Kelvin-Helmholtz shear instability with strong thermal nonequilibrium

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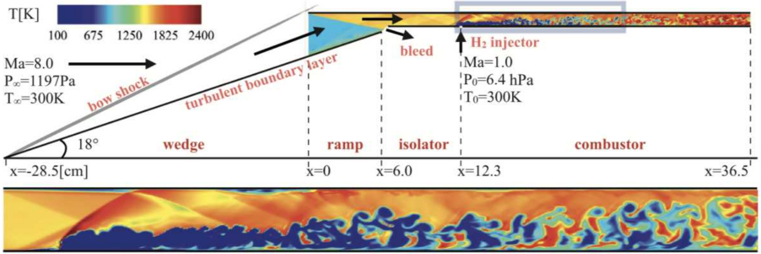
Combustion process in extreme conditions

(Source: NASA)

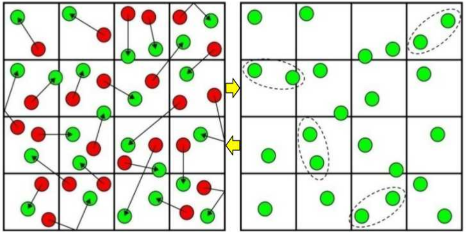


Fiévet et al., *Proc. Combustion Institute*, 2017

- Supersonic $\rightarrow$ short mixing and reaction time
- Interactions between shock wave, cross-jet shear layer, and boundary layer
- Strong **thermal** and chemical nonequilibrium

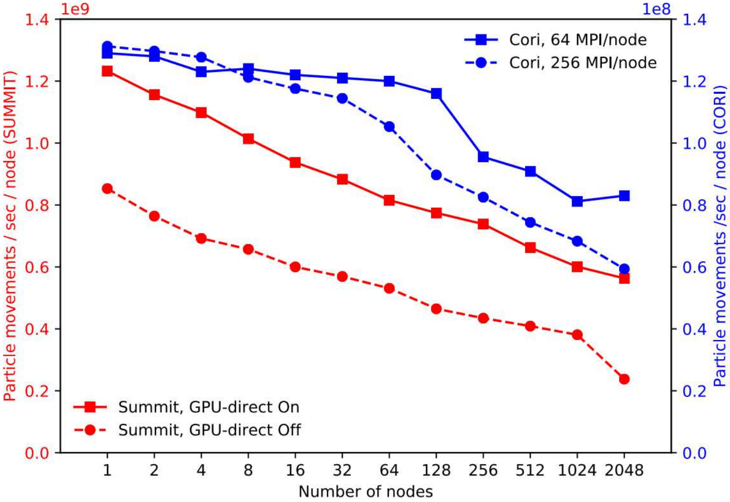
What is the effect of thermal nonequilibrium on Kelvin-Helmholtz instability?

Direct Simulation Monte Carlo (DSMC)



- Proposed by G. A. Bird
- Solves the Boltzmann equation stochastically
- Prove to be very accurate for rarefied gas flows
- Track the motion of a large number of simulators in physical space and time
- Each simulator represents a group of particles which follows same probability distribution functions
- Collisions between simulators are computed in a stochastic manner
- SPARTA (**S**tochastic **PA**rallel **R**arefied-gas **T**ime-accurate **A**nalyzer)
  - `https://sparta.sandia.gov/`

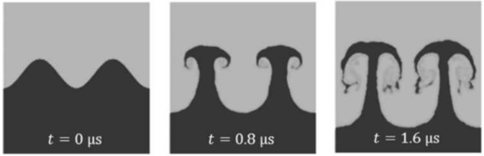
SPARTA Performance - Weak scale



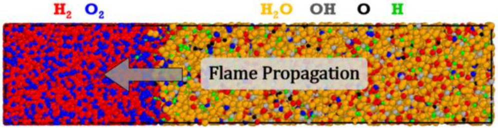
- Kokkos
- Cori, NERSC
  - Intel Xeon Phi Processor 7250
  - 68 core/node
  - 28M particle/node
  - 262144 cell/node
- Summit, OLCF, ORNL
  - Nvidia V100 GPU
  - 6 gpu/node
  - 57M particle/node
  - 442368 cell/node

DSMC at low Kn flows

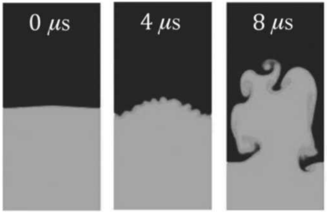
- Richtmyer-Meshkov Instability
  ($Kn = 3.5 \times 10^{-3}$)
  Gallis et al., *Physics of Fluids*, 2015



- 1D flame propagation ($Kn = 3 \times 10^{-3}$)
  Sebastião et al, *Combustion and Flame*, 2018



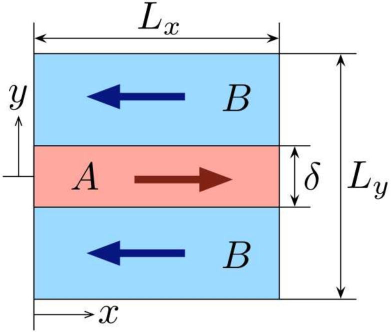
- Rayleigh-Taylor Instability
  ($Kn = 2 \times 10^{-4}$)
  Gallis et al., *Physical Review Fluids*, 2016



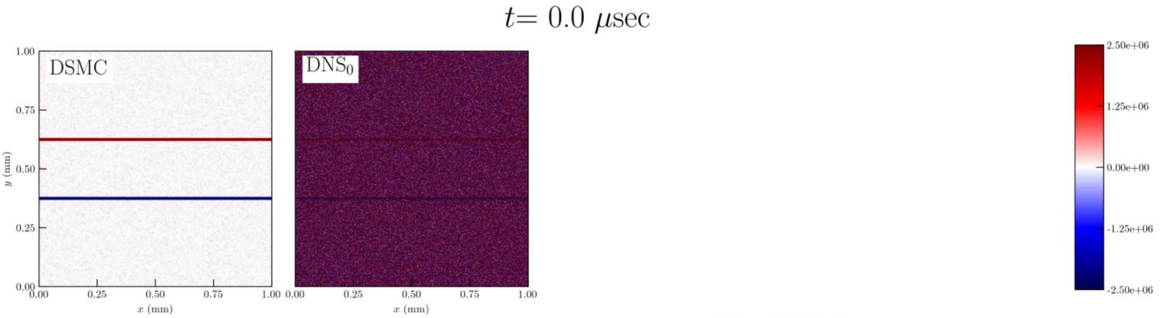
Simulation setup

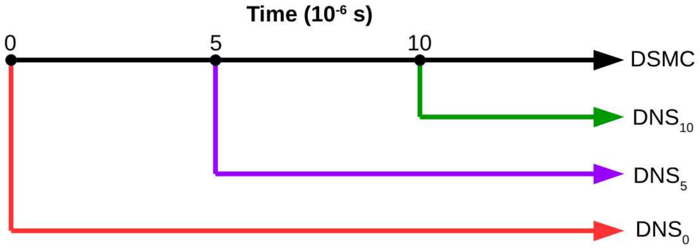
- O_2 gases
- 2 Dimensional, Periodic BCs
- $P = 1$atm
- $U_A = -U_B = 50m/s$
- Convective $Ma = U_A/C \approx 0.15$
- $L_x = L_y = 1$ mm, $\delta/L_y = 0.25$
- $Kn = \lambda/\delta = 2.4 \times 10^{-4}$
- DSMC - SPARTA
  - 100 particle/cell, $\Delta t = 100$ ps
  - No. of Cells $= 20000 \times 20000$
- DNS - 2D Incompressible
  - No. of grids $= 2000 \times 2000$, $\Delta t = 1$ ns

Method	$T_A^{trans} = T_A^{rot} = T_B^{trans} = T_B^{rot}$	T_A^{vib}	T_B^{vib}
DNS	300K	300K	300K
DSMC (Eq)	300K	300K	300K
DSMC (Non-Eq)	300K	**1800K**	300K



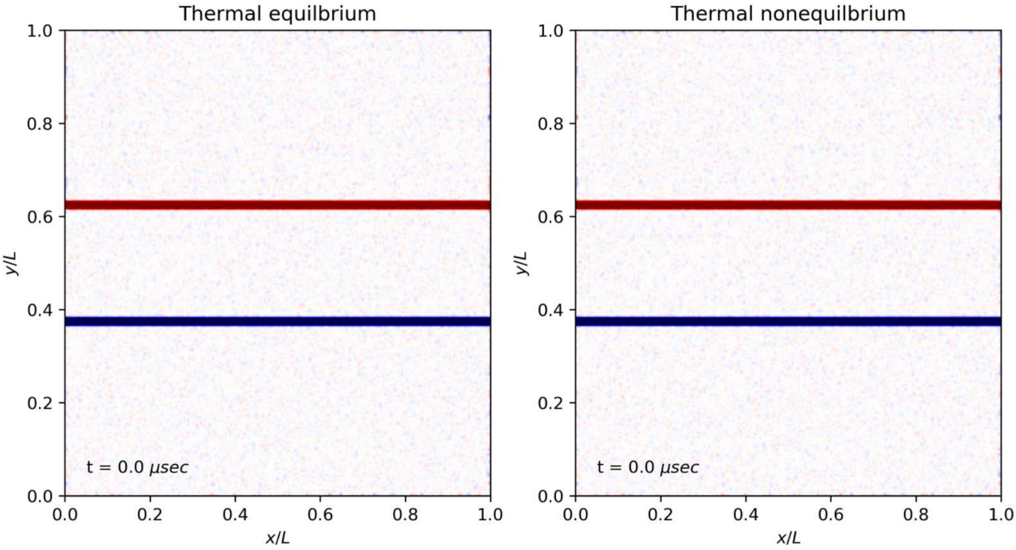
DSMC vs DNS - Vorticity evolution





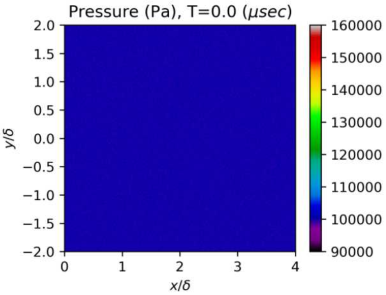
- DSMC results are smoothed by Gaussian filtering.
- DNS results are not filtered.

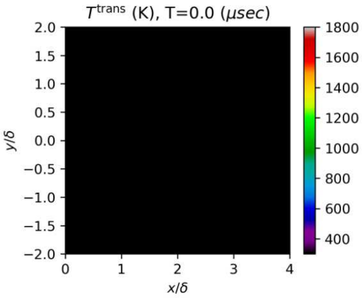
Vorticity evolution, DSMC

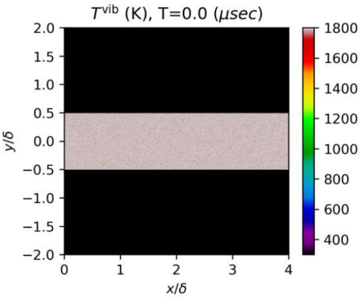


Pressure and temperatures, SEIZURE ALERT!!

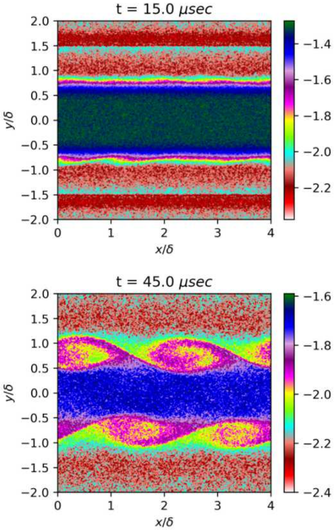
- Nonequilibrium case

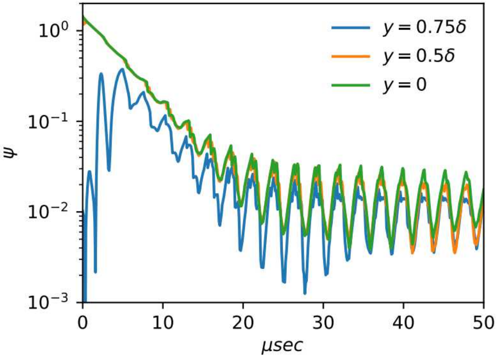






Reaching equilibrium





$$\psi = \frac{|T_y^{\text{vib}} - T_y^{\text{trans}}|}{(T_y^{\text{vib}} + T_y^{\text{trans}})/2}, \quad T_y = \frac{\int \rho T \, \mathrm{d}x}{\int \rho \, \mathrm{d}x}$$

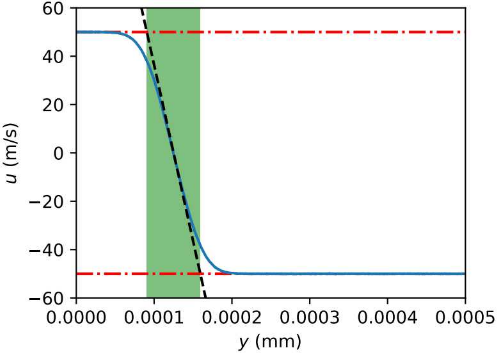
Speed of sound

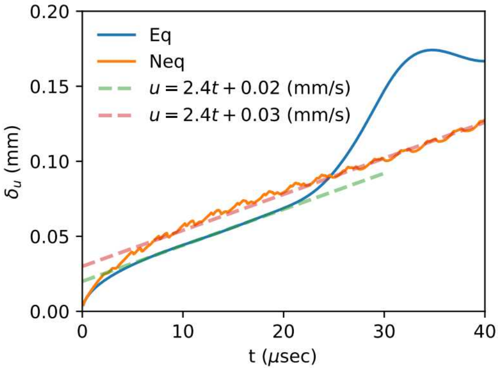
$V_{O_2,s} \approx 330 ms^{-1}$

$(300K, 1\ atm)$

$$f = V_{O_2,s}/Ly$$
$$\approx 3.3 \times 10^5 s^{-1}$$

Growth Rate, vorticity thickness

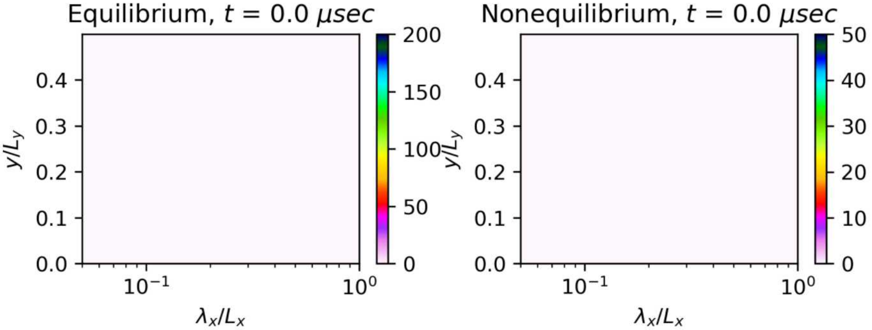




$$\delta_u \equiv \frac{1}{\left(\int |\omega| dx\right)_{\max}} \iint |\omega| dx dy$$

Turbulent kinetic energy spectra

$$\frac{1}{2}\langle \rho u_i'' u_i'' \rangle_x(y)$$
$$= \int E(k_x, y)\, \mathrm{d}k_x$$
$$\approx \int k_x E(k_x, y)\, \mathrm{d}\log k_x$$



With thermal nonequilibrium

- Growth of shear layer is delayed
- Instability initiates in larger-scale motions

Conclusion

- K-H instability simulation with DSMC and DNS
- Equilibrium process $\rightarrow$ Acoustic wave

Discussion and future work

- Adding chemical reaction
- 3D flow?
- Interaction with shock

Thank you!!

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