# Aerothermal Environments (Convective Heating)

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# Speaker Bio

- B. Tech (Aero. E.): Indian Institute of Technology, Madras, India
- M. S. & Ph. D. (Aero. E.): Iowa State University, Ames, Iowa
  - Dissertation: A new parabolized Navier-Stokes code for chemically reacting flow fields
  - Advisors: Prof. John Tannehill (ISU), (late) John Rakich (NASA ARC), and Joseph Marvin (NASA ARC)
- Worked at NASA Ames Research Center and at National Aerospace Laboratories, India
- Projects: X-33, X-37, Space Shuttle Orbiter (both High AoA aero and Return-To-Flight), TSTO, Entry System Architecture Study, CEV/MPCV/Orion, ADEPT, SIAD, MSL, Mars2020, MSR-SRL, Arc jet & Ground Test, and numerous other projects/proposals (mostly canceled ☺)

# Definition or Problem Statement

- Aerothermal environments mean *temporal & spatial distributions of physical quantities* that are required *for selection, sizing, testing/qualification of materials* that make up the thermal protection system around the atmospheric entry vehicle/capsule

- The required physical quantities, for widely used materials response code, *e.g.*, FIAT, are:
  - Pressure ($p$)
  - Convective film coefficient ($C_H$)
    - Laminar, transitional, or turbulent
    - Hot wall or cold wall
    - Catalycity
    - Smooth wall or rough wall
  - Radiative heat flux ($q_{\text{Rad}}$)
  - Recovery enthalpy ($H_{\text{rec}}$)

- Optional physical quantity of interest is:
  - Surface shear ($\tau$)

$$C_H = \frac{q_{\text{Conv}}}{H_{\text{rec}} - h_w}$$

$$H_{\text{rec}} = H_e + \frac{r-1}{2} u_e^2 \qquad r = Pr^{\varsigma}$$

$$\varsigma = \begin{cases} 1/2 & \text{laminar} \\ 1/3 & \text{turbulent} \end{cases}$$

# Approach

- There are 3 approaches to determine aerothermal environments
  - **Engineering models, or simply scaling laws**
    - Rapid assessment of environments and used in conceptual studies or very early design
    - Almost always for the stagnation point
    - Scaling laws are usually from boundary-layer theory and/or distillation of results from CFD
  - **Modern numerical solutions (read "CFD") of "Navier-Stokes" equations and/or radiation transport equation**
    - No need to invoke a boundary-layer argument; although slower, high-performance computing makes approach competitive
    - Consideration of the full spatial problem, not just the stagnation point; focus would also be on special features (geometric, RCS, antennas, …)
    - Involve loose coupling of flow and radiation solvers, and perhaps materials response solvers as well
    - Results most often feed into engineering models to speed up design
  - **Numerical solutions of "High-Fidelity" models**
    - Would be extremely slow and resource intensive
    - Tight coupling of all models, i.e., consideration of all time/length scales of multiple models – flow, radiation, materials, …
    - Results would be most useful in evaluating margins in the final design

# General Ideas (1/2)

- The entry problem is all about transformation of energy between thermal, chemical, radiative, and kinetic and energy management (thermal protection)

- Total enthalpy ($H$) of the gas is the “energy” that is referred to above

$$H = \overbrace{\sum_{s=1}^{n_s} Y_s h_s(T)}^{\text{Thermal}} + \overbrace{\sum_{s=1}^{n_s} Y_s \Delta_f^o H_s}^{\text{Chemical}} + \overbrace{\frac{1}{2}\boldsymbol{u}\cdot\boldsymbol{u}}^{\text{Kinetic}}$$

$$\begin{cases} Y_s & \text{mass fraction of } s \\ \Delta_f^o H_s & \text{enthalpy of formation of } s \text{ at STP} \\ h_s & \text{thermal enthalpy of } s \\ T & \text{temperature} \\ \boldsymbol{u} & \text{velocity vector} \end{cases}$$

- Notes:
  1. Usually, thermal enthalpy content in the ambient gas is negligibly small compared to the kinetic energy and chemical energy except for the case of $CO_2$ atmospheres (Venus and Mars) – $CO_2$ has $\Delta_f^o H_s \cong -9$ MJ/kg
  2. Atmospheric entry – ambient gas is (bow) shock heated, high KE in the freestream is reduced post-shock & chemical and thermal energy is increased; chemical energy is recovered at the surface
  3. Arc jet testing – low KE ambient gas is arc heated; dissociated gas acquires KE in a convergent-divergent nozzle, but reduces thermal energy due to expansion; KE reduced again behind bow shock around the test article

# General Ideas (2/2)

- Energy conservation equation for a steady flow

$$\boldsymbol{\nabla}\cdot(\rho\boldsymbol{u}H) = \overbrace{\boldsymbol{\nabla}\cdot\overbrace{[\kappa\boldsymbol{\nabla}T]}^{\text{Thermal}} + \boldsymbol{\nabla}\cdot\overbrace{\left(\sum_{s=1}^{n_s}\left[h_s(T)+\Delta_f^{\mathrm{o}}H_s\right]\rho\mathcal{D}\boldsymbol{\nabla}Y_s\right)}^{\text{Chemical}}}^{\text{Diffusive}} + \overbrace{\int q_{\mathrm{rad}}^{\nu}}^{\text{Radiative}}$$

  - A constant amount of enthalpy can be added or subtracted from above equation without changing the balance
    - Useful idea if $\Delta_f^{\mathrm{o}}H_s$ of dominant species is negative, *e.g.*, $CO_2$ has $\Delta_f^{\mathrm{o}}H_s \cong -9$ MJ/kg
  - IF viscous terms are small (high Reynolds number) AND there is no radiative heating, then

$$\boldsymbol{\nabla}\cdot(\rho\boldsymbol{u}H) = 0 \quad \Longrightarrow \quad \rho\boldsymbol{u}\cdot\boldsymbol{\nabla}H = 0$$

    - Total enthalpy is a constant – a result that is useful in defining the boundary layer edge
  - IF viscous terms are small (high Reynolds number) AND there is radiative heating, then

$$\boldsymbol{\nabla}\cdot(\rho\boldsymbol{u}H) = \int q_{\mathrm{rad}}^{\nu}$$

    - Total enthalpy is *not* a constant and might have to consider coupling radiation and flow

# Need Knowledge Of…

- Destination
  - Estimate of entry kinetic energy and comparison with chemical bond energies
- Entry vehicle geometry
  - Shape (aerodynamic drag) and size (drag area), which along with mass => ballistic coefficient
- Trajectory (or trajectories)
  - Dispersions – either due to entry state or atmospheric uncertainties and/or aerodynamics
- Computing tools
  - Flow and radiation field codes
  - Materials thermal response codes
- Scaling laws
  - Pressure
  - Convective heat flux
- Examples

# Destinations

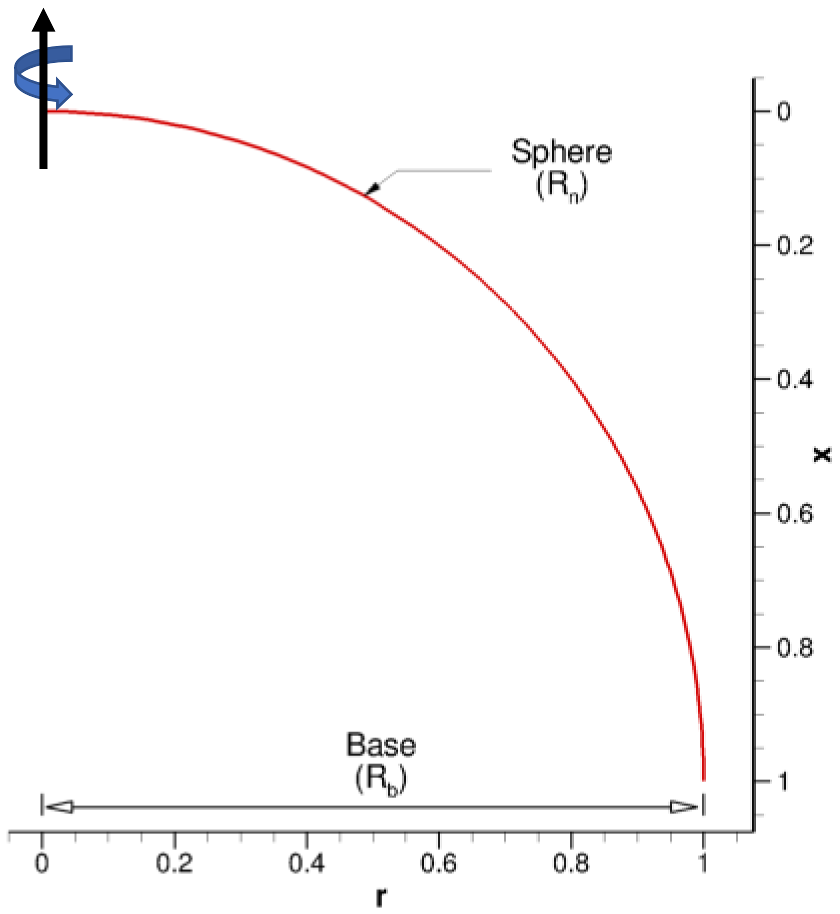
<table>
<tr><th>Destination</th><th>Esc. Vel. km.s$^{-1}$</th><th>Rot. Vel. km.s$^{-1}$</th><th>Ent. Vel. km.s$^{-1}$</th><th>Rel. Vel. km.s$^{-1}$</th><th>Ref. KE MJ/kg</th><th>Composition (by vol.)</th><th>BDE MJ/kg</th><th>Ion. potential MJ/kg</th></tr>
<tr><td>Saturn</td><td>36.09</td><td>9.54</td><td>37.54</td><td>28</td><td>392</td><td>95:5 ($H_2$:He)</td><td rowspan="8">$O_2$: 15.6<br>NO: 21.0<br>$C_2$: 25.2<br>$CH_4$: 25.9<br>$CO_2$: 28.7<br>CN: 28.8<br>$H_2$: 31.1<br>$N_2$: 33.7<br>CO: 38.4</td><td rowspan="8">NO: 29.8<br>$CO_2$: 30.2<br>$O_2$: 36.4<br>Ar: 38.1<br>$C_2$: 47.7<br>CO: 48.3<br>CN: 51.6<br>$N_2$: 53.7<br>CH: 78.9<br>O: 82.1<br>C: 90.5<br>N: 100.2<br>He: 592.7<br>$H_2$: 738.4<br>H: 1302</td></tr>
<tr><td>Jupiter</td><td>60.2</td><td>12.29</td><td>59.89</td><td>47.6</td><td>1133</td><td>90:10 ($H_2$:He)</td></tr>
<tr><td>Uranus</td><td>21.38</td><td>-2.57</td><td>22.57</td><td>20.0</td><td>200</td><td>85:15 ($H_2$:He)</td></tr>
<tr><td>Neptune</td><td>23.56</td><td>2.67</td><td>27.67</td><td>25.0</td><td>313</td><td>80:20 ($H_2$:He)</td></tr>
<tr><td>Titan</td><td>2.64</td><td>0.01</td><td>8.01</td><td>8.0</td><td>32</td><td>98:2 ($N_2$:$CH_4$)</td></tr>
<tr><td>Earth</td><td>11.19</td><td>0.46</td><td>13.46</td><td>13.0</td><td>85</td><td>79:21 ($N_2$:$O_2$)</td></tr>
<tr><td>Mars</td><td>5.03</td><td>0.24</td><td>6</td><td>5.76</td><td>17</td><td>95.5:4.5 ($CO_2$:$N_2$)</td></tr>
<tr><td>Venus</td><td>10.36</td><td>0</td><td>11.5</td><td>11.5</td><td>66</td><td>96:5:3.5 ($CO_2$:$N_2$)</td></tr>
</table>

- Only 6 elements – C, H, O, N, He, Ar, free electrons (e-), and compounds made up of these elements need to be considered
- Bond dissociation enthalpy (BDE) is the *average* energy required to break a molecule into its constituent elements

# Geometries (1/5)

**TYPE 1 GEOMETRY**

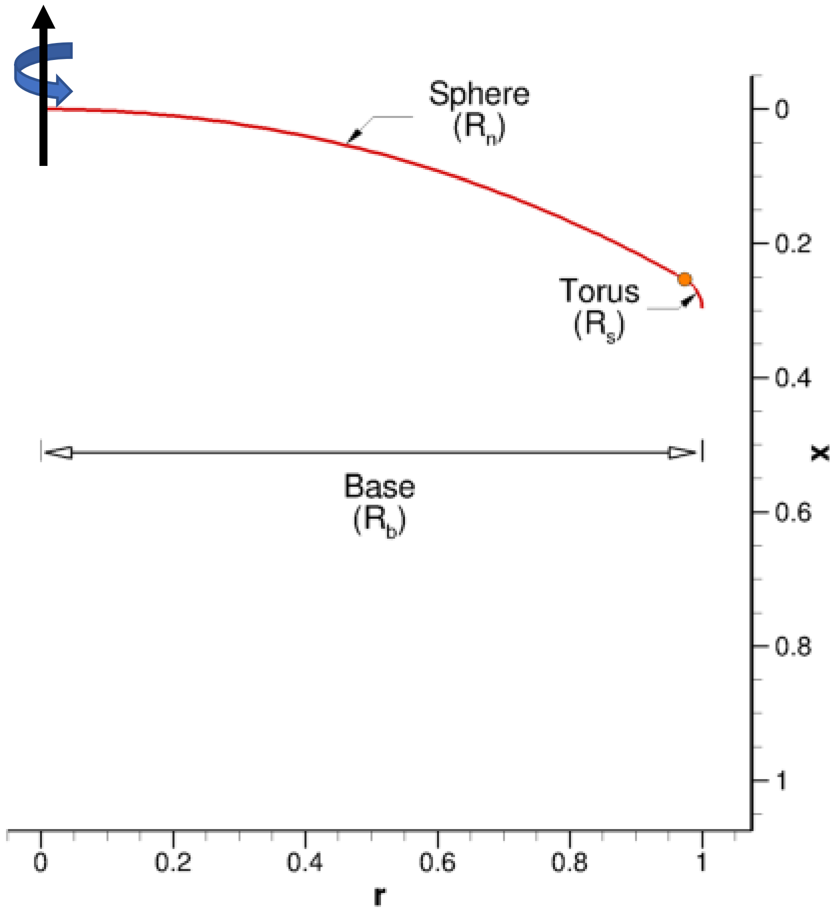
**[Generatrix: No Discontinuity in Curvature]** $\kappa(r) = |d^2x/dr^2|/[1 + (dx/dr)^2]^{3/2}$




- Any conic section will have smooth curvature
- 2 parameters $(R_b, R_n)$ needed for analytical description
  - For a hemisphere: $R_b = R_n$
- A hemisphere is the simplest geometry
- Basis for stagnation point theory
- Reference geometry for arc jet calorimetry
- Only one known instance of atmospheric entry – Mirka/ [DLR/1997]

# Geometries (2/5)

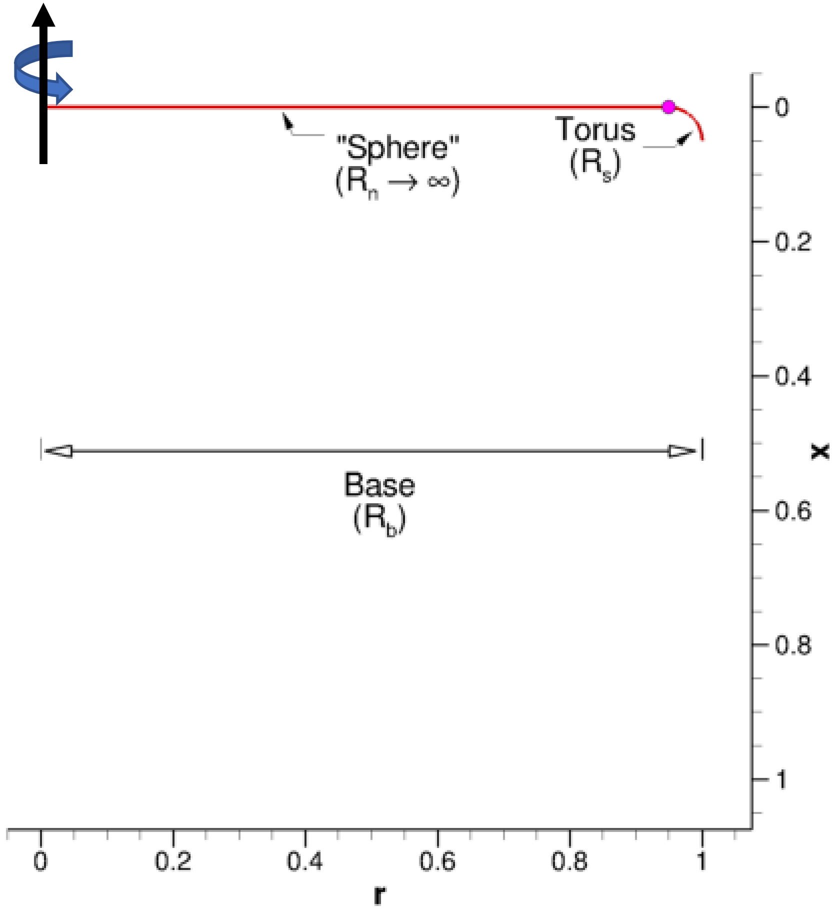
**TYPE 2 GEOMETRY**
**[Generatrix: 1 Discontinuity in Curvature]**




- Any conic section will have smooth curvature
- 3 parameters ($R_b, R_n, R_s$) needed for analytical description
  - For an iso-q: $R_n = 2R_b$
- An iso-q geometry is the preferred geometry for materials testing in an arc jet
- The spherical section shape is almost exclusively used for human missions and almost always at angle of attack (lifting entry)
  - Mercury (1950s), Gemini (1960s), Apollo (1970s), Orion (2014), …

# Geometries (3/5)

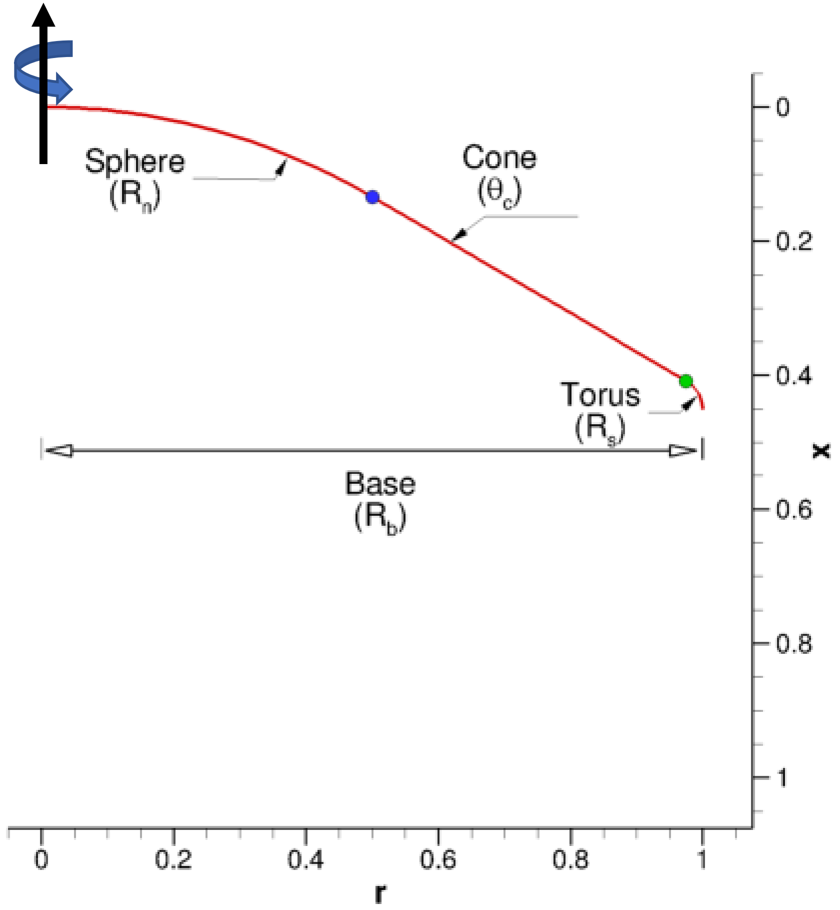
**TYPE 2 GEOMETRY**
**[Generatrix: 1 Discontinuity in Curvature]**




- Strictly, only 2 parameters ($R_b, R_s$) needed for analytical description
  - $R_n \longrightarrow \infty$
- A flat-faced cylinder geometry is also an often-used geometry for materials testing in an arc jet
  - Stagnation region experiences “uniform” pressure and heat flux (at low shear) over the test face
- Never used in flight (and hopefully, never will be ☺)

# Geometries (4/5)

**TYPE 3 GEOMETRY**
**[Generatrix: 2 Discontinuities in Curvature]**




- 4 parameters $(R_b, R_n, R_s, \theta_c)$ needed for analytical description

- Standard geometry for planetary atmosphere entry
  - 45° sphere-cone is preferred for its dyn. stability
    - Pioneer-Venus, Galileo, Haybusa 1 & 2, …
  - 55° sphere-cone one-off Earth entry
    - PAET
  - 60° sphere-cone is preferred for Earth return missions
    - Genesis, Stardust, OSIRIS-REx, …
  - 70° sphere-cone is preferred for Mars entries
    - Viking, Pathfinder, MER, MSL, Mars2020, …
    - Entries are almost always lifting (low L/D)

# Geometries (5/5)

- Two additional geometry types are:
  - Type 4 – Asymmetric blunt bodies with bilateral (pitch) symmetry
    - Geometry can be described analytically
    - No flight heritage, although AFE (Aeroassist Flight Experiment) came close
    - Note: A rotationally symmetric geometry with added features such as a trim tab would fall in this category
  - Type 5 – Winged geometry or Ellipsled geometry with bilateral (pitch) symmetry, *e.g.*, Space Shuttle Orbiter
    - Complex geometry & control system
    - L/D ≈ 1
    - Good flight heritage for LEO entries. Maybe bright future for Mars entries?

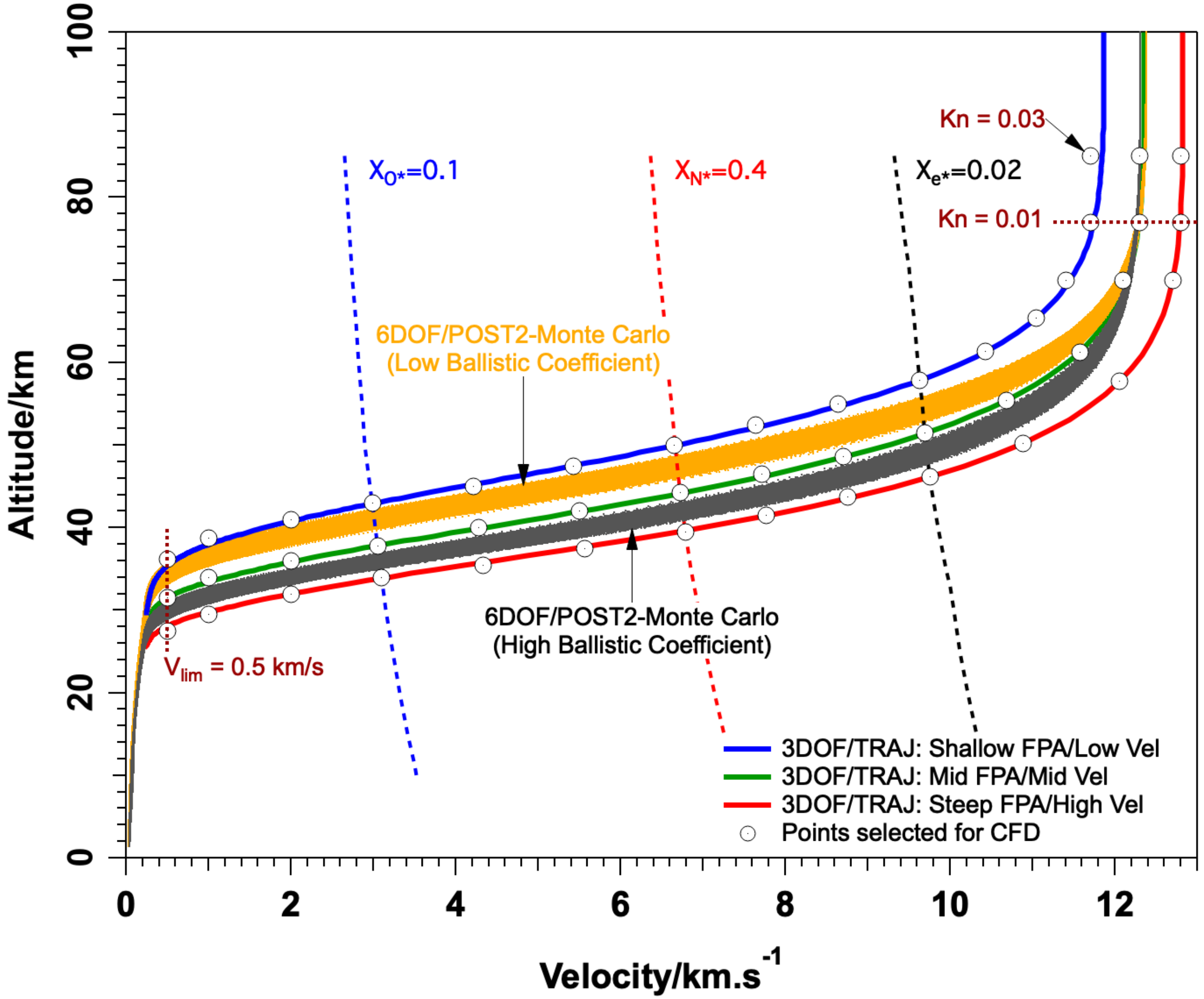
- Geometries that can be developed analytically allow for systematic exploration of impact of geometric parameters on aerothermal environments
  - Opens up the case for traceability of ground-test environments to flight?

- Choice of geometry for the entry capsule/vehicle depends on drag requirements and dyn. stability

# Trajectories (1/2)

- Simple view of atmospheric entry is that the atmospheric density reduces the velocity magnitude while gravity turns the velocity vector
- For the restrictive case of no change in flight path angle *and* an isothermal atmosphere:
  - The product $\rho_\infty^a V_\infty^b$ reaches a maximum when $V_\infty = V_E \exp\left(-\frac{a}{b}\right)$
    - Peak convective heating ($\propto \rho_\infty^{0.5} V_\infty^3$) occurs when $V_\infty = V_E \exp\left(-\frac{1}{6}\right) \cong 0.85 V_E$
    - Peak stagnation pressure ($\propto \rho_\infty V_\infty^2$) occurs when $V_\infty = V_E \exp\left(-\frac{1}{2}\right) \cong 0.61 V_E$
  - Peak radiative heating depends on dominant wavelength range
    - If short wavelength (UV) dominant, then peak radiative heating occurs *before* peak convective heating
    - If long wavelength (IR) dominant, then ($2^{nd}$?) peak radiative heating occurs *after* peak dynamic pressure
- For a single flight trajectory time histories of relevant physical quantities rather easy to compute
  - Discretize the heat pulse and stagnation pressure times histories for flow computations (continuum or other)
- For multiple trajectories (including atmospheric dispersions, aerodynamic uncertainties, uncertainties in entry state, …) need to delink trajectories from environments
  - Tacit assumption is that there isn't substantial shape change (due to ablation mass loss)

# Trajectories (2/2): Design Space




- Discretize the density (equiv. altitude)-velocity space as desired for flow computations
  - For lifting entries, *each point* in the $\rho_\infty$-$V_\infty$ space could have several angles of attack!
- Impose upper and lower limits $\rho_\infty$-$V_\infty$ space
  - Upper limit – Knudsen number cutoff
    - $Kn = \lambda/R_n \leq 0.01$
    - $\lambda$ is the mean free path & $R_n$ is a characteristic length (=nose radius)
    - Limit value of 0.01 is subjective, but represents a limit up to which the continuum approximation holds
  - Lower limit – Mach number cutoff ($M_\infty$ > 1?)
    - $M_\infty > 1$ is also subjective and depends on the choice of flow solver [how best to handle diminishing compressibility of flow medium]
- Additional guides provided by *equilibrium* estimates of post-shock chemical composition

# Computing Tools

- Volume grid generation software (usually commercial)
  - Pointwise, Link3D, GridPro, …
  - For simple geometries (with rotational symmetry), CAPSULE_GRID developed by D. Saunders (Ames) is sufficient
- High-temperature flow field computations
  - DPLR, LAURA, FUN3D, US3D, …
  - BLAYER to extract boundary-layer data from computed flow field
- Radiation field computations
  - NEQAIR, HARA, …
- Materials thermal response computations
  - FIAT, TITAN, PATO, …
- The tools could be used standalone, or coupled together loosely
- If there is substantial mass loss due to ablation, then trajectory codes (POST2, TRAJ, …) would have to be coupled too
  - Jovian entry would be a case in point

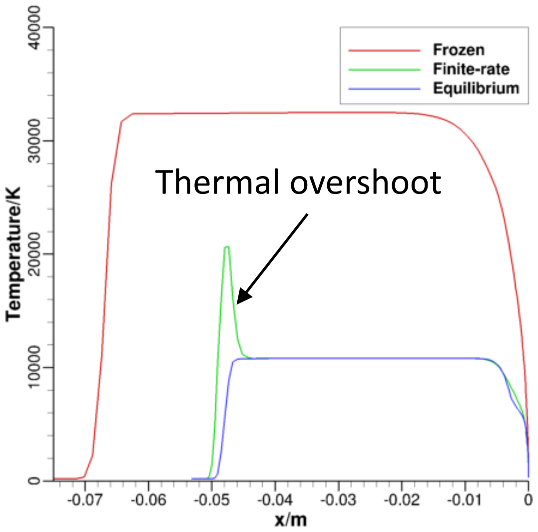
# Features of High-Temperature Flow Field Codes

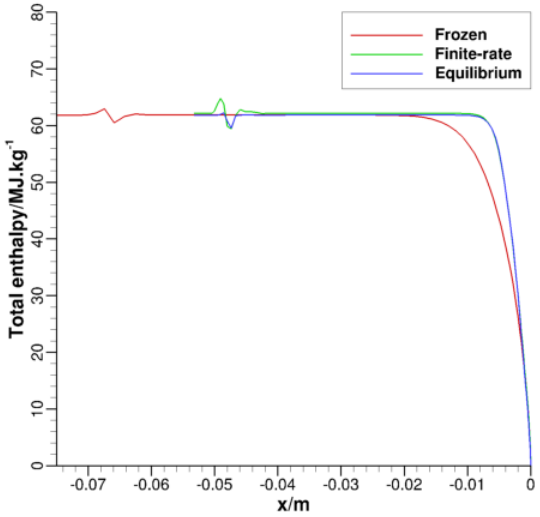
- Chemistry
  - Reaction mechanism & rates
- Thermodynamic properties – curve fits or analytical expressions
  - Atomic species and their ions (if necessary) – Translational energy (continuous) & electronic energy (discrete/quantal)
  - Molecular species and their ions (if necessary) – Translational energy (continuous), rotational, vibrational, & electronic energy (discrete/quantal)
  - Free electrons (if necessary)
- Transport properties – curve fits or analytical expressions
  - Coefficients of mass diffusion, viscosity, and thermal conductivity – collision integrals of pairs of species
- Mixing rules for mixture properties
- Models for turbulent transport of mass, momentum, and energy, perhaps including surface roughness
  - Baldwin-Lomax, SST, or Spalart-Allmaras, …
- Gas-Surface Interaction – “catalysis”
  - Baldwin-Lomax, SST, or Spalart-Allmaras, …
- Blowing boundary conditions to consider injection of pyrolysis products from TPS material

# Wall Boundary Conditions

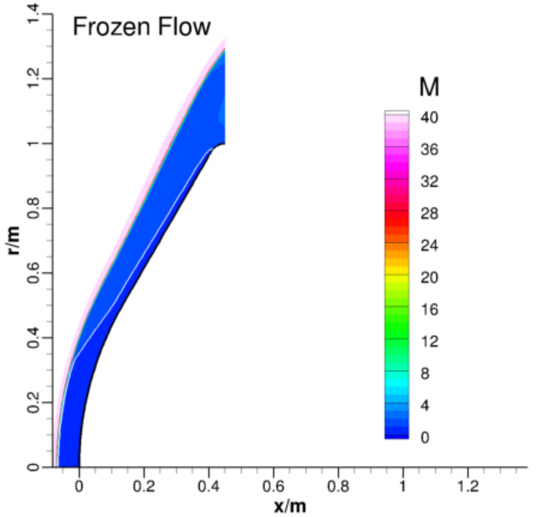
- Three types of walls
  - Cold wall – wall temperature fixed at 298 K (usually), but species chemistry allowed to float
  - Hot wall – wall temperature AND species chemistry allowed to float, usually conduction into the material is ignored
    $q_{\text{thermal}} + q_{\text{chemical}} = \epsilon_w \sigma \left(T_{\text{wall}}^4 - T_{\text{sink}}^4\right)$ where $\epsilon_w = \epsilon(T)$ is the emissivity and $\sigma$ is the Stefan-Boltzmann constant
  - What is the wall composition ($Y_{s,w}$)?
    - Atoms are allowed to recombine (with consequent heat release), but gradients of mass of molecular species are set to zero
      1. $\mathrm{O_2 + M \leftarrow O + O + M}$ $\quad [\Delta H_r^{\mathrm{o}} = -498.458\,\frac{\mathrm{kJ}}{\mathrm{mol}}]$
      2. $\mathrm{N_2 + M \leftarrow N + N + M}$ $\quad [\Delta H_r^{\mathrm{o}} = -944.87\,\frac{\mathrm{kJ}}{\mathrm{mol}}]$
      3. $\frac{\partial}{\partial n} Y_s = 0, s \neq \mathrm{N\ or\ O}$
  - For either kind of wall, atom recombination reactions are modeled as 1st-order *gas-phase* reactions, usually without being tempered by the corresponding equilibrium constant
    - Percentage completion of recombination reaction is controlled by the efficiency parameter $\gamma$; $\gamma = 1$ is a fully "catalytic" wall and $\gamma = 0$ is a "noncatalytic wall"
    - The efficiencies could be temperature dependent and would be different for different materials
  - Equilibrium wall – wall composition is determined by $p_{\text{wall}}$ and $T_{\text{wall}}$ (fixed or floating)
    - Works well in most cases except for $CO_2$ flow over a cold wall – CO + O has a significant thermal barrier

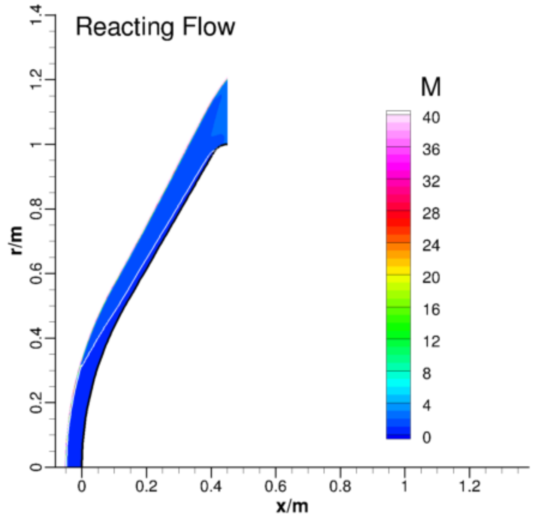
# Warm up Exercise 1

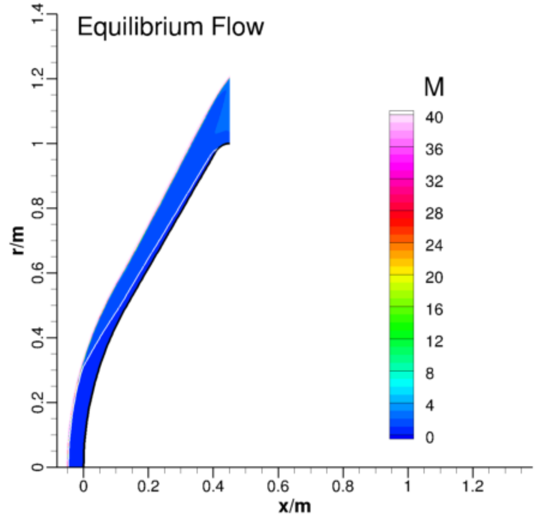


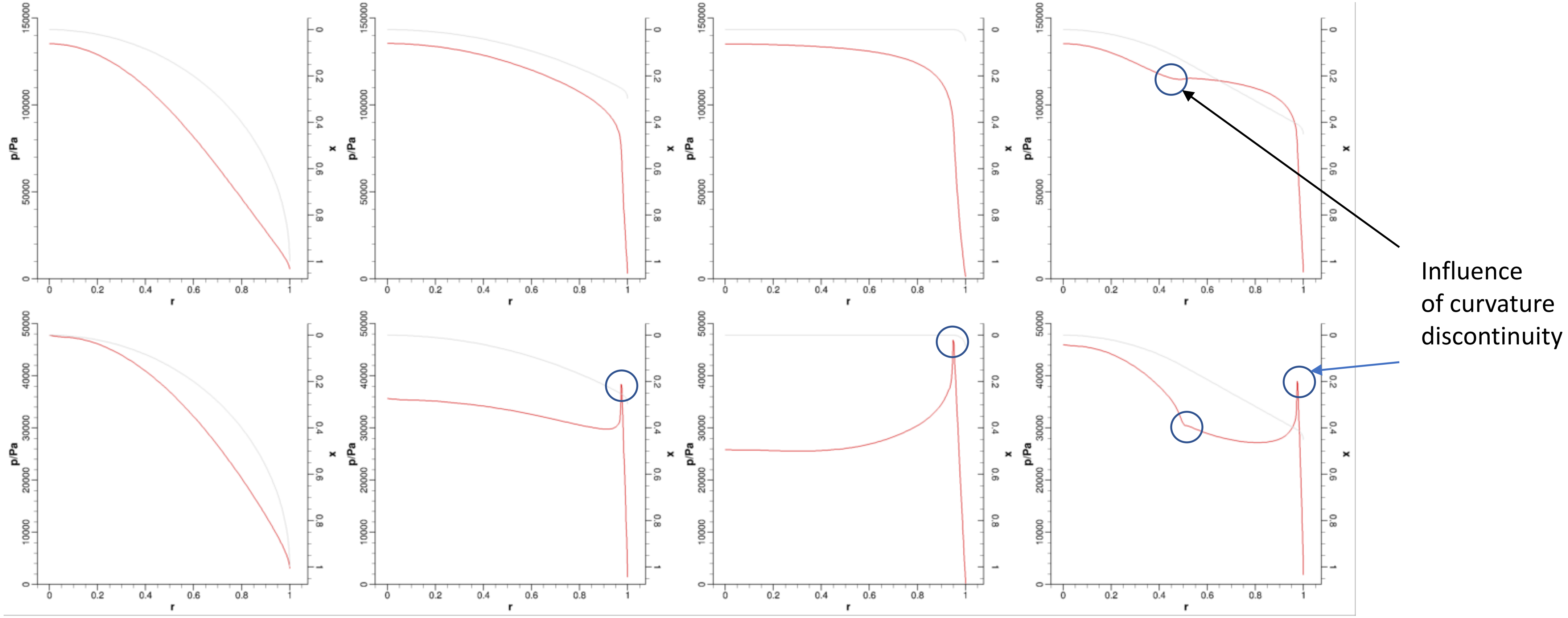

- $V_\infty$ = 11.1 km.s$^{-1}$, $\rho_\infty$ = 1.18 10$^{-4}$ kg.m$^{-3}$, $T_\infty$ = 200 K
- 11-sp air model, Park 90 mechanism & rates
- Temperature overshoot for rate chemistry case is the one of primary interest – implications to radiative heating



# Warm up Exercise 2




- $V_\infty$ = 1.1 km.s$^{-1}$, $\rho_\infty$ = 0.118 kg.m$^{-3}$, $T_\infty$ = 57.5 K
- Perfect air, thermodynamic properties vary with temperature; Sutherland's law & constant Prandtl #
- The sphere-section and flat-faced cylinder shapes are heavily used in materials testing; the hemisphere is used in calorimetry only

# Scaling Laws

- Simply functional relations between physical quantities, such as pressure, heat flux, … and ambient atmospheric properties, vehicle speed, and size, i.e., power laws of the type

$$R_{\mathrm{aerothermal}}^{a}\rho_{\infty}^{b}\,V_{\infty}^{c}$$

  - $R_{\mathrm{aerothermal}}$ is a characteristic length scale/aerothermal radius/effective radius
  - $\rho_{\infty}$ is ambient atmospheric density
  - $V_{\infty}$ is flight speed

- Require these for pressure, convective heat flux, radiative heat flux, and enthalpy

- Focus on the stagnation point because there is good theoretical considerations for this

# Stagnation Point Environments: Pressure

- Scaling law for pressure at the stagnation point

$$p_{\text{stag}} = f \rho_\infty V_\infty^2 \qquad 0.9 < f < 1$$

- Modified Newtonian impact theory is the basis for this scaling law
  - Newtonian impact theory is strictly for $M_\infty \rightarrow \infty$ and $\gamma \rightarrow 1$, which gives a max pressure coefficient of 2
  - Modification to impact theory is necessary for finite $M_\infty$ and $\gamma > 1$

- There is no geometric scale in this law and holds for a blunt body of any shape or size

# Stagnation Point Environments: Conv. Ht. Flux

- Scaling law for convective heat flux

$$q_{\text{stag}} = K \frac{\sqrt{p_{\text{stag}}}}{\sqrt{R_{\text{aerothermal}}}} \left(H_{\text{edge}} - h_{\text{wall}}\right)$$

- Simplified version of the Fay-Riddell correlation
  - Assumes 1st-order boundary-layer theory, *i.e.*, thin shear layer attached to the wall is driven by the inviscid streamwise pressure gradient
  - Fay-Riddell correlation developed from boundary-layer computations with either frozen flow or equilibrium flow AND Sutherland's law for viscosity
  - Correlation revisited by Zoby, Deiwert-Marvin, and Sutton-Graves in the 1960s-1970s – still in use today!

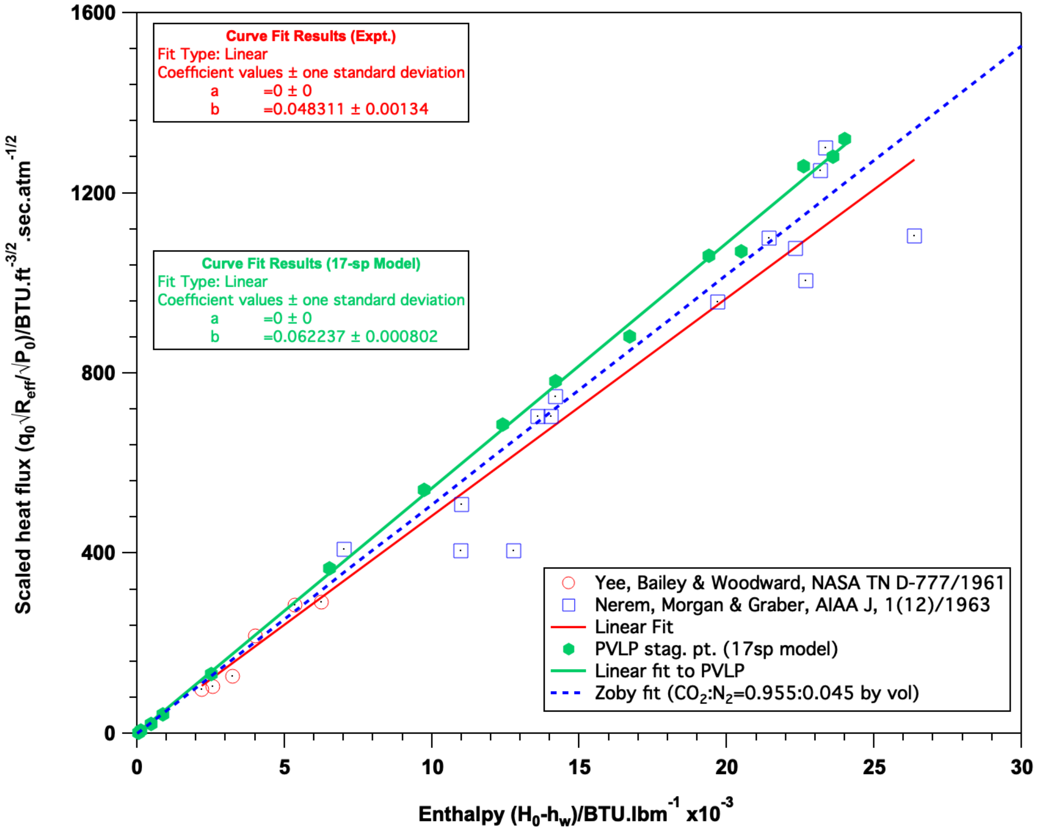
- There IS a geometric scale in this law

- Requires estimate of the enthalpy difference that drives heating

- $K$ is constant, but value depends on the gas mixture AND is dependent on the choice of transport property model

# Stagnation Point Environments: Conv. Ht. Flux

- Example for $CO_2$ shown below




- The experimental data and fits shown (red line and dashed blue line) are for pure $CO_2$, the flow computations are for a Venus mixture ($CO_2$:$N_2$=0.965:0.035, by volume)

# Stagnation Point Environments: Conv. Ht. Flux

- Scaling law for convective film coefficient is then

$$C_H = \frac{q_{\text{stag}}}{\left(H_{\text{edge}} - h_{\text{wall}}\right)} = K\,\frac{\sqrt{p_{\text{stag}}}}{\sqrt{R_{\text{aerothermal}}}}$$

- In the 1st approximation, film coefficient is independent of wall type – cold *vs.* hot – and depends solely on stagnation pressure and the aerothermal length scale

- Convective film coefficient peaks when stagnation pressure peaks

- The edge enthalpy required by the materials response solver is simply the freestream total enthalpy
  - Assumption valid if boundary-layer thickness is significantly smaller than the shock-layer thickness
  - At the stagnation point there is no distinction between edge enthalpy and recovery enthalpy

$$H_e = H_\infty = \overbrace{\sum_{s=1}^{n_s} Y_{s,\infty} h_s(T_\infty)}^{\text{Thermal}} + \overbrace{\sum_{s=1}^{n_s} Y_{s,\infty} \Delta_f^{\text{o}} H_s}^{\text{Chemical}} + \overbrace{\frac{1}{2}\boldsymbol{u}_\infty \cdot \boldsymbol{u}_\infty}^{\text{Kinetic}}$$

# Stagnation Point Environments: Conv. Ht. Flux

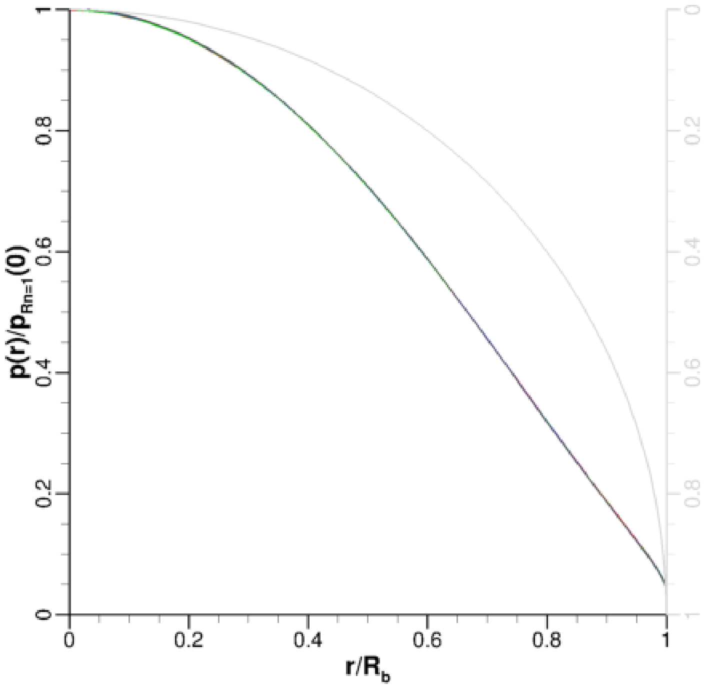
- The aerothermal radius for an arbitrary blunt body has to be determined relative to a hemisphere
  - The aerothermal radius for a hemisphere is its geometric radius $R_{\mathrm{Hemi}}$
  - If the heat flux at the stagnation point of the arbitrary blunt body is known (from experiment or CFD), then

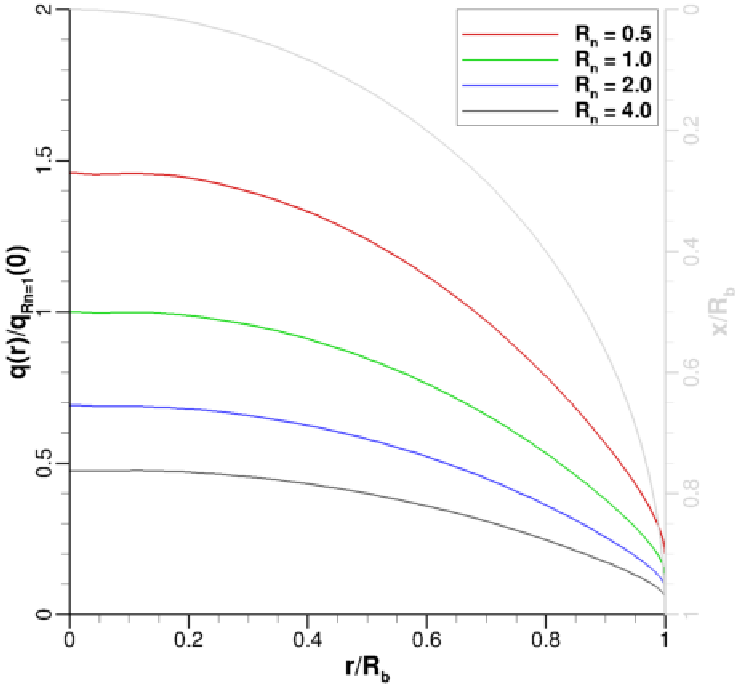
$$\frac{q_{\mathrm{stag,BB}}}{q_{\mathrm{stag,Hemi}}} = \frac{\sqrt{R_{\mathrm{Hemi}}}}{\sqrt{R_{\mathrm{BB}}}} \Longrightarrow R_{\mathrm{BB}} = \left(\frac{q_{\mathrm{stag,Hemi}}}{q_{\mathrm{stag,BB}}}\right)^2 R_{\mathrm{Hemi}}$$

- Such computations have been performed by Zoby in the 1960s and used till today in arc jet testing
- Essentially, the arbitrary blunt body is transformed into an equivalent hemisphere of radius $R_{\mathrm{BB}}$
  - The argument is based on the equivalence of streamwise velocity gradient at the stagnation points of the two bodies

# Stagnation Point Environments: Conv. Ht. Flux

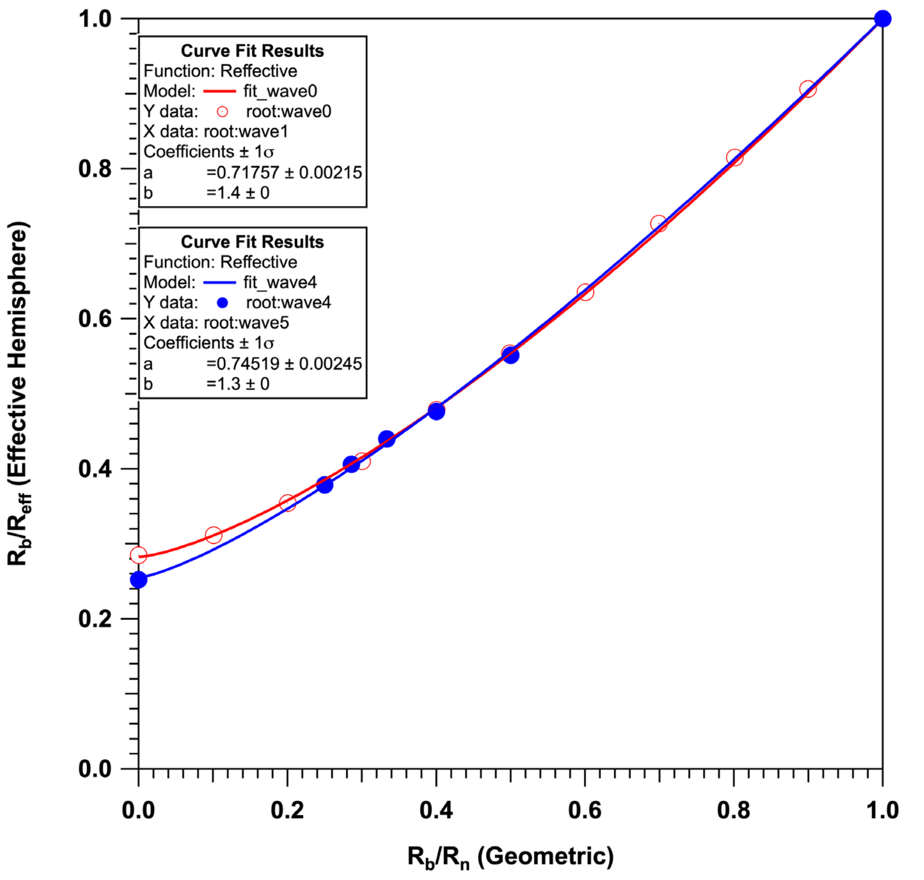
- That convective heat flux goes at the inverse square root of the aerothermal radius (same as the geometric radius in the case of a hemisphere) is shown below



# Stagnation Point Environments: Conv. Ht. Flux

- An example is shown below
  - Note: Curves shown here are for a single & fixed value of corner radius (torus section); for each corner radius, there is a curve
  - The smaller the corner radius, the smaller the “effective radius”



# Stagnation Point Environments: Conv. Ht. Flux

- The constant K for various gas mixtures is given in the table below
  - Values are based on newer CFD computations with "improved" transport data

| Planet | $K_{\text{CFD}}$ (kg.s$^{-1}$.m$^{-3/2}$.atm$^{-1/2}$) | $K_{\text{Sutton-Graves}}$ (kg.s$^{-1}$.m$^{-3/2}$.atm$^{-1/2}$) | Source |
|---|---|---|---|
| Earth | 0.1439 | 0.1113 | Hayabusa-2 trajectory |
| Mars, Venus | 0.1467 | 0.1210[a] | PVLP trajectory |
| Gas/Ice Giants | 0.0592 | 0.0454[a] | FAR presentation |
| Titan | ?[c] | 0.1112 | |

[a]Pure $CO_2$ value quoted from Sutton and Graves report.

[b]Composition assumed is 85% $H_2$ and 15% He (by volume)

[c]Probably okay to assume this value is the same as that for Earth?

# Stagnation Point Environments: Rad. Ht. Flux

- The scaling law for radiation at the stagnation point must be developed from radiative heating computations
  - Radiative heating is extremely important for Jovian entry and hyperbolic Earth entries
  - Known expressions are from the work of Tauber and Sutton, and Johnston & Brandis
  - Computations for a sphere indicate that radiative heat flux is proportional to $\sqrt{R_{\mathrm{aerothermal}}}$ the larger the body radius, the larger the radiative heat flux at the stagnation point
  - An *equilibrium* scaling law would be a good start to see if the aerothermal radius from convective heating is the same for radiative heating

Details to follow in Brett Cruden's companion presentation

# Stagnation Point Environments: Summary

- For the stagnation point of a blunt body, the four scaling laws are

$$p_{\text{stag}} = f \rho_\infty V_\infty^2 \qquad 0.9 < f < 1$$

$$C_H = K \frac{\sqrt{p_{\text{stag}}}}{\sqrt{R_{\text{aerothermal}}}}$$

$$H_e = \sum_{s=1}^{n_s} Y_{s,\infty} h_s(T_\infty) + \sum_{s=1}^{n_s} Y_{s,\infty} \Delta_f^o H_s + \frac{1}{2} \boldsymbol{u}_\infty \cdot \boldsymbol{u}_\infty$$

$$q_{\text{rad}} \propto \sqrt{R_{\text{aerothermal}}} \rho_\infty^b V_\infty^c \quad b, c = ?$$

We have accomplished what we set out to do, at least for the stagnation point. What about 3D?

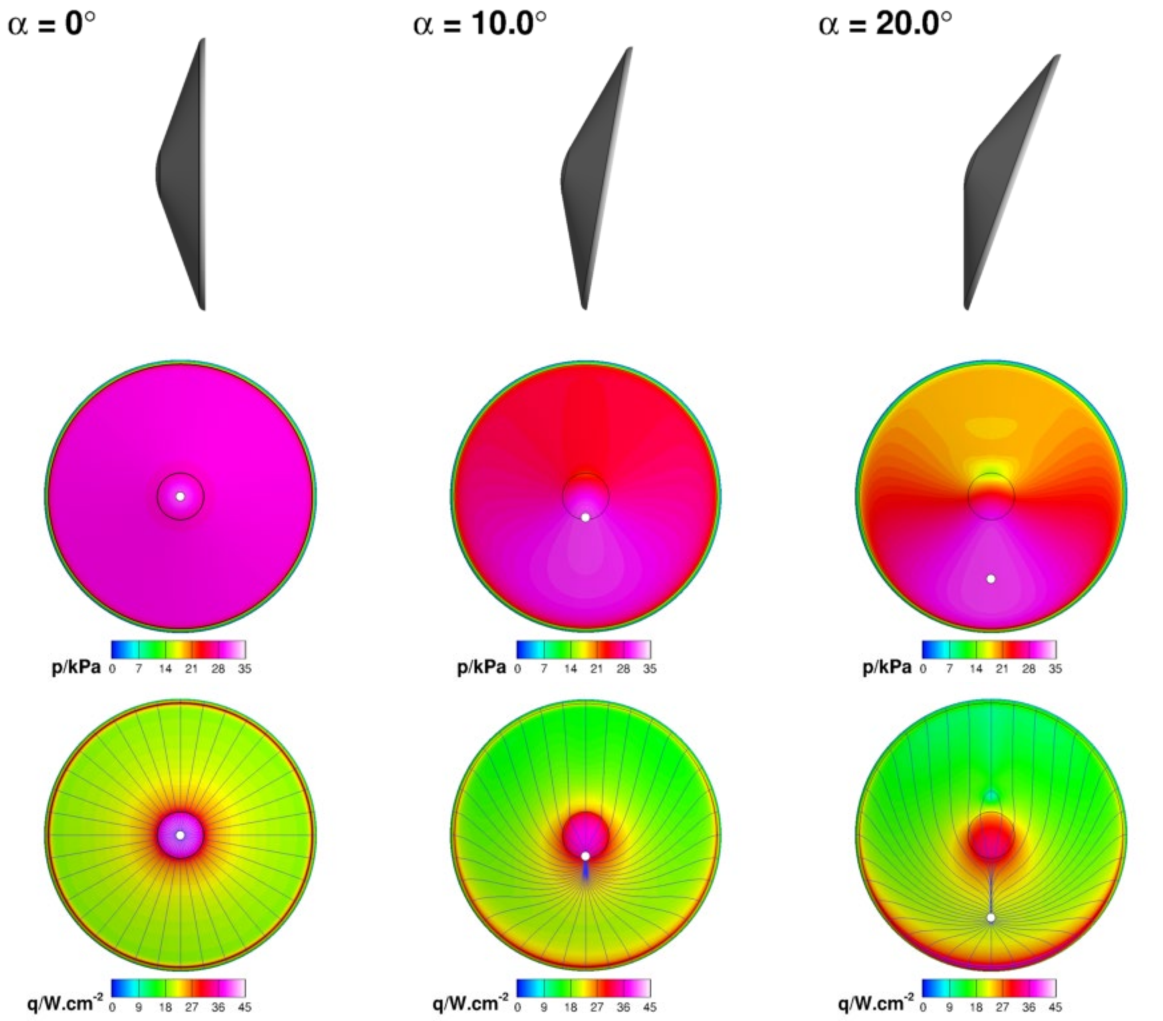
# 3D Environments

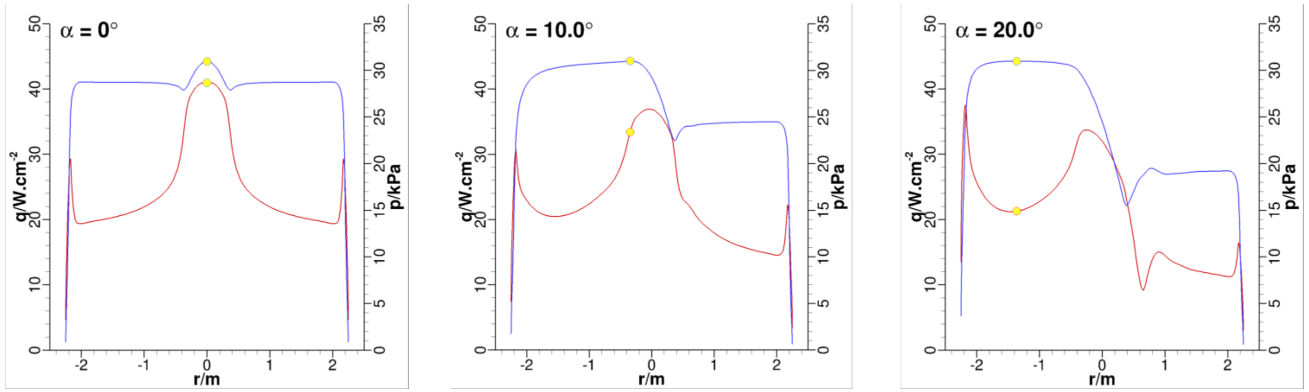
- Problem is likely tractable for laminar flows, but there is no theoretical guide for turbulent flow
  - Aerothermal radius will now depend on angle of attack because the stagnation point will shift from the spherical nose cap at $\alpha = 0°$ to the conical frustum for $\alpha > \alpha_{crit}$

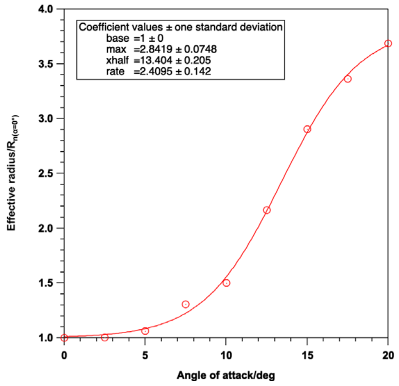
- Must rely completely on CFD for the acreage

- Stagnation point can rely on the methodology outlined
  - Aerothermal radius will now depend on angle of attack because the stagnation point will shift from the spherical nose cap at $\alpha = 0°$ to the conical frustum for $\alpha > \alpha_{crit}$

# Example




- $V_\infty$ = 4.2 km.s$^{-1}$, $\rho_\infty$ = 1.8 10$^{-3}$ kg.m$^{-3}$, $T_\infty$ = 178.4 K, $CO_2/N_2$ mixture
- The aerothermal radius (for the stagnation point) increases with angle of attack
- Inflections in pressure and heat flux at the sphere-cone tangency point on the leeward side

# Closing Remarks

- Trajectory codes *do not* provide aerothermal environments
  - Stagnation point scaling laws are added on to the codes to provide environments
  - Simplifications to the convective heating scaling law are $p_{\text{stag}} \cong \rho_\infty V_\infty^2$, $H_e \cong \frac{1}{2} V_\infty^2$, $H_e \gg h_w$ to get

$$q_{\text{stag}} \cong K_2 \frac{\sqrt{\rho_\infty}}{\sqrt{R_{\text{ref}}}} V_\infty^3$$

  - $H_e \gg h_w$ implies a *cold wall*, which is fine for most cases except $CO_2$ flows – $CO_2$ and CO have large $\Delta_f^o H$
  - Heat pulse useful in picking points for detailed flow computations

- Film coefficient-based approach is attractive due its being "agnostic" to wall type – cold *vs.* hot
  - The methodology is rooted in (1$^{st}$-order) boundary-layer theory
  - The methodology is tenuous for a high Mach number – low Reynolds number combination
    - Boundary layer is no longer "thin"; Shock layer could be merged too => no clearly identifiable "edge"
    - Total enthalpy is no longer a "constant of the motion"

# Closing Remarks

- One could (should?) use a heat flux-based methodology
  - Obviates the need for boundary layer information in materials response
  - Wall boundary condition will matter
    - Cold-wall BC, while enforceable from a physics/chemistry viewpoint, is probably not useful
    - Hot-wall BC would mean including material characteristics such as adsorption, etc.; consideration of heterogenous catalysis

- Scaling laws are “correlations” of either experimental data or flow computations
  - Remain skeptical of “validating” results against these; arguments can be (will be?) circular

- Other open issues (ongoing work)
  - Transition/Turbulence and influence of surface roughness
  - Fluid dynamics & chemistry of wall blowing
  - Backshell environments

# Questions?

National Aeronautics and Space Administration

Ames Research Center
Entry Systems and Technology Division