau$$

Total energy

$$\partial_t (\rho \mathcal{E}_t) + \nabla \cdot \left[(\rho \mathcal{E}_t + p)\, u \right] = \nabla \cdot (\tau u - q)$$

Species

$$\partial_t (\rho Y_\alpha) + \nabla \cdot (\rho Y_\alpha u) = -\nabla \cdot (\rho Y_\alpha V_\alpha) + \rho \dot{\omega}_\alpha, \quad \alpha \in \mathcal{S}$$

CREAMS solver

$$p = \rho \mathcal{R} T / \mathcal{W}, \quad \mathcal{W} = \left(\Sigma_{\alpha \in \mathcal{S}} Y_\alpha / \mathcal{W}_\alpha\right)^{-1}, \quad h_\alpha(T) = \varphi_\alpha \mathcal{R} T / \mathcal{W}_\alpha$$

with the polynomial φ_α being determined from `JANAF` tables

Spatial and temporal discretizations

- Convective fluxes are discretized using 7^{th} order accurate `WENO` scheme
  - ✓ Shock sensor based on Adams & Shariff works
- Molecular fluxes are discretized using 8^{th} order accurate centred difference scheme
- Temporal integration is performed using RK3 scheme combined with *Strang*'s splitting

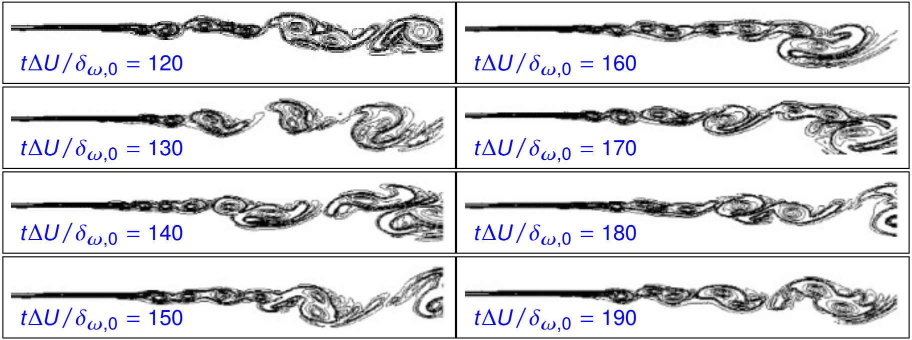
- Multicomponent transport (Soret and Dufour): `EGLIB` library[a]
- Chemical reactions: `CVODE` with `CHEMKIN II` library

[a] Ern, A., & Giovangigli, V. (1995). Fast and accurate multicomponent transport property evaluation. Journal of Computational Physics.

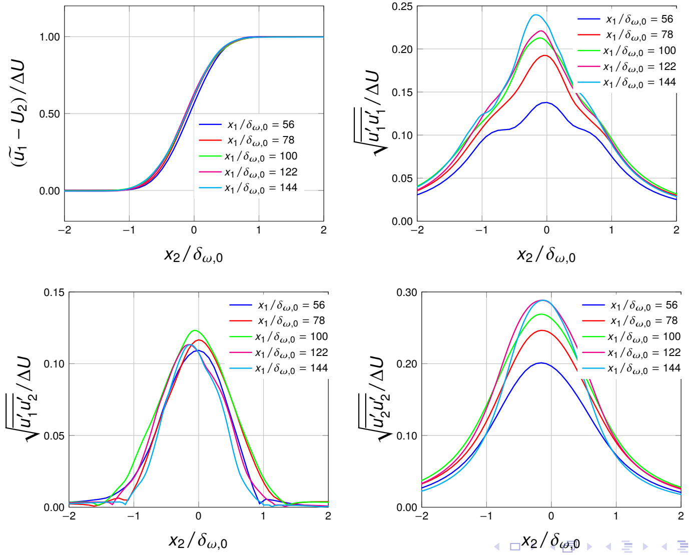
Incompressible mixing layer

- $M_c = 0.074$, $Re_\omega = \bar{\rho}\Delta U \delta_{\omega,0}/\bar{\mu} = 5333$ ($U_1 = 100$ (m/s), $U_2 = 50$ (m/s)
- $L_1 \times L_2 = 320\delta_{\omega,0} \times 200\delta_{\omega,0}$, $N_1 \times N_2 = 1000 \times 280$

Contour distributions of vorticity



Incompressible mixing layer



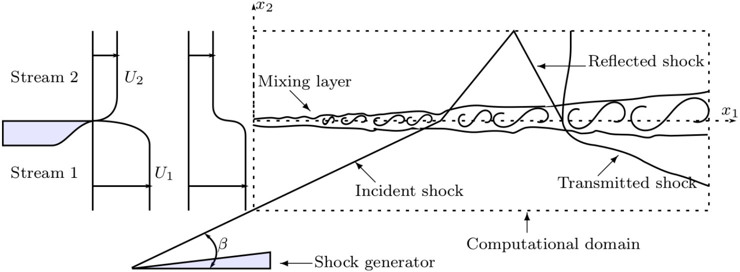
Incompressible mixing layer

Compilation of results obtained for different shear layers

$Re_{\omega,0}$	$\sigma_{11\max}$	$\sigma_{22\max}$	$\sigma_{12\max}$	$\eta^{-1}\mathrm{d}\delta_\omega/\mathrm{d}x_1$	Type	Reference
-	0.190	0.120	0.114	0.160	Exp.	Spencer & Jones (1971)
1800	0.180	0.140	0.100	0.163	DNS-3D	Bell & Mehta (1990)
3200	0.160	0.130	0.100	0.130	DNS-3D	Rogers & Moser (1994)
5333	0.200	0.260	0.140	0.180	DNS-2D	Bogey (2000)
5333	**0.240**	**0.280**	**0.120**	**0.166**	**DNS-2D**	**Present simulation**

- Good match with previous results

Numerical configuration



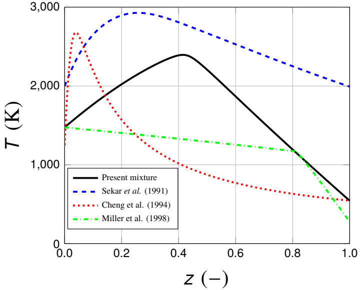
- $Re_\omega = \bar{\rho}\Delta U \delta_{\omega,0} / \bar{\mu} = 640$, $M_c = 0.48$, $\beta = 33^\circ$
- $L_1 \times L_2 \times L_3 = 275\delta_{\omega,0} \times 120\delta_{\omega,0} \times 15\delta_{\omega,0}$, $N_1 \times N_2 = 1700 \times 720 \times 180$
- Slip wall BC at top, R-H relations for a gas mixture at bottom and periodic BC in x_3-directions
- O'Conaire reaction mechanism: 10 species, 21 elementary reaction steps

Numerical configuration

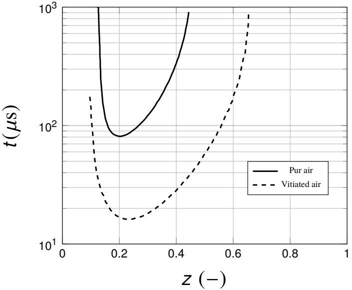
Inlet stream conditions retained for inert and reactive numerical simulations

Quantity	Fuel stream	Oxidizer stream
p (Pa)	94232.25	94232.25
T (K)	545.0	1475.0
ρ (kg/m^3)	0.354	0.203
Y_{H_2} (−)	0.05	0.0
Y_{O_2} (−)	0.0	0.278
Y_{H_2O} (−)	0.0	0.17
Y_H (−)	0.0	5.60×10^{-7}
Y_O (−)	0.0	1.55×10^{-4}
Y_{OH} (−)	0.0	1.83×10^{-3}
Y_{HO_2} (−)	0.0	5.10×10^{-6}
$Y_{H_2O_2}$ (−)	0.0	2.50×10^{-7}
Y_{N_2} (−)	0.95	0.55

Numerical configuration



(a)

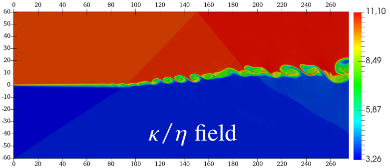


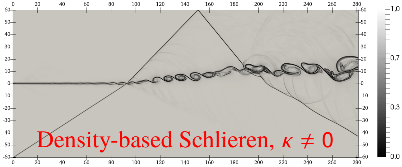
(b)

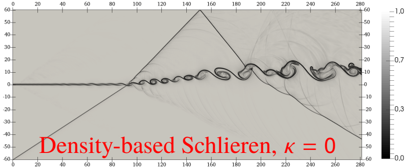
- Species concentrations have been determined from equilibrium conditions
- Maximum value of the equilibrium temperature is approximately 2400 K
  - ✓ heat release level induces significant modifications to the large-scale development of SL

Non-reacting case

- κ/η reaches values greater than unity
  - ✓ dilatation may effect the instantaneous development of SL

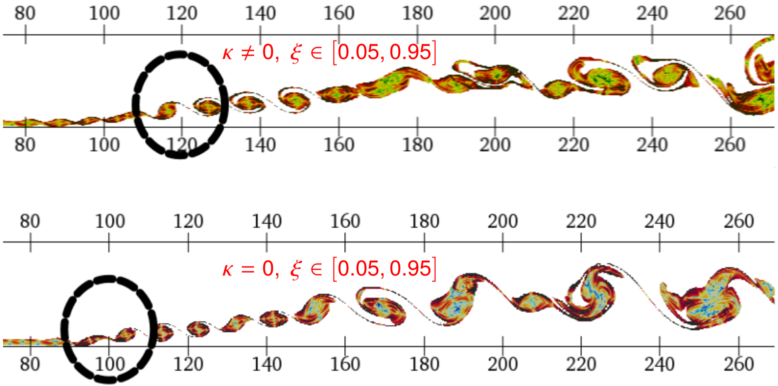






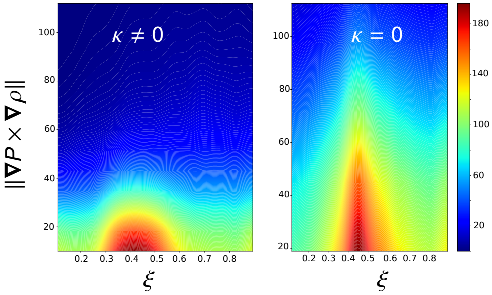
- $\kappa = 0$ generates more spurious reflections

Non-reacting case



- Large values in the border of the mixing's region where ∇P and $\nabla \rho$ are significantly non-aligned
- Roll up process into vortices started earlier in the presence of bulk viscosity

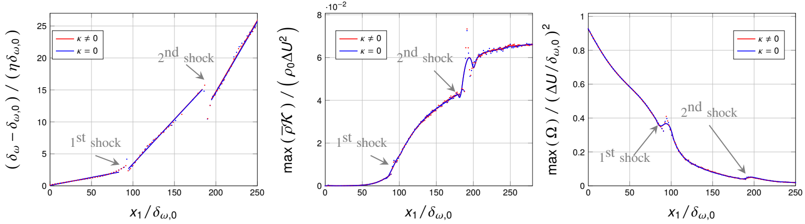
Non-reacting case



- Bulk viscosity tends to favour the baroclinic term
- Production of baroclinic vorticity is more concentrated around $\xi_{\mathrm{st}} = 0.41$.

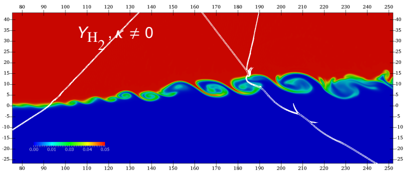
$$\frac{\mathrm{D}\Omega}{\mathrm{D}t} = \underbrace{\frac{1}{2}\omega \cdot (\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^{\top}) \cdot \omega}_{\text{Vortex stretching}} - \underbrace{\Omega \nabla \cdot \boldsymbol{u}}_{\text{Dilatation}} + \underbrace{\omega \cdot \left(\frac{\nabla P \times \nabla \rho}{\rho^2} \right)}_{\text{Baroclinic torque}} + \underbrace{\omega \cdot \left(\nabla \times \left[\frac{\nabla \cdot \tau}{\rho} \right] \right)}_{\text{Viscous diffusion}}$$

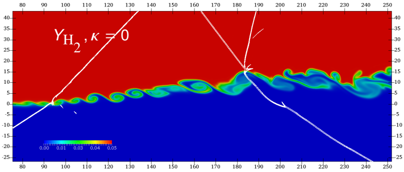
Non-reacting case

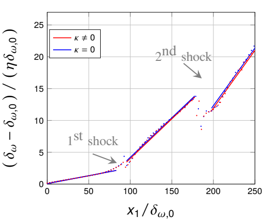


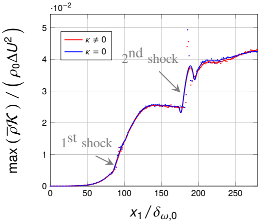
- Profiles of longitudinal evolution of the three quantities are almost everywhere superimposed
- Shift to averaged time statistics tends to dwindle the differences observed in the instantaneous field

Reacting case



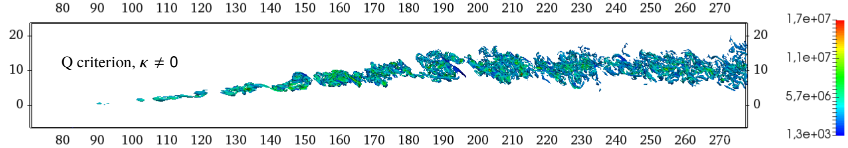


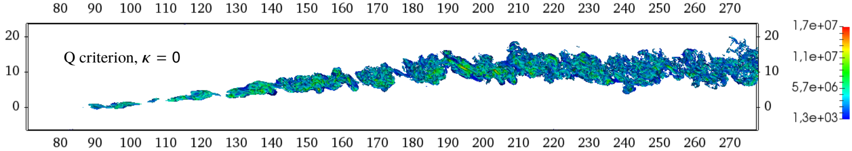




- δ_ω in the case $\kappa \neq 0$ develops less substantially than in the case $\kappa = 0$

Instantaneous fields (non-reacting case)



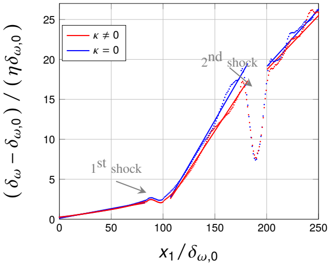


- Vortical structure's density is higher in the absence of bulk viscosity
- Vortex mechanisms are highly influenced by the effects of dilatation
- Bulk viscosity tends to increase turbulent dissipation

Vorticity thickness

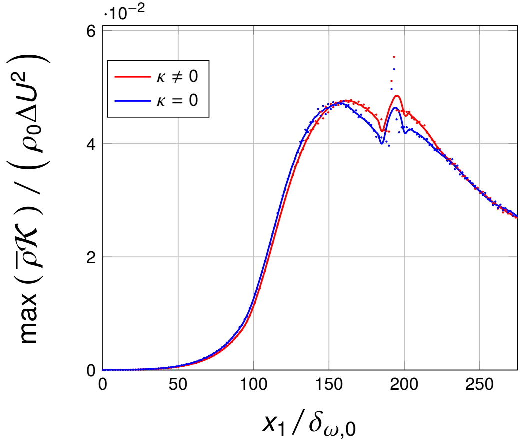
Case	1st region	2nd region	3rd region
$\kappa = 0$	0.023	0.223	0.142
$\kappa \neq 0$	0.022	0.192	0.137

Values of $\eta^{-1} \mathrm{d}\delta_\omega / \mathrm{d}x_1$ (−)



- Inhibition of the expansion of the mixing layer is consistent with the morphology of the roll-up of the vortices
- Growth rate of the vorticity thickness in the case $\kappa = 0$ is substantially greater than that calculated in the case $\kappa \neq 0$.

Turbulent kinetic energy



- 3D character of simulation has a much greater effect on the spatial evolution of TKE
- Up to the abscissa $x_1 / \delta_{\omega,0} = 150$, the absence of bulk viscosity overestimates the case where the effect of κ is considered. The opposite happens after this abscissa

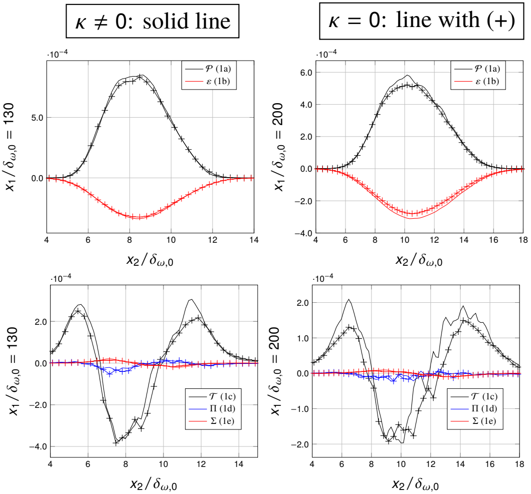
Turbulent kinetic energy

$$\frac{\partial(\overline{\rho}\mathcal{K})}{\partial t} + \frac{\partial(\overline{\rho}\widetilde{u_k}\mathcal{K})}{\partial t} = \underbrace{\mathcal{P}}_{\text{Production}} + \underbrace{\varepsilon}_{\text{Dissipation}} + \underbrace{\mathcal{T}}_{\text{Transport}} + \underbrace{\Pi}_{\text{Pressure-strain}} + \underbrace{\Sigma}_{\text{Mass flow}}$$

where:

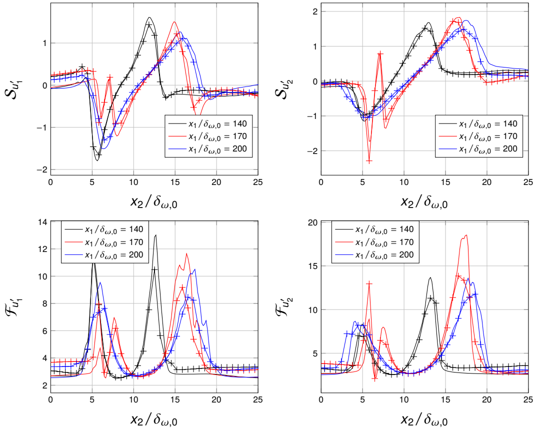
$$\begin{cases}
\mathcal{P}_{ij} = -\overline{\rho}\left(R_{ik}\dfrac{\partial\widetilde{u_j}}{\partial x_k} + R_{jk}\dfrac{\partial\widetilde{u_i}}{\partial x_k}\right) & \text{(1a)}\\
\varepsilon_{ij} = -\overline{\tau'_{ik}\dfrac{\partial u''_j}{\partial x_k}} - \overline{\tau'_{jk}\dfrac{\partial u''_i}{\partial x_k}} & \text{(1b)}\\
\mathcal{T}_{ij} = -\dfrac{\partial}{\partial x_k}\left(\overline{\rho u''_i u''_j u''_k} + \overline{P' u''_i}\delta_{jk} + \overline{P' u''_j}\delta_{ik} - \overline{\tau'_{jk} u''_i} - \overline{\tau'_{ik} u''_j}\right) & \text{(1c)}\\
\Pi_{ij} = \overline{P'\dfrac{\partial u''_i}{\partial x_j}} + \overline{P'\dfrac{\partial u''_j}{\partial x_i}} & \text{(1d)}\\
\Sigma_{ij} = \left(\overline{u''_i}\dfrac{\partial\overline{\tau_{jk}}}{\partial x_k} + \overline{u''_j}\dfrac{\partial\overline{\tau_{ik}}}{\partial x_k}\right) - \left(\overline{u''_i}\dfrac{\partial\overline{P}}{\partial x_j} + \overline{u''_j}\dfrac{\partial\overline{P}}{\partial x_i}\right) & \text{(1e)}
\end{cases}$$

Turbulent kinetic energy



- Slightly smaller amplitude of production and dissipation terms in the case $\kappa = 0$

Skewness and flatness coefficients



- Amplitude of peaks in the intermittent zone higher for both the asymmetry and flatness coefficients in the presence of bulk viscosity

Summary

Conclusions

- Three-dimensional effects are more important than chemical kinetics effects
- Vorticity growth rate reduction behaviour modified by bulk viscosity
- Instantaneous effects are both affected in both 2D and 3D cases
- High order moments are more affected by bulk viscosity effect

Future works

- Three-dimensional reacting case
- 3D turbulent DNS with increasing M_c to increase compressibility (on going)
- Mixture featuring higher mixture κ values

Thanks for your attention!

If you have any questions, please feel free to ask.