Skewness effects on the turbulence structure in a high-speed compressible and multi-component inert mixing layers

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Contents

Problem description

- Scramjet engines are exciting candidates for the next generation air-breathing propulsion.
- Mixing layer is a classical paradigm case for free-shear turbulent flows.
- Emergence and evolution of turbulent features exhibit high sensitivity to the parametric set-up of the test case.
  - ✓ Compressibility effects quantified with convective Mach number

    $$\mathrm{Ma}_c = (\mathbb{U}^h - \mathbb{U}^l)/(\mathfrak{c}^h + \mathfrak{c}^l)$$

  - ✓ Pressure influence quantified with the gradient Mach number

    $$\mathrm{Ma}_g = \mathrm{S}\ell/\langle\mathfrak{c}\rangle$$

  - ✓ Inlet density ratio $\mathfrak{s} = \varrho^h/\varrho^l$
- Most classical analysis assume that $\mathbb{U}^h$ and $\mathbb{U}^l$ are perfectly aligned.

PROBLEM DESCRIPTION

- Few studies dedicated to the analysis of skewing effect
  - ✓ Skewing effects on incompressible shear layer (Meldi *et al.* 2020)[1]
  - ✓ Sweeping effects in a backward-facing step (Kaltenbach 2004)[2]
- Numerous features of the inlet flow can affect the features of the turbulent mixing region.

Assessment of the present study

- Investigation of the skewing effects on shear layer development
- Inert configuration
- Direct numerical simulations: no turbulence models
- High-speed combustion regimes: Scramjet engines
- Multicomponent transport
- Gas mixtures: hydrogen, air …

[1] Meldi, M., Mariotti, A., Salvetti, M. V., & Sagaut, P. (JFM-2020). Numerical investigation of skewed spatially evolving mixing layers.
[2] Kaltenbach, H. J. (EJMB/F-2004). Turbulent flow over a swept backward-facing step.

Computational methodology

- Cartesian Navier-Stokes solver, three-dimensional, compressible, unsteady, viscous, multi-species, massively parallel in-house solver

$$\begin{cases} \partial_t \varrho + \partial_j \left(\varrho \mathfrak{u}_j \right) = 0, \\ \partial_t \left(\varrho \mathfrak{u}_i \right) + \partial_j \left(\varrho \mathfrak{u}_i \mathfrak{u}_j \right) + \partial_i \mathfrak{p} = \partial_j \tau_{ij}, \\ \partial_t \left(\varrho \mathfrak{e}_t \right) + \partial_j \left(\varrho \mathfrak{e}_t + \mathfrak{p} \right) \mathfrak{u}_i = \partial_j \left(\mathfrak{u}_i \tau_{ij} \right) - \partial_j \mathfrak{q}_j, \\ \partial_t \left(\varrho \mathcal{Y}_\alpha \right) + \partial_j \left(\varrho \mathfrak{u}_j \mathcal{Y}_\alpha \right) = -\partial_j \left(\varrho \mathcal{Y}_\alpha \mathfrak{u}_{\alpha j} \right), \quad \alpha \in \mathcal{S} \\ \mathfrak{p} = \varrho \mathcal{R} \mathcal{T} / \mathcal{W}, \ \ \mathcal{W} = 1 / \left(\Sigma_{\alpha \in \mathcal{S}} \mathcal{Y}_\alpha / \mathcal{W}_\alpha \right), \ \ h_\alpha \left(\mathcal{T} \right) = \varphi_\alpha \mathcal{R} \mathcal{T} / \mathcal{W}_\alpha \end{cases} \tag{1}$$

with the polynomial φ_α being determined from `JANAF` tables

- Convective fluxes are discretized hybrid energy-conservative shock–capturing scheme in locally conservative form with *Ducros* sensor[a].
- Molecular fluxes: Laplacian form with fourth-order formulas.
- Temporal integration: RK3 scheme
- Multicomponent transport (Soret and Dufour): `EGLIB` library[b].

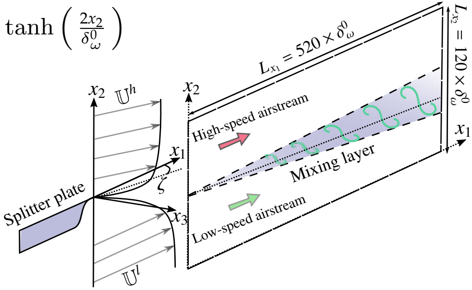
[a] Pirozzoli, S. (JCP-2010). Generalized conservative approximations of split convective derivative operators.

[b] Ern, A., & Giovangigli, V. (JCP-1995). Fast and accurate multicomponent transport property evaluation.

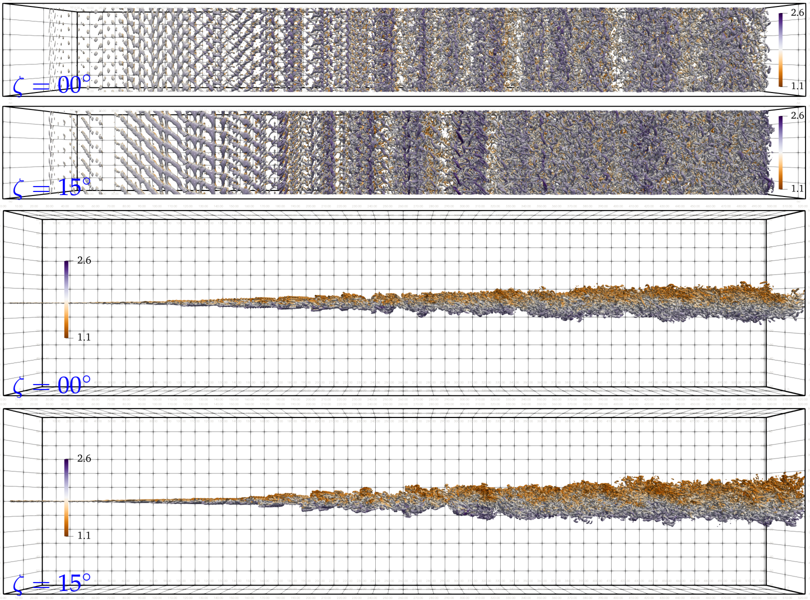
Numerical configuration

- $L_1 \times L_2 \times L_3 = 520\delta_{\omega,0} \times 120\delta_{\omega,0} \times 60\delta_{\omega,0}$, $N_1 \times N_2 \times N_3 = 2500 \times 380 \times 180$.
- Dirichlet BC at the inlet, perfectly non–reflecting BCs at the the outflow and the x_2–directions, and periodic BCs along x_3–directions.
- Air-fuel (OConaire) : H_2, H, H_2O, HO_2, HO_2, O_2, O, OH, N_2
- $\mathrm{Re}_\omega = \bar{\varrho}\Delta U \delta_{\omega,0}/\bar{\mu} = 640$, $\mathrm{Ma}_c = 0.48$, $\xi = 0^\circ,\ 5^\circ,\ 10^\circ$ and 15°.

$$\begin{cases} \varphi(x_1=0,x_2,x_3) = \frac{\varphi^h+\varphi^l}{2} + \frac{\varphi^h-\varphi^l}{2}\tanh\left(\frac{2x_2}{\delta_\omega^0}\right) \\ \mathbf{u}^h = \left(\mathbb{U}^h\cos\zeta, 0, \mathbb{U}^h\sin\zeta\right) \\ \mathbf{u}^l = \left(\mathbb{U}^l, 0, 0\right) \\ \delta_\omega^0 = \left(\mathbb{U}^h - \mathbb{U}^l\right)/\max|\partial_2\langle u_1\rangle_F| \end{cases}$$

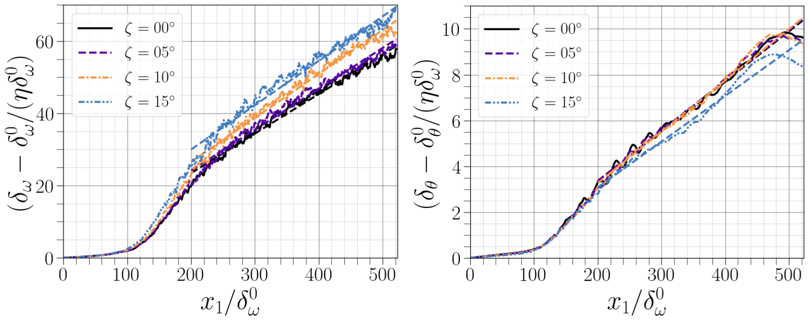


Instantaneous Flow

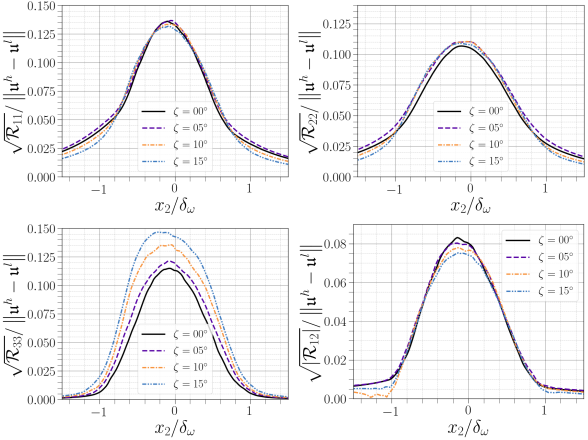


Quantitative analysis

- Growth rates of δ_ω and $\delta_\theta = \frac{1}{\varrho_0} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \langle \varrho \rangle \frac{\langle u_1 \rangle_f - \mathbb{U}^h}{\|\mathbf{u}^h - \mathbf{u}^l\|} \left(1 - \frac{\langle u_1 \rangle_f - \mathbb{U}^h}{\|\mathbf{u}^h - \mathbf{u}^l\|}\right) \mathrm{d}x_2 \mathrm{d}x_3$



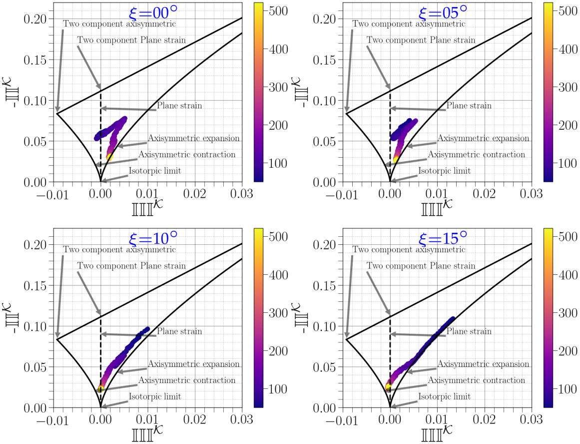
REYNOLDS STRESSES



- As ξ get higher $\mathcal{R}_{33} > \mathcal{R}_{11} > \mathcal{R}_{22} > \mathcal{R}_{12} \equiv \mathcal{R}_{23} > \mathcal{R}_{13}$.
- Skewing SLs induce more intense turbulence and enlarge the momentum exchange between the turbulent structures and the inflow mainstream.

Anisotropy effect

- Reynolds stress anisotropy $\mathfrak{b}_{ij}^{\mathcal{K}} = \dfrac{\mathcal{R}_{ij} - \frac{2}{3}\delta_{ij}\mathcal{K}}{2\mathcal{K}}$.
- Invariants of $\mathfrak{b}^{\mathcal{K}}$: $\mathbb{II}^{\mathcal{K}} = -\frac{1}{2}\left(\Lambda_1^2 + \Lambda_2^2 + \Lambda_3^2\right)$, $\mathbb{III}^{\mathcal{K}} = \frac{1}{3}\left(\Lambda_1^3 + \Lambda_2^3 + \Lambda_3^3\right)$.



Conclusions & perspectives

Perspectives

- Inlet skewing tends to amplify the inlet disturbances resulting in a faster increase of the mixing process
  - ✓ An increase of the cross-wise velocity fluctuation energy.
- Longitudinal evolution of vorticity thickness exhibit remarkable modification with inlet skewing

Perspectives

- application towards flow control, and reliable comparison.
- Investigation of the skewing effects in combination with inlet perturbations.
- Heat release effects.
- Variations of the Reynolds number.

Thanks for tuning in!
Please leave comments & questions

Acknowledgments