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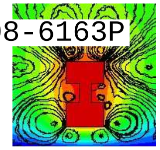

DSMC Noncontinuum Gas Flow Simulations: An Enabling Technology for Designing Microscale Vacuum Pumps

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Engineering Sciences Center 1500

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Albuquerque, New Mexico

DARPA Program Review for Dr. Dennis Polla

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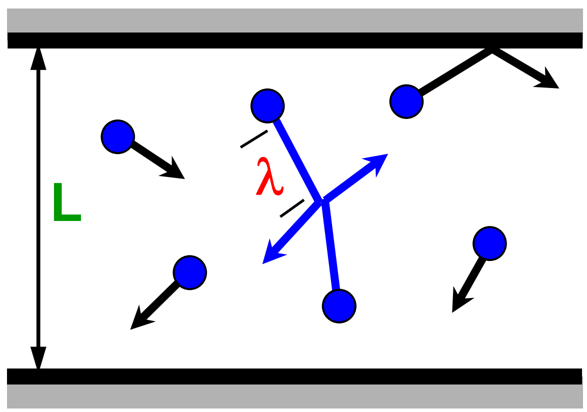
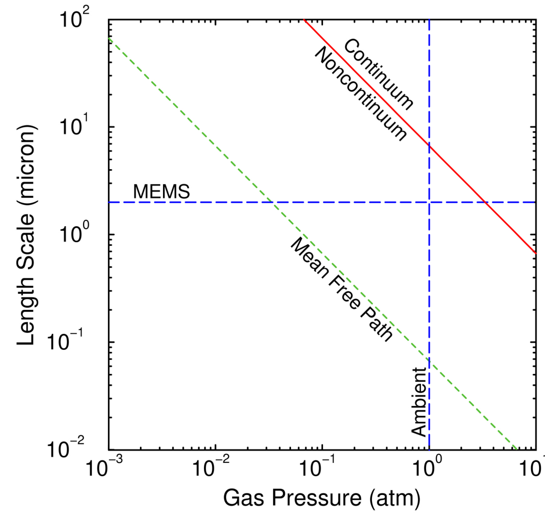
Gas Is Noncontinuum at Microscale



mean free path λ ~ L



Continuum heat flux, stress

$$\mathbf{q} = -K \frac{\partial T}{\partial \mathbf{x}}$$

$$\boldsymbol{\sigma} = -p\mathbf{I} + \mu\left(\frac{\partial \mathbf{u}}{\partial \mathbf{x}} + \frac{\partial \mathbf{u}}{\partial \mathbf{x}}^{\mathrm{T}}\right) + \left(\lambda - \frac{2}{3}\mu\right)\left(\frac{\partial}{\partial \mathbf{x}} \cdot \mathbf{u}\right)$$

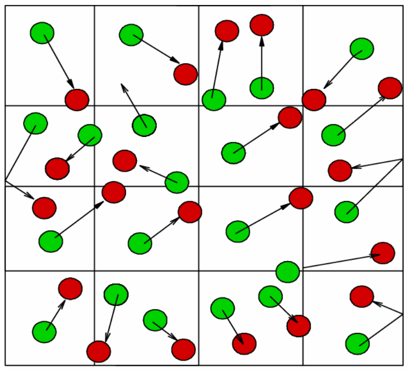
"Ordinary" flow codes

At low pressures and small scales, gas is noncontinuum

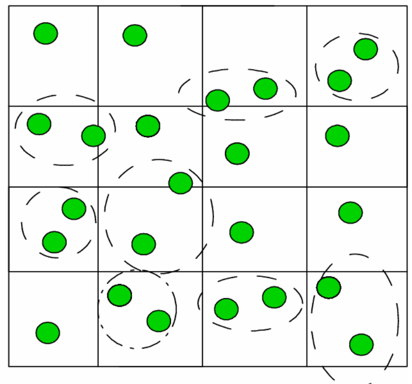
- **Molecule mean free path λ is similar to geometry size L**
  - **Mean free path: 0.07 μm at 1 atm, λ ∝ 1/p, p is gas pressure**
  - **Molecules hit surfaces more often than they hit each other**
- **Cannot simulate accurately with "ordinary" flow codes**
  - **Continuum heat-flux and stress expressions break down**
  - **New phenomena: slip, ballistic transport, thermal-stress flows**

Molecular gas dynamics is required for this regime

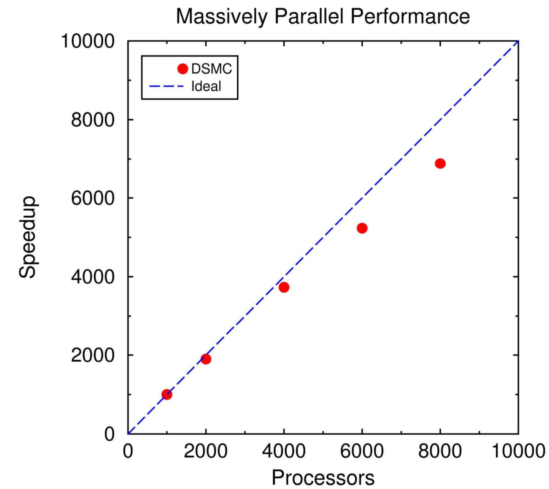
Direct Simulation Monte Carlo Method



molecules move



molecules collide



Direct Simulation Monte Carlo (DSMC) uses molecular gas dynamics to simulate noncontinuum gas flows

- **Computational molecules move, reflect, and collide like real gas molecules; statistics give “average” gas behavior**
  - **Monatomics (argon), polyatomics (nitrogen), mixtures (air)**
- **Works better at lower pressures and smaller sizes**
  - **Billions of molecules, great parallel performance if needed**
- **Extensively applied and validated over last half-century**

DSMC is only general method for this regime

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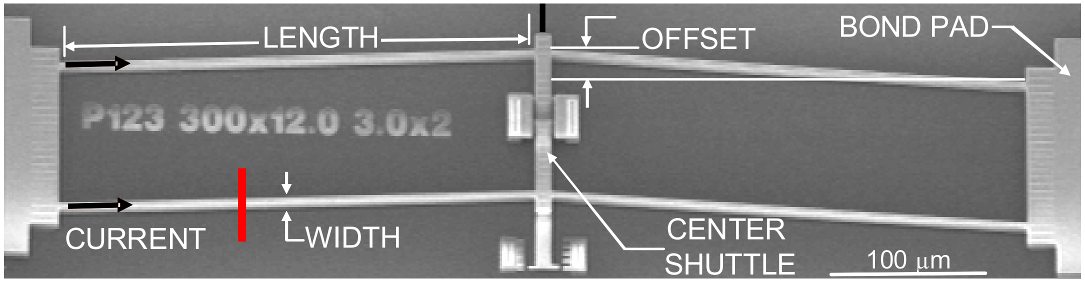
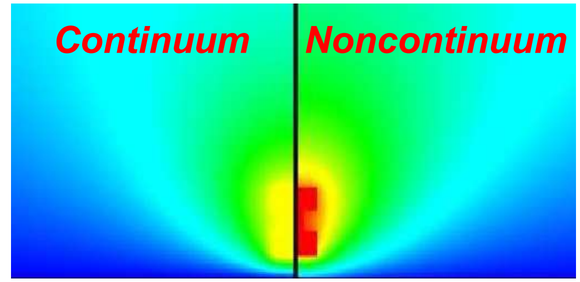
DSMC for Air-Based Thermal MEMS

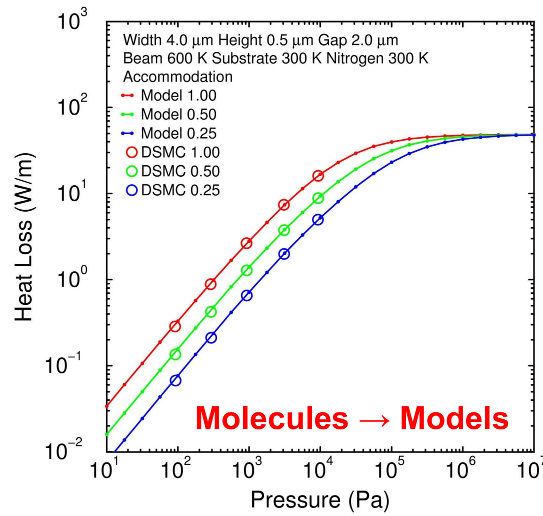


SUMMiT V thermal actuator, I-beam cross section

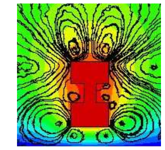


thermal actuator temperature

- **MEMS thermal actuator performance is limited by gas-phase heat transfer**
  - **Electrical current heats beams**
  - **Expansion controlled by temperature**
- **Compute gas heat transfer with DSMC**
  - **Develop noncontinuum-gas model**
  - **Implement in ordinary conduction code**
- **Noncontinuum gas inhibits heat transfer**
  - **Beam temperature is significantly higher**
  - **Essential to include for accurate results**



Sandia DSMC Technology Is Mature

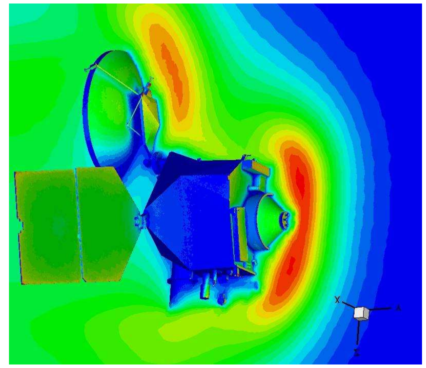


Traditional Applications

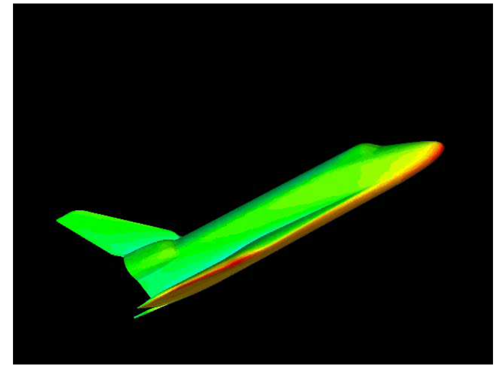
- Hypersonics and spacecraft
- Semiconductor equipment

Newer Applications

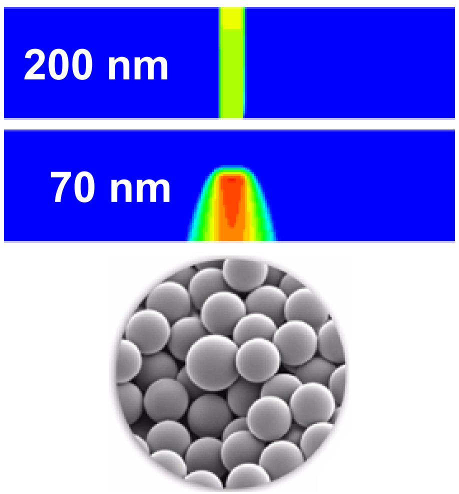
- MEMS damping, heat transfer
- Nanoparticle transport in gas



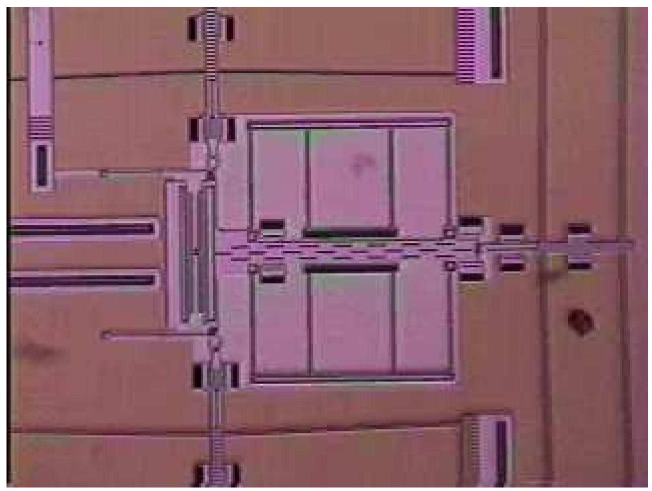
Mars Recon. Orbiter



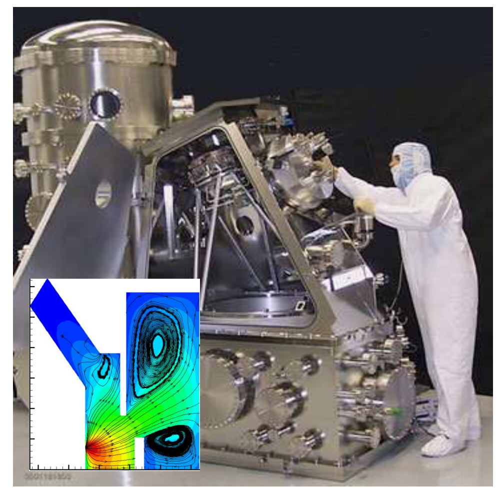
Space Shuttle



PSL Nanoparticles



Thermal Actuators



Semiconductor Tools

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