Multiscale Study of Hypersonic Vehicles: From Turbulence to Ceramics

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Webinar with DSIAC
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Contact James Chen for a high resolution version of the presentation with embedded videos.

About Me

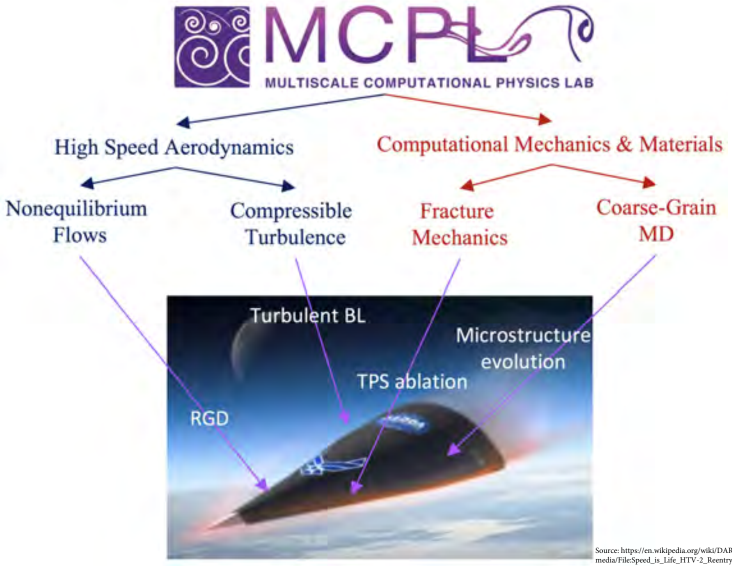
Current Position

- Associate Professor of Mechanical and Aerospace Engineering
- Undergraduate Director of Aerospace Engineering

Selected Honors & Awards

- Fellow of ASME, 2022
- Associate Fellow of AIAA, 2022
- Outstanding Young Engineer Award, AIAA Wichita Section, 2018
- Young Investigator Award, AFOSR, 2017

Research at MCPL



Source: https://en.wikipedia.org/wiki/DARPA_Falcon_Project#/media/File:Speed_is_Life_HTV-2_Reentry_New.jpg

Rotation or Not?

Source: https://www.flickr.com/photos/cseeman/27442272417

Boltzmann Equation and Navier-Stokes Equations are for Monatomic Gas or Volumeless Point Mass.

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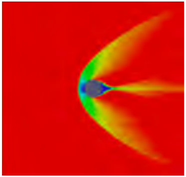
Boltzmann Equation and Navier-Stokes Equations are for Monatomic Gas or Volumeless Point Mass.

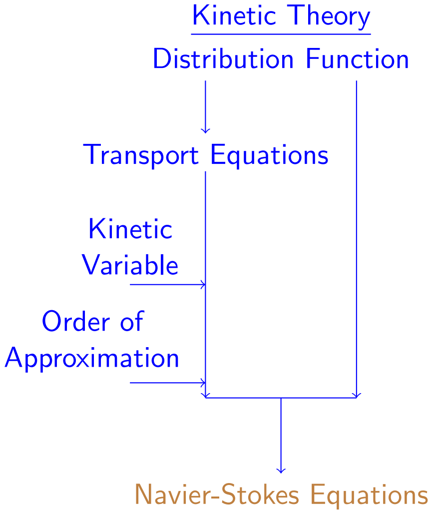


Source: James Chen, University at Buffalo

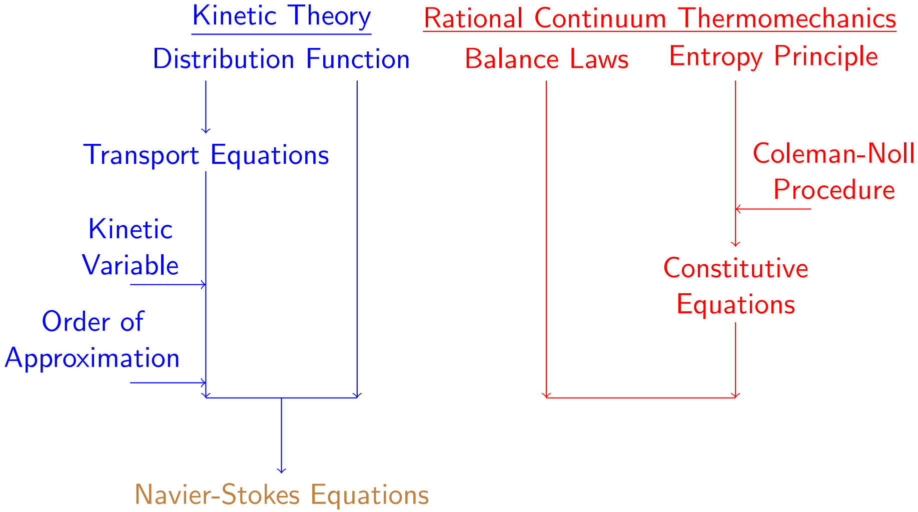
Continuum Theory for Flow with Inner Structures ?

1. Real fluids - Polyatomic molecules
2. High Mach or rarefied flow - Rotation and/or vibration nonequilibrium
3. Turbulence - Eddies

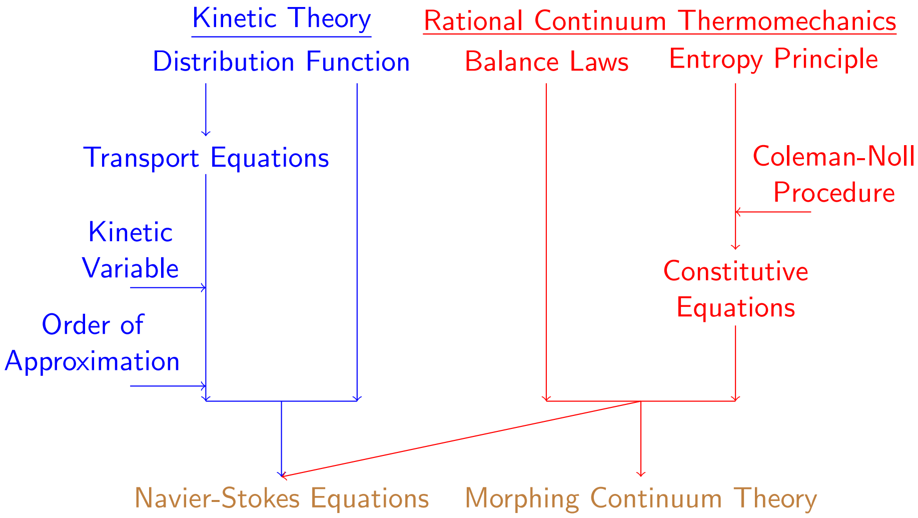
Roadmap to Continuum Theory



Roadmap to Continuum Theory



Roadmap to Continuum Theory



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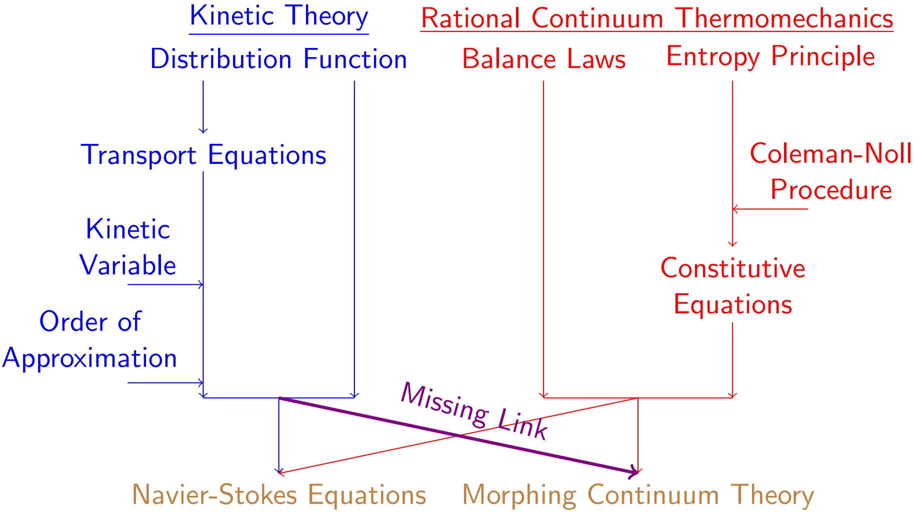
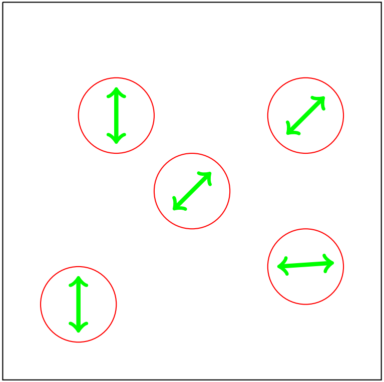


Advanced Kinetic Theory - Boltzmann-Curtiss Equations



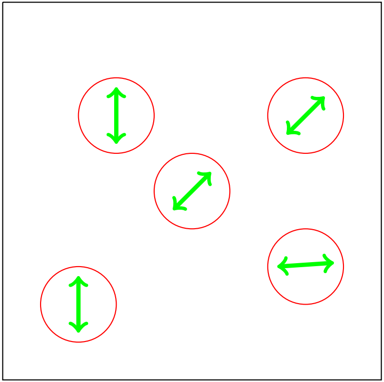
$$\bar{f}(\mathbf{x}, \mathbf{p}, \phi, \mathbf{M}, t) = \int f(\mathbf{x}, \mathbf{p}, \phi, \mathbf{M}, E_{\text{vib}}, t) dE_{\text{vib}} d\tau,$$

$$\left(\frac{\partial}{\partial t} + \frac{\mathbf{p}}{m}\frac{\partial}{\partial \mathbf{x}} + \frac{\mathbf{M}}{I}\frac{\partial}{\partial \phi}\right)\bar{f} = \sum_{\beta} \mathbf{Z}_{\beta}$$

$$\frac{\partial}{\partial t} n\chi + \frac{\partial}{\partial x_i} n\chi v_i - n v_i \frac{\partial \chi}{\partial x_i} + \frac{\partial}{\partial \phi_i} n\chi\omega_i - n\omega_i \frac{\partial \chi}{\partial \phi_i} = 0$$

(Curtiss, 1992)

Advanced Kinetic Theory - Boltzmann-Curtiss Equations



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(Curtiss, 1992)

$$\bar{f}(\mathbf{x}, \Delta\mathbf{v}, \Delta\boldsymbol{\omega}) = \left(\frac{\sqrt{mI}}{2\pi k\theta}\right)^3 \exp\left[-\frac{m\Delta\mathbf{v}^2 + I\Delta\boldsymbol{\omega}^2}{2k\theta}\right]$$

Boltzmann-Curtiss Distribution

$$\bar{f}(\mathbf{x}, \Delta\mathbf{v}, \Delta\omega) = \left(\frac{\sqrt{mI}}{2\pi k\theta}\right)^3 \exp\left[-\frac{m\Delta\mathbf{v}^2 + I\Delta\omega^2}{2k\theta}\right]$$

Boltzmann's H-Theorem

$$H(t) = \int_0^\infty f(E,t)[log(\frac{f(E,t)}{\sqrt{E}}) - 1]dE$$

Boltzmann-Curtiss Distribution

$$\bar{f}(\mathbf{x}, \Delta\mathbf{v}, \Delta\omega) = \left(\frac{\sqrt{mI}}{2\pi k\theta}\right)^3 \exp\left[-\frac{m\Delta\mathbf{v}^2 + I\Delta\omega^2}{2k\theta}\right]$$

Boltzmann's H-Theorem

$$H(t) = \int_0^\infty f(E,t)[log(\frac{f(E,t)}{\sqrt{E}}) - 1]dE$$

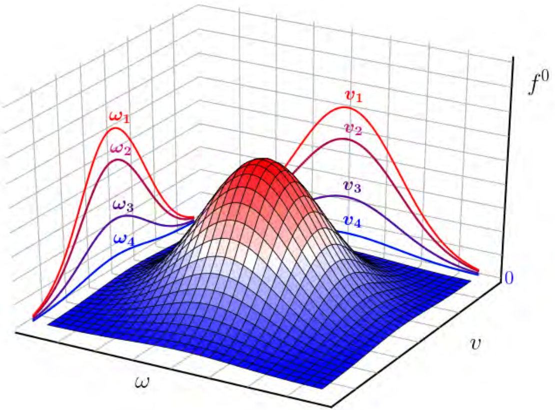
Method of the Most Probable Distribution (Schrödinger, 1989)

$$W = \frac{N!}{\prod_{i=0}^{m} n_i!} \qquad S = k\ln W$$

Chen, 2017; Wonnell and Chen, 2019

Maxwell-Boltzmann vs. Boltzmann-Curtiss Distribution

$$\bar{f}(\mathbf{x}, \Delta\mathbf{v}, \Delta\omega) = \left(\frac{\sqrt{mI}}{2\pi k\theta}\right)^3 \exp\left[-\frac{m\Delta\mathbf{v}^2 + I\Delta\omega^2}{2k\theta}\right]$$



Source: https://doi.org/10.1115/1.4045761

From Kinetic Variables to Transport Equations

B-C Equation

$$(\frac{\partial}{\partial t} + \frac{\mathbf{p}}{m}\frac{\partial}{\partial \mathbf{x}} + \frac{\mathbf{M}}{I}\frac{\partial}{\partial \phi})\bar{f} = \sum_{\beta} \mathbf{Z}_{\beta},$$

Kinetic Variables

1. Mass
2. Linear Momentum
3. Angular Momentum
4. Internal Energy

B-C Distribution and Transport Equations

$$\bar{f}(\mathbf{x}, \Delta\mathbf{v}, \Delta\boldsymbol{\omega}) = \left(\frac{\sqrt{mI}}{2\pi k\theta}\right)^3 \exp\left[-\frac{m\Delta\mathbf{v}^2 + I\Delta\boldsymbol{\omega}^2}{2k\theta}\right]$$

$$\frac{\partial}{\partial t} n\chi + \frac{\partial}{\partial x_i} n\chi v_i - n v_i \frac{\partial \chi}{\partial x_i} = 0$$

Kinetic Variables in Advanced Kinetic Theory

Mass, $\chi_1 = m$

$$\frac{\partial}{\partial t}\rho + \frac{\partial}{\partial x_i}(\rho U_i) = 0$$

Linear Momentum, $\chi_2 = mv_i^* = m(v_i + e_{ijk}\omega_j r_k)$

$$\frac{\partial}{\partial t}(\rho U_j) + \frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial}{\partial x_i}(\rho < v'_i v'_j > + \rho e_{jmn} r_n < v'_i \omega'_m >)$$

Angular Momentum, $\chi_3 = mr_j r_m \omega_m$

$$\frac{\partial}{\partial t}(\rho i_{jm} W_m) + \frac{\partial}{\partial x_i}(\rho i_{jm} W_m U_i) = -\frac{\partial}{\partial x_i}(\rho i_{jm} < \omega'_m v'_i >)$$

Internal Energy, $\chi_4 = \frac{1}{2}(< v'_m v'_m > + < r_m r_n \omega'_m \omega'_n >)$

$$\frac{\partial}{\partial t}(\rho e) + \frac{\partial}{\partial x_i}(\rho e U_i)$$
$$= -\frac{\partial}{\partial x_i}(\frac{1}{2}\rho(< v'_m v'_m v'_i > + i_{mn} < \omega'_m \omega'_n v'_i >)) + \rho < v_i \frac{\partial e}{\partial x_i} >$$

First-order Approximation

B-C Equation

$$(\frac{\partial}{\partial t} + \frac{\mathbf{p}}{m}\frac{\partial}{\partial \mathbf{x}} + \frac{\mathbf{M}}{I}\frac{\partial}{\partial \phi})\bar{f} = (\frac{\partial \bar{f}}{\partial t})_{collision},$$

BGK Approach

$$(\frac{\partial \bar{f}}{\partial t})_{collision} \Rightarrow -\frac{\bar{f} - \bar{f}^0}{\tau} = -\frac{g}{\tau}$$

Comparison with Morphing Continuum Theory

The classical Boltzmann's equation with a distribution linearly deviates from the Boltzmann distribution (first-order approximation), leads to the celebrated Navier-Stokes equations. Will the B-C equation with a distribution linearly deviated from the B-C distribution give the MCT governing equations?

Wonnell and Chen, 2019

Linear Momentum

Morphing Continuum Theory

$$\frac{\partial}{\partial t}(\rho v_j^{MCT}) + \frac{\partial}{\partial x_i}(\rho v_i^{MCT} v_j^{MCT}) = -\frac{\partial p}{\partial x_j} + (\lambda + \mu)\frac{\partial^2 v_i^{MCT}}{\partial x_i x_j} + (\mu + \kappa)\frac{\partial^2 v_j^{MCT}}{\partial x_i \partial x_i} + \kappa e_{jlm}\frac{\partial \omega_m^{MCT}}{\partial x_l}$$

Advanced Kinetic Theory

$$\frac{\partial}{\partial t}(\rho U_j) + \frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial p}{\partial x_j} + \frac{2n\tau\theta}{3}\frac{\partial^2 U_i}{\partial x_i x_j} + n\tau\theta\frac{\partial^2 U_j}{\partial x_i \partial x_i} + n\tau\theta e_{jlm}\frac{\partial W_m}{\partial x_l}$$

Angular Momentum

Morphing Continuum Theory

$$\frac{\partial}{\partial t}(\rho j \omega_j^{\mathrm{MCT}}) + \frac{\partial}{\partial x_i}(\rho j v_i^{\mathrm{MCT}} \omega_j^{\mathrm{MCT}}) = (\alpha + \beta)\frac{\partial^2 \omega_i^{\mathrm{MCT}}}{\partial x_i x_j} + \gamma \frac{\partial^2 \omega_j^{\mathrm{MCT}}}{\partial x_i \partial x_i} + \kappa (e_{jlm}\frac{\partial v_m^{\mathrm{MCT}}}{\partial x_l} - 2\omega_j^{\mathrm{MCT}})$$

Advanced Kinetic Theory

$$\frac{\partial}{\partial t}(\rho j W_j) + \frac{\partial}{\partial x_i}(\rho j U_i W_j) = n j \tau \theta \frac{\partial^2 W_j}{\partial x_i \partial x_i} + \nu_r (e_{jlm}\frac{\partial U_m}{\partial x_l} - 2W_j)$$

Pathway to Navier-Stokes Equations

$$\frac{\partial}{\partial t}(\rho U_j) + \frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial p}{\partial x_j} + \frac{2n\tau\theta}{3}\frac{\partial^2 U_i}{\partial x_i x_j} + n\tau\theta\frac{\partial^2 U_j}{\partial x_i \partial x_i} + n\tau\theta e_{jlm}\frac{\partial W_m}{\partial x_l}$$

Pathway to Navier-Stokes Equations

$$\frac{\partial}{\partial t}(\rho U_j) + \frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial p}{\partial x_j} + \frac{2n\tau\theta}{3}\frac{\partial^2 U_i}{\partial x_i x_j} + n\tau\theta\frac{\partial^2 U_j}{\partial x_i \partial x_i} + n\tau\theta e_{jlm}\frac{\partial W_m}{\partial x_l}$$

Angular Motion Equivalence

$$\vec{W} = \frac{1}{2}\nabla \times \vec{U}$$

Pathway to Navier-Stokes Equations

$$\frac{\partial}{\partial t}(\rho U_j) + \frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial p}{\partial x_j} + \frac{2n\tau\theta}{3}\frac{\partial^2 U_i}{\partial x_i x_j} + n\tau\theta\frac{\partial^2 U_j}{\partial x_i \partial x_i} + n\tau\theta e_{jlm}\frac{\partial W_m}{\partial x_l}$$

Angular Motion Equivalence

$$\vec{W} = \frac{1}{2}\nabla \times \vec{U}$$

Navier-Stokes Equations Type II

$$\frac{\partial}{\partial t}(\rho U_j) + \frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial p}{\partial x_j} + \frac{7n\tau\theta}{6}\frac{\partial^2 U_i}{\partial x_i x_j} + \frac{n\tau\theta}{2}\frac{\partial^2 U_j}{\partial x_i \partial x_i}$$

Navier-Stokes Equations Type I & II

Navier-Stokes Equations Type II - reduced from MCT

$$\frac{\partial}{\partial t}(\rho U_j) + \frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial p}{\partial x_j} + \frac{7n\tau\theta}{6}\frac{\partial^2 U_i}{\partial x_i x_j} + \frac{n\tau\theta}{2}\frac{\partial^2 U_j}{\partial x_i \partial x_i}$$

Navier-Stokes Equations Type I - classical framework

$$\frac{\partial}{\partial t}(\rho U_j) + \frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial p}{\partial x_j} + \frac{n\tau\theta}{3}\frac{\partial^2 U_i}{\partial x_i x_j} + n\tau\theta\frac{\partial^2 U_j}{\partial x_i \partial x_i}$$

Boltzmann-Curtiss Equation

$\frac{\partial}{\partial \phi_i} = 0$ ↓ No angular dependence

Boltzmann Equation

A Map between Kinetic Theory and Continuum Theory

Boltzmann-Curtiss Equation

$\frac{\partial}{\partial \phi_i} = 0$ ↓ No angular dependence

Boltzmann Equation

Euler

NS Type I

NS Type II

MCT

A Map between Kinetic Theory and Continuum Theory

Boltzmann-Curtiss Equation

$\frac{\partial}{\partial \phi_i} = 0$ No angular dependence

Boltzmann Equation

$f_{\mathrm{B}}^{(1)}$

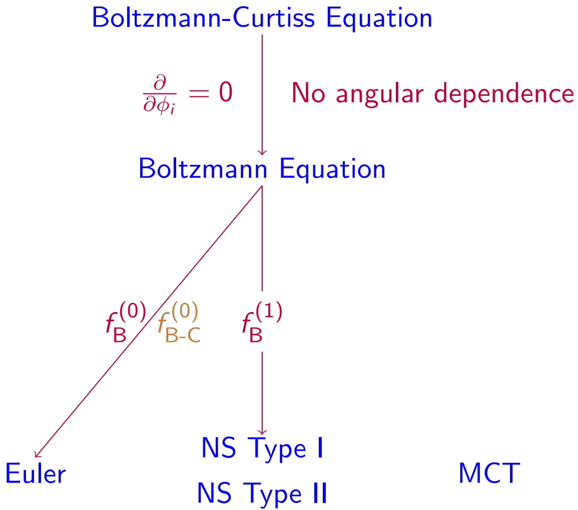
Euler

NS Type I

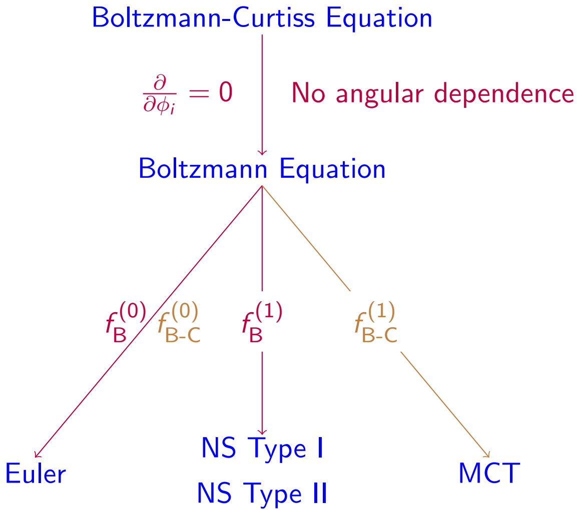
NS Type II

MCT

A Map between Kinetic Theory and Continuum Theory



A Map between Kinetic Theory and Continuum Theory



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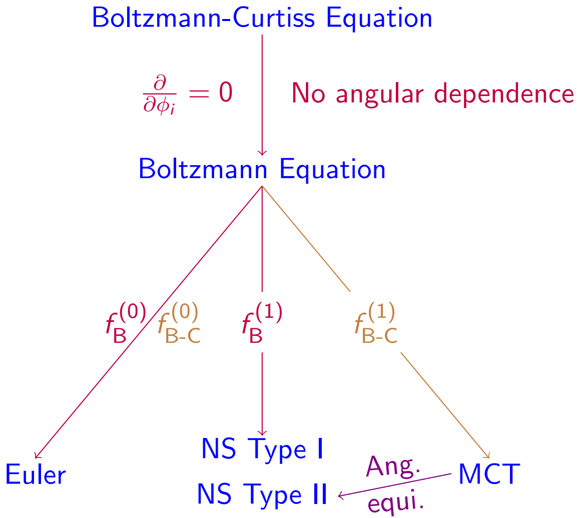
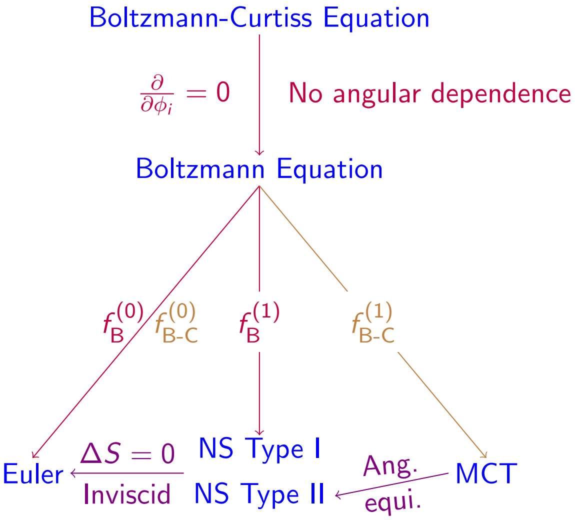


A Map between Kinetic Theory and Continuum Theory



Morphing Continuum Theory for Incompressible Fluids

Conservation of Mass

$$\frac{\partial}{\partial t}\rho + \frac{\partial}{\partial x_i}(\rho U_i) = 0$$

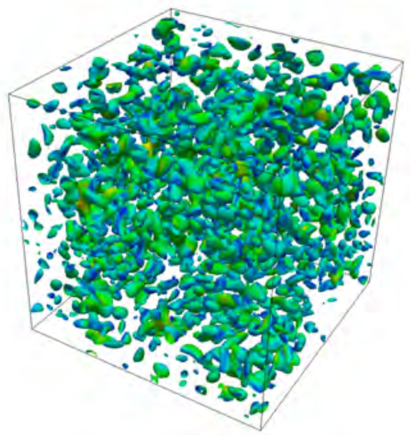
Balance Law of Linear Momentum

$$\frac{\partial}{\partial t}(U_j) + U_i \frac{\partial}{\partial x_i}(U_j) = \frac{1}{\rho}\frac{\partial p}{\partial x_j} + \frac{\mu+\kappa}{\rho}\frac{\partial^2 U_j}{\partial x_i \partial x_i} + \frac{\kappa}{\rho} e_{jkl}\frac{\partial W_l}{\partial x_k}$$

Balance Law of Angular Momentum

$$\frac{\partial}{\partial t}(W_m) + U_i \frac{\partial}{\partial x_i}(W_m) = \frac{\gamma}{\rho j}\frac{\partial W_j}{\partial x_i \partial x_i} + \frac{\kappa}{\rho j}\left(e_{jkl}\frac{\partial U_l}{\partial x_k} - 2W_j\right)$$

Homogeneous Isotropic Turbulence



Source: James Chen, University at Buffalo

Linear Momentum Equations

Balance Law of Linear Momentum

$$\frac{d}{dt}\langle U_j \rangle = \frac{1}{\rho}\left\langle \frac{\partial p}{\partial x_j} \right\rangle + \frac{\mu+\kappa}{\rho}\left\langle \frac{\partial^2 U_j}{\partial x_i \partial x_i} \right\rangle + \frac{\kappa}{\rho}\left\langle e_{jkl}\frac{\partial U_l}{\partial W_k} \right\rangle$$

$$\frac{d\langle U_j \rangle}{dt} = \frac{1}{\rho}\cancel{\left\langle \frac{\partial p}{\partial x_j} \right\rangle} + \frac{\mu+\kappa}{\rho}\cancel{\left\langle \frac{\partial^2 U_j}{\partial x_i \partial x_i} \right\rangle} + \frac{\kappa}{\rho}\cancel{\left\langle e_{jkl}\frac{\partial W_l}{\partial x_k} \right\rangle}$$

$$\frac{d}{dt}\langle U_j \rangle = 0$$

Angular Momentum Equations

Balance Law of Angular Momentum

$$\frac{d}{dt}\langle W_j\rangle = \frac{\gamma}{\rho j}\left\langle \frac{\partial^2 W_j}{\partial x_i \partial x_i}\right\rangle + \frac{\kappa}{\rho j}\left(\left\langle e_{jkl}\frac{\partial U_l}{\partial x_k}\right\rangle - 2\left\langle W_j\right\rangle\right)$$

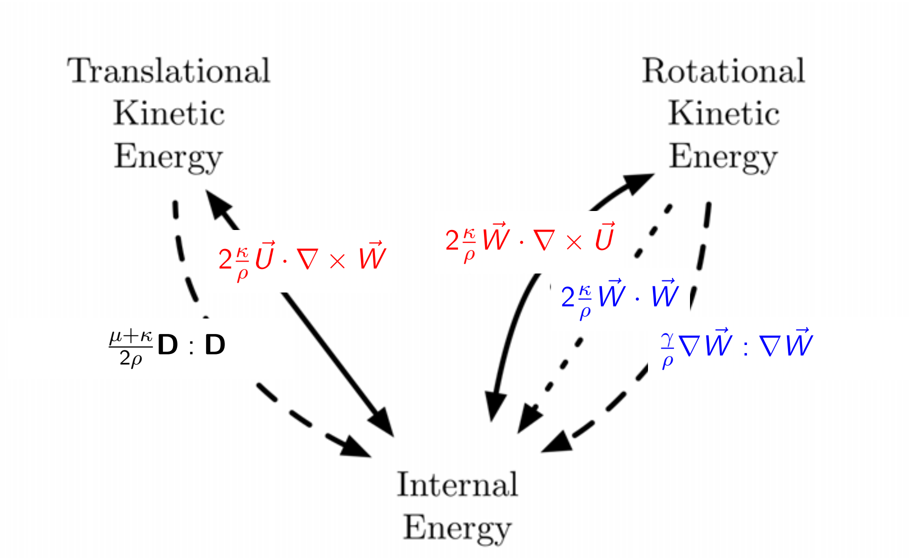
$$\frac{d}{dt}\langle W_j\rangle = \frac{\gamma}{\rho j}\left\langle \frac{\partial^2 W_j}{\partial x_i \partial x_i}\right\rangle + \frac{\kappa}{\rho j}\left(\left\langle e_{jkl}\frac{\partial U_l}{\partial x_k}\right\rangle - 2\left\langle W_j\right\rangle\right)$$

$$\frac{d}{dt}\langle W_j\rangle = -\frac{2\kappa}{\rho j}\left\langle W_j\right\rangle$$

$\langle W_j\rangle = Ce^{-\tau_w t}$ $\tau_w = \frac{2\kappa}{\rho j}$: turbulence relaxation time

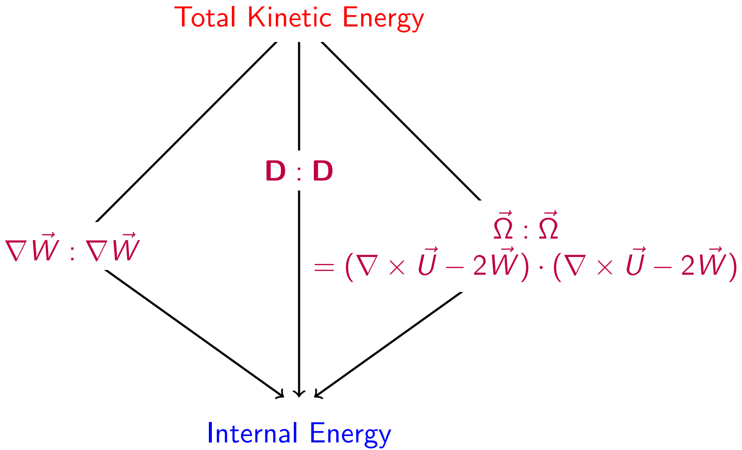
Wonnell and Chen, 2019; Chen, 2003 (Science)

Energy Equation

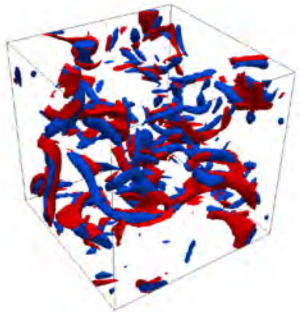


Total Energy Cascade

Energy Transfer & Absolute Rotation

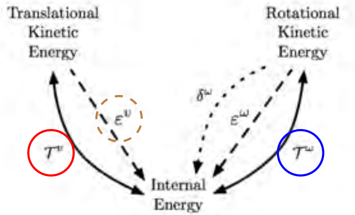


Homogeneous Isotropic Turbulence - Energy Transfer



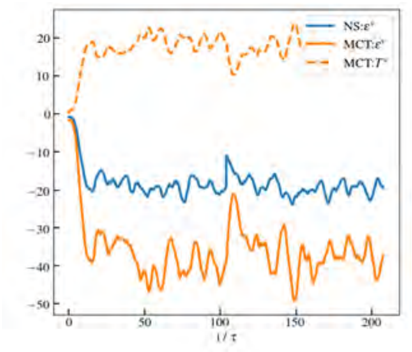
Source: James Chen, University at Buffalo

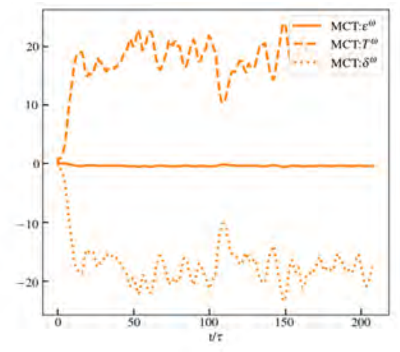
Translational energy cascade



Rotational energy cascade

Homogeneous Isotropic Turbulence - MCT vs. NS





Source: James Chen, University at Buffalo

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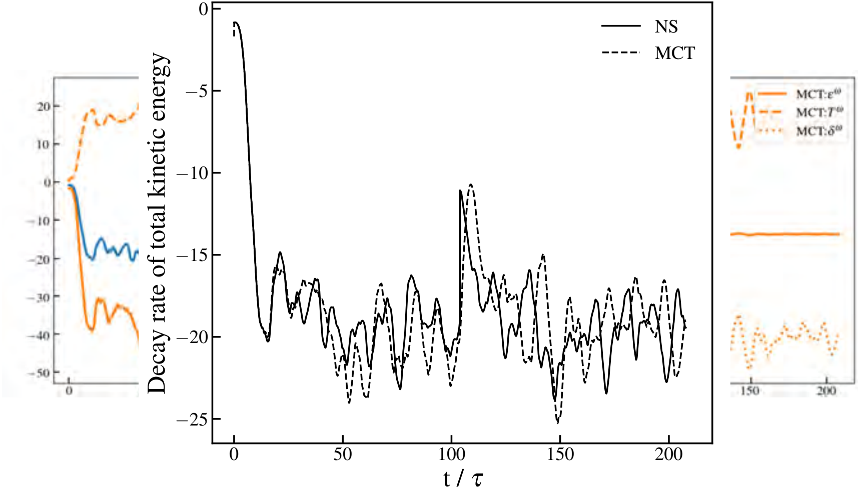
Homogeneous Isotropic Turbulence - MCT vs. NS



Source: https://doi.org/10.1103/PhysRevFluids.4.104610

Source: James Chen, University at Buffalo

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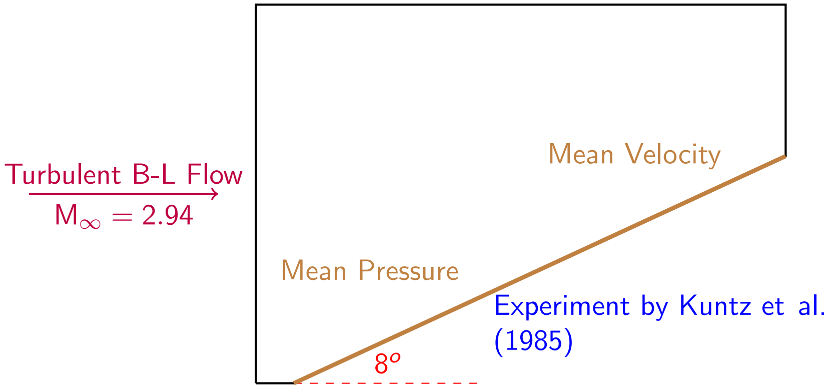
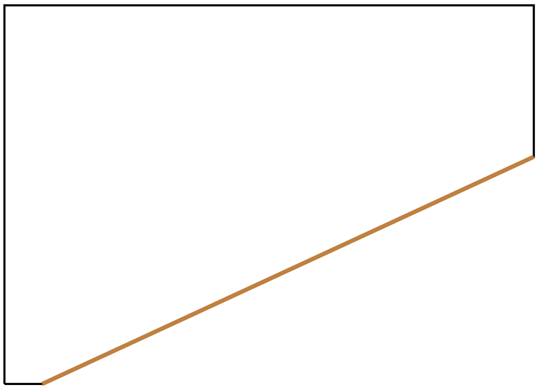
Supersonic Flow Over an 8^o Compression Ramp

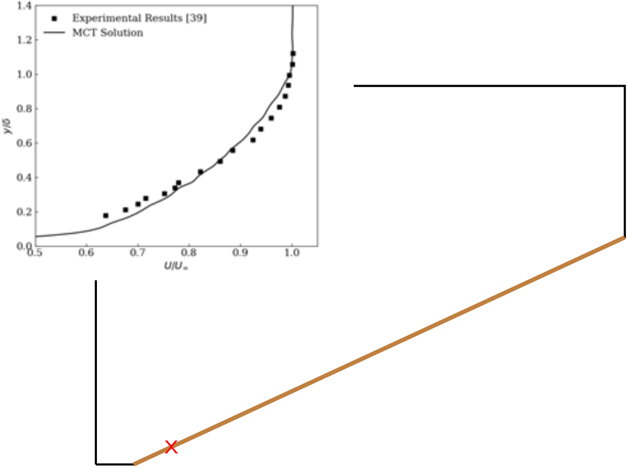


(Cheikh et al., 2018)

Supersonic Flow - Compression Ramp

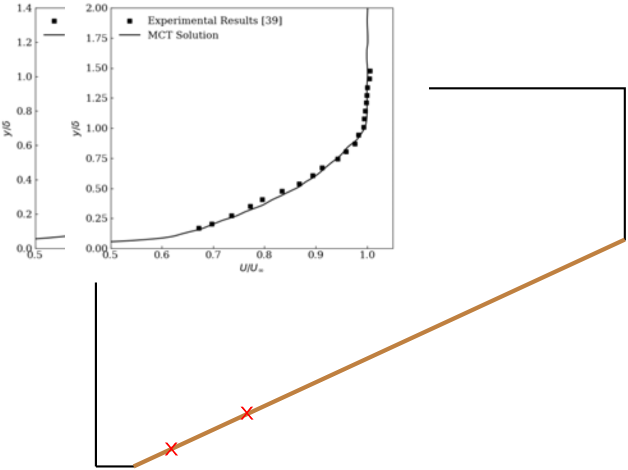


Supersonic Flow - Compression Ramp



Source: https://doi.org/10.1103/PhysRevFluids.3.024604

Supersonic Flow - Compression Ramp



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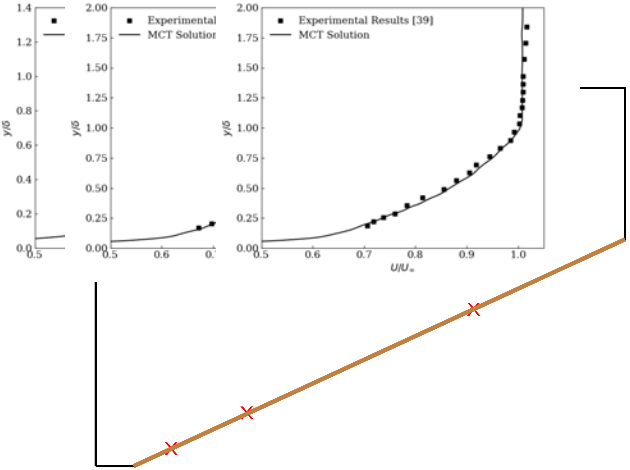
Supersonic Flow - Compression Ramp



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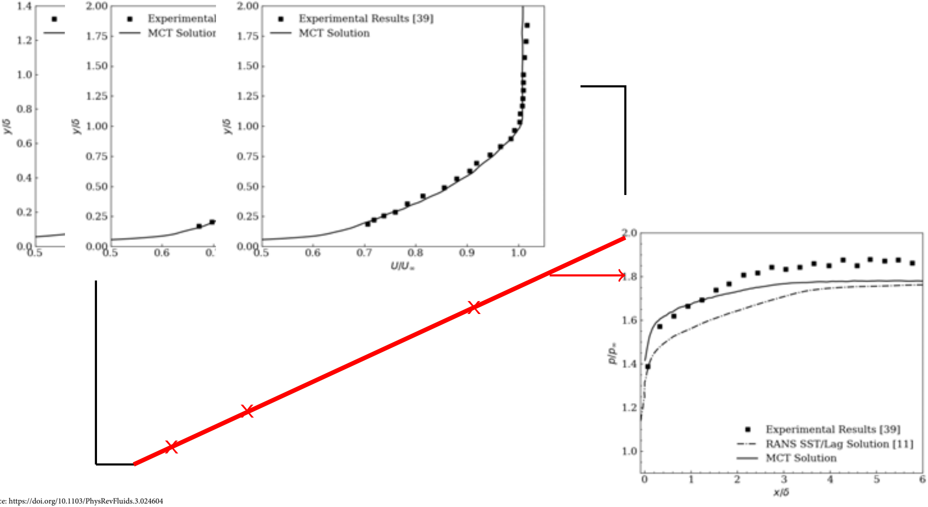


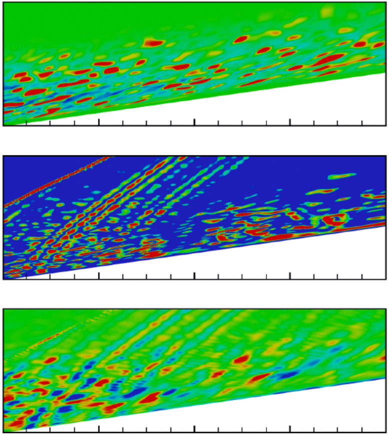
Source: https://doi.org/10.1103/PhysRevFluids.3.024604

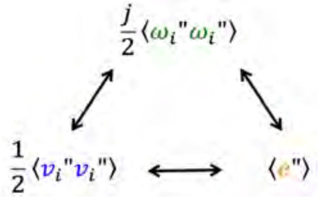
Supersonic Flow - Energy Analysis

Rotation

Translation

Internal





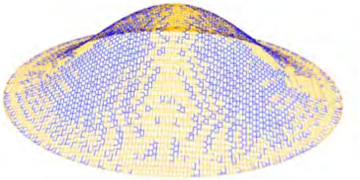
Source: James Chen, University at Buffalo

Transonic Flow Over an Axisymmetric Hill

Flow Profile

M_∞	0.6
δ_{inlet}	0.039 m
H_{bump}	0.078 m
Re_H	6709

Hill Surface Pressure Coefficient



From "Morphing Continuum Simulation of Transonic Flow over Axisymmetric Hill" by Louis B. Wonnell, Mohamad I. Cheikh and James Chen; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc. Source: https://doi.org/10.2514/1.J057064

- Experiment: Simpson et al. (2002)
- NS-based DNS: Castagna et al. (2014)
- MCT-based DNS: Wonnell, Cheikh, and Chen (2018)

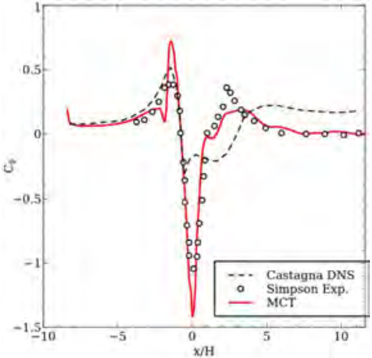
Transonic Flow - Vortex Visualization and Surface Pressure

Objective Q-Criterion for Vortex Visualization

$$2II_a = (\nabla \cdot \vec{v})^2 - \nabla\vec{v} : \nabla\vec{v}^T - 2(\nabla \times \vec{v}) \cdot \vec{\omega} + 2\vec{\omega} \cdot \vec{\omega}$$

Source: James Chen, University at Buffalo

Hill Surface Pressure Coefficient



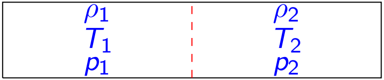
Computation Cost:

MCT: 6M cells

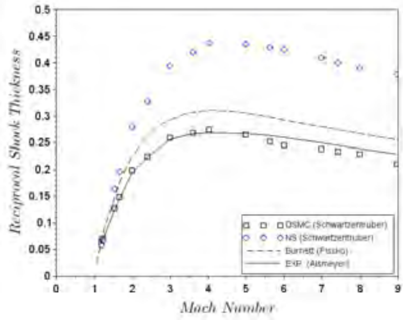
DNS: 54M cells

From "Morphing Continuum Simulation of Transonic Flow over Axisymmetric Hill" by Louis B. Wonnell, Mohamad I. Cheikh and James Chen; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc. Source: https://doi.org/10.2514/1.J057064

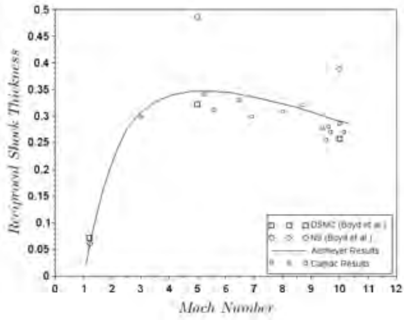
1-D Shock Profile – Argon and Nitrogen



Argon

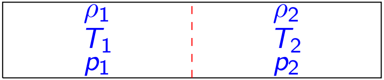


Nitrogen

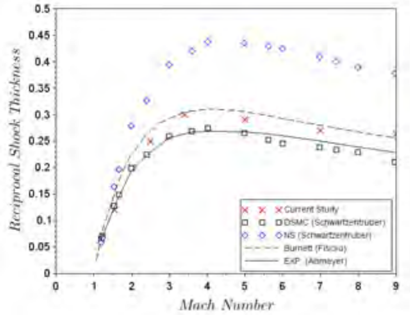


Source: https://doi.org/10.1115/1.4045761

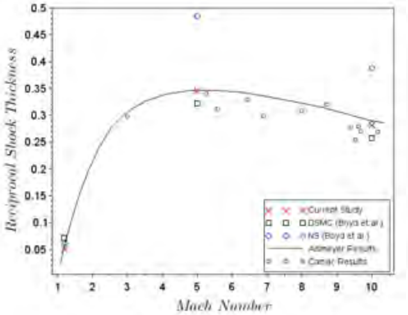
1-D Shock Profile – Argon and Nitrogen



Argon

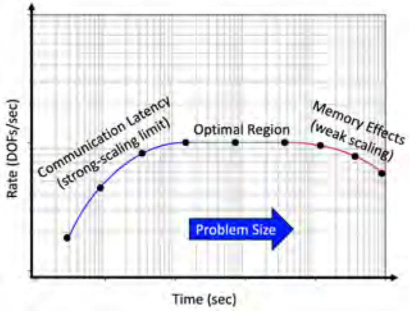


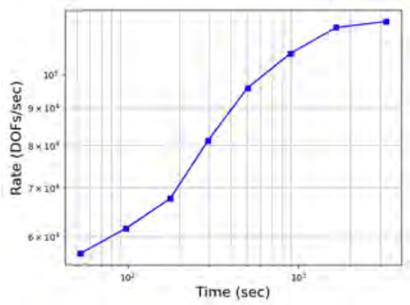
Nitrogen



Source: https://doi.org/10.1115/1.4045761

Scalability - Static Scaling





Sementilli, McGurn, and Chen, 2023

- Number of Cores Tested: 32,768 (DoE Quartz)
- Test Case: Multiphase (liquid and gas) Kelvin-Helmholtz instability
- Degrees of Freedom Tested: 48M

Source: https://doi.org/10.1002/fld.5169

Integrated Computational Materials Engineering for Hypersonics

- Insufficient understanding at vehicle/flow interface
  - Artificial Neural Network with Bayesian statistics
  - Physics-based models with exascale simulaiton

Source: https://en.wikipedia.org/wiki/Atmospheric_entry#/media/File:Apollo_cm.jpg

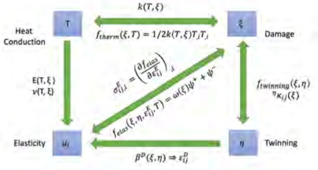
- Limited data availability for ceramics under hypersonic condition
  - Bayesian-based uncertainty management

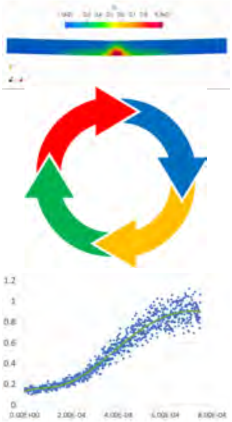
Source: Getty Images

ICME Framework for Ceramics

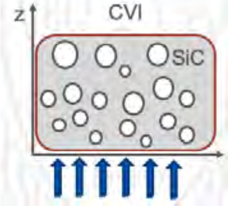
Performance

Properties





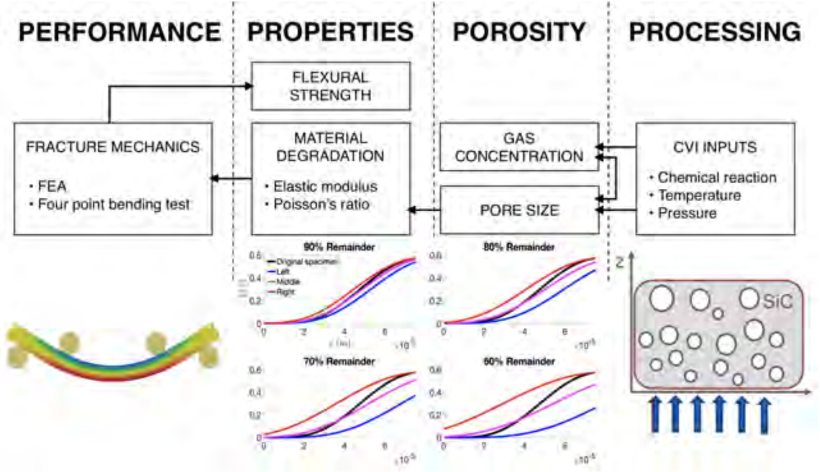
Process



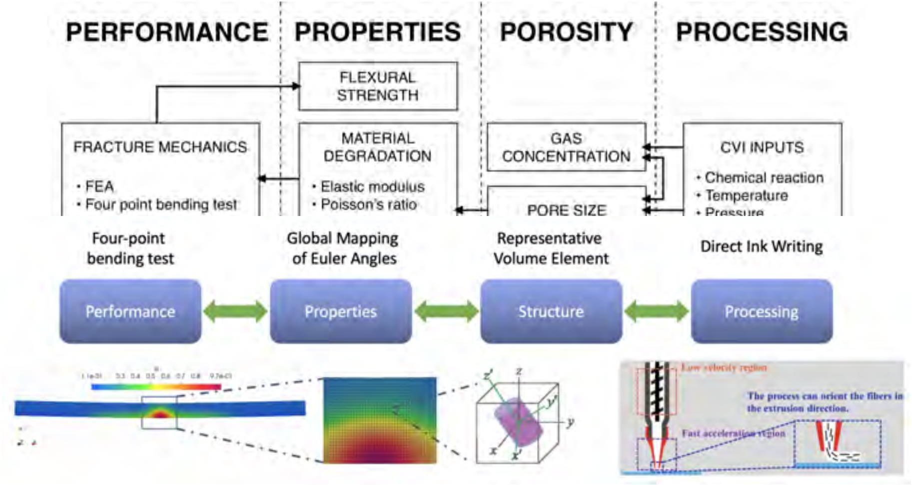
Structure

Source: James Chen, University at Buffalo

Manufacturing-Driven ICME for CMC in Hypersonics



Source: James Chen, University at Buffalo

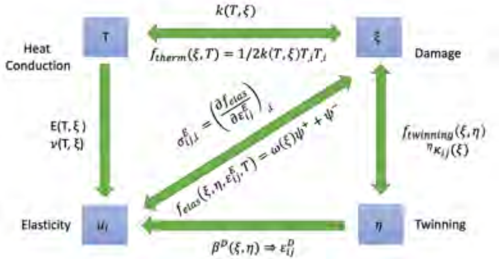


Source: James Chen, University at Buffalo

Four-Way Thermo-Mechanical Coupling

$$\frac{\partial T}{\partial t} = w(\xi)k(T)T_{,ii}$$

$$\frac{\partial \xi}{\partial t} = -L_\xi\left(\frac{\partial f_{loc}(\xi,\epsilon,T,\eta)}{\partial \xi} - \kappa\xi_{,ii}\right)$$



$$\sigma_{ij.i} = 0$$

$$\frac{\partial \eta}{\partial t} = -L_\eta\left(\frac{\partial f_{loc}(\xi,\epsilon,T,\eta)}{\partial \eta} - \kappa\eta_{,ii}\right)$$

Four-Way Thermo-Mechanical Coupling

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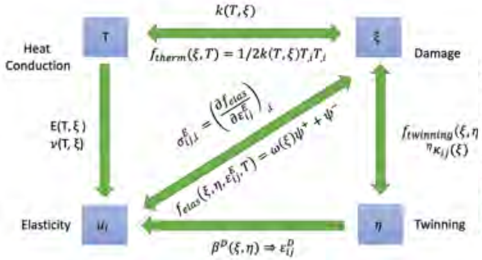
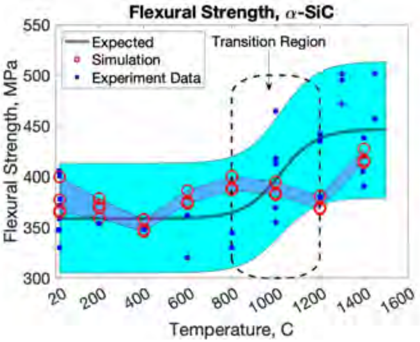


$$\sigma_{ij.i} = 0$$



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(Sun et al., 2023) Source: https://doi.org/10.1111/jace.19202

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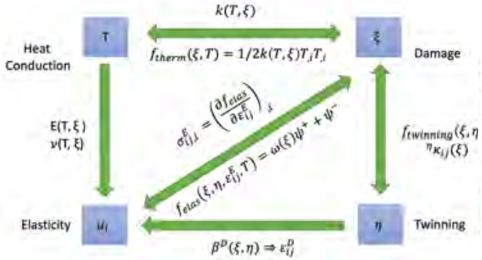
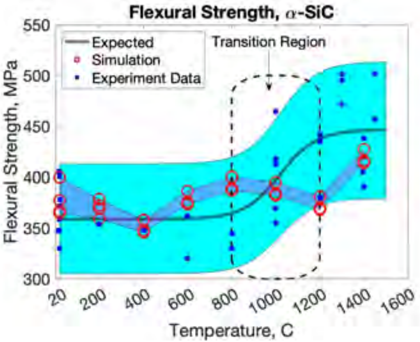


$$\sigma_{ij.i} = 0$$

$20 \sim 1400^o C$

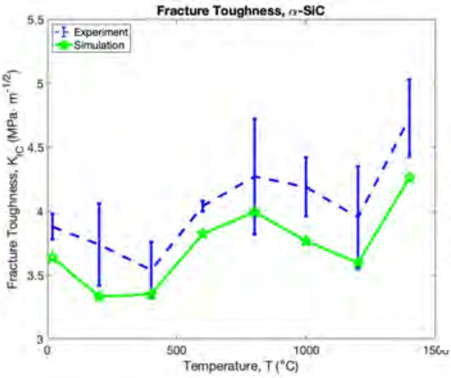


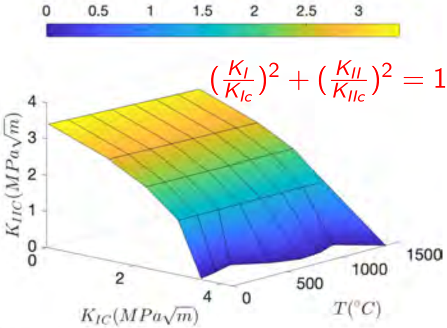
(Sun et al., 2023)

Source: https://doi.org/10.1111/jace.19202

$$\frac{\partial \eta}{\partial t} = -L_\eta\left(\frac{\partial f_{loc}(\xi,\epsilon,T,\eta)}{\partial \eta} - \kappa\eta_{,ii}\right)$$

Damage Criteria of α-SiC



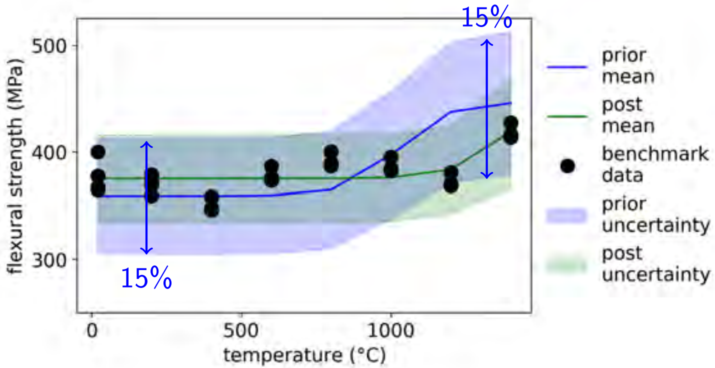


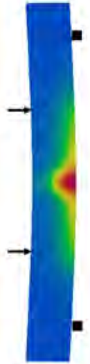
$$\left(\frac{K_I}{K_{Ic}}\right)^2 + \left(\frac{K_{II}}{K_{IIc}}\right)^2 = 1$$

(Sun et al., 2023)

Source: https://doi.org/10.1111/jace.19202

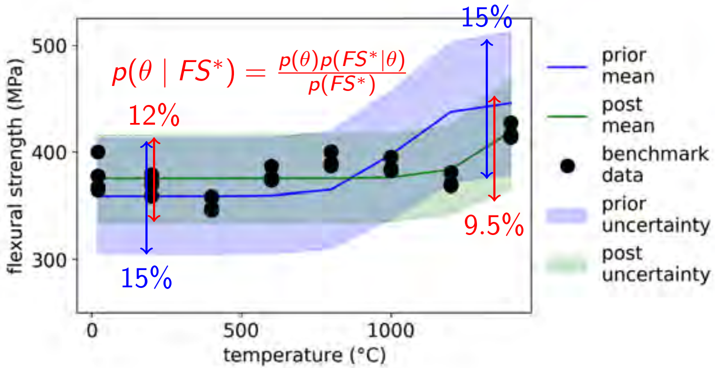
Uncertainty Management with Bayesian Update

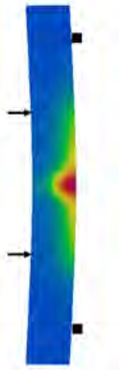




Source: James Chen, University at Buffalo

Uncertainty Management with Bayesian Update





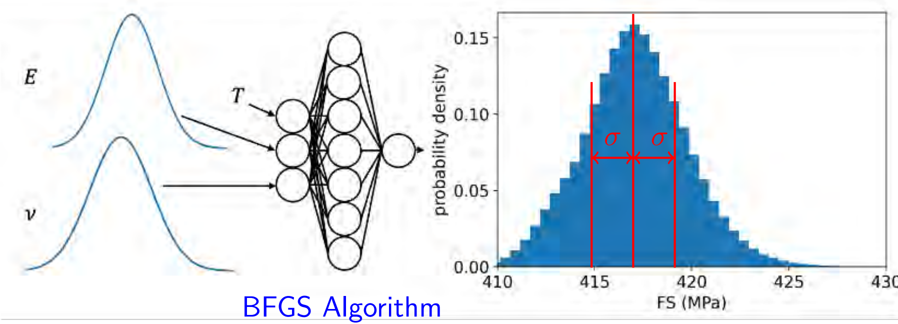
Source: James Chen, University at Buffalo

(Walker, Sun, and Chen, under revision)

Uncertainty-Informed Artificial Neural Network

Forward Uncertainty Sampling

α−SiC at 1400 ^oC



BFGS Algorithm

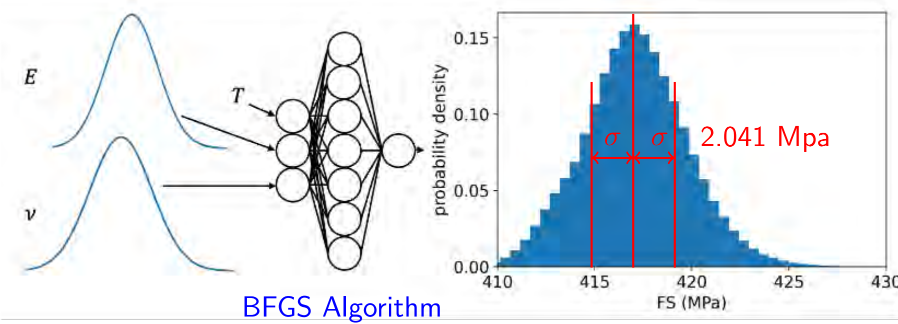
$$y^k = g^{k+1} - g^k$$

Source: James Chen, University at Buffalo

Uncertainty-Informed Artificial Neural Network

Forward Uncertainty Sampling

$\alpha-$SiC at 1400 ^{o}C



BFGS Algorithm

$$y^k = g^{k+1} - g^k$$

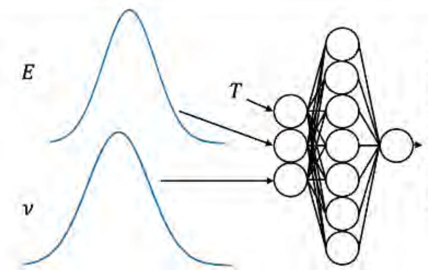
417.03 MPa

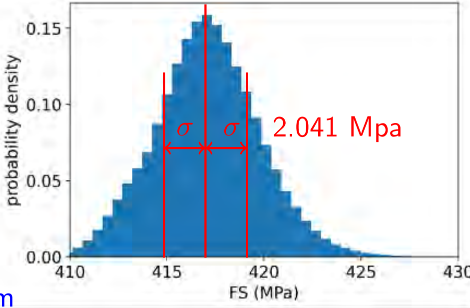
Source: James Chen, University at Buffalo

Uncertainty-Informed Artificial Neural Network

Forward Uncertainty Sampling

$\alpha-$SiC at 1400 ^oC





BFGS Algorithm

$$y^k = g^{k+1} - g^k$$

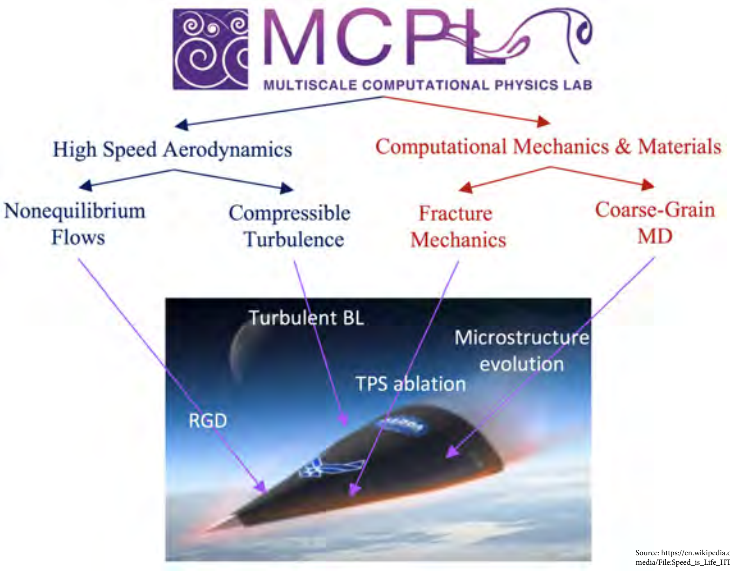
Source: James Chen, University at Buffalo

417.03 MPa

416.84 MPa (Physics-based Simulation)

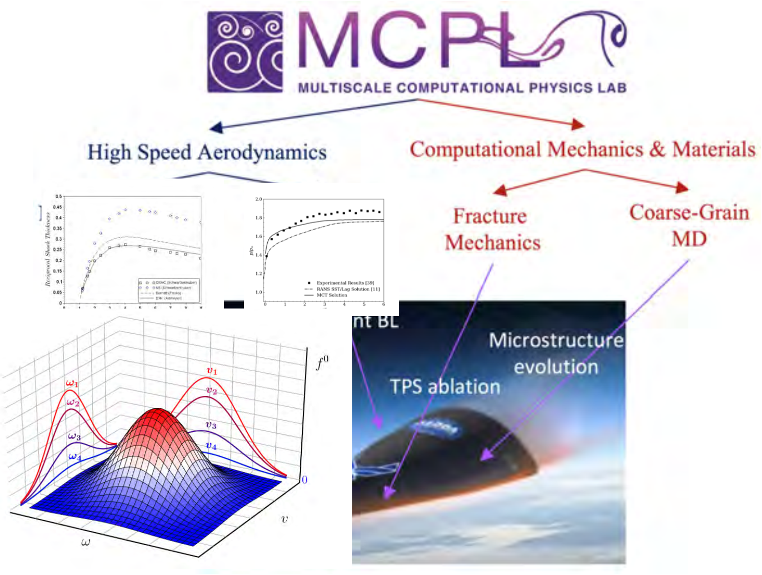
(Walker, Sun, and Chen, accepted for publication)

Design of Hypersonic Vehicles

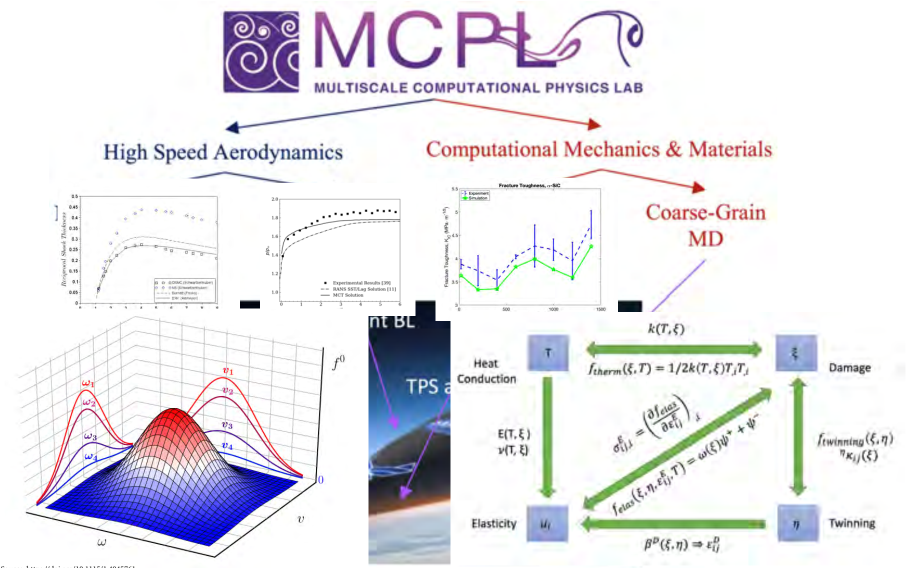


Source: https://en.wikipedia.org/wiki/DARPA_Falcon_Project#/media/File:Speed_is_Life_HTV-2_Reentry_New.jpg

Design of Hypersonic Vehicles



Source: https://doi.org/10.1115/1.4045761



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Acknowledgments

- Dr. Paul DesJardin
- Dr. David Salac
- Dr. Matt McGurn
- Dr. Eric Walker
- Dr. Rozie Zangeneh
- Mae Sementilli
- Jason Sun
- Joe Marziale
- Yu Chen

The relentless pursuit of hypersonic flight

How much new science will it take to design a vehicle that can routinely fly at many times the speed of sound? (I. Leyva)

James Chen; (716) 645-3162; chenjm@buffalo.edu

Source: James Chen, University at Buffalo