



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_{Rad})
 - Recovery enthalpy (H_{rec})
- Optional physical quantity of interest is:
 - Surface shear (τ)

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

$$H_{\text{rec}} = H_e + \frac{r-1}{2} u_e^2 \quad r = Pr^\zeta$$
$$\zeta = \begin{cases} 1/2 & \text{laminar} \\ 1/3 & \text{turbulent} \end{cases}$$

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

$$H = \underbrace{\sum_{s=1}^{n_s} Y_s h_s(T)}_{\text{Thermal}} + \underbrace{\sum_{s=1}^{n_s} Y_s \Delta_f^\circ H_s}_{\text{Chemical}} + \underbrace{\frac{1}{2} \mathbf{u} \cdot \mathbf{u}}_{\text{Kinetic}}$$

Y_s	mass fraction of s
$\Delta_f^\circ H_s$	enthalpy of formation of s at STP
h_s	thermal enthalpy of s
T	temperature
\mathbf{u}	velocity vector

- 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 $\Delta_f^\circ H_s \cong -9 \text{ MJ/kg}$
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

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

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

$$\nabla \cdot (\rho \mathbf{u} H) = 0 \quad \Rightarrow \quad \rho \mathbf{u} \cdot \nabla H = 0$$

- 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

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

- 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



Destination	Esc. Vel. km.s ⁻¹	Rot. Vel. km.s ⁻¹	Ent. Vel. km.s ⁻¹	Rel. Vel. km.s ⁻¹	Ref. KE MJ/kg	Composition (by vol.)	BDE MJ/kg	Ion. potential MJ/kg
Saturn	36.09	9.54	37.54	28	392	95:5 (H ₂ :He)	O ₂ : 15.6 NO: 21.0 C ₂ : 25.2 CH ₄ : 25.9 CO ₂ : 28.7 CN: 28.8 H ₂ : 31.1 N ₂ : 33.7 CO: 38.4	NO: 29.8
Jupiter	60.2	12.29	59.89	47.6	1133	90:10 (H ₂ :He)		O ₂ : 36.4
Uranus	21.38	-2.57	22.57	20.0	200	85:15 (H ₂ :He)		Ar: 38.1
Neptune	23.56	2.67	27.67	25.0	313	80:20 (H ₂ :He)		C ₂ : 47.7
Titan	2.64	0.01	8.01	8.0	32	98:2 (N ₂ :CH ₄)		CO: 48.3
Earth	11.19	0.46	13.46	13.0	85	79:21 (N ₂ :O ₂)		CN: 51.6
Mars	5.03	0.24	6	5.76	17	95.5:4.5 (CO ₂ :N ₂)		N ₂ : 53.7
Venus	10.36	0	11.5	11.5	66	96:5:3.5 (CO ₂ :N ₂)		CH: 78.9
							O: 82.1	
							C: 90.5	
							N: 100.2	
							He: 592.7	
							H ₂ : 738.4	
							H: 1302	

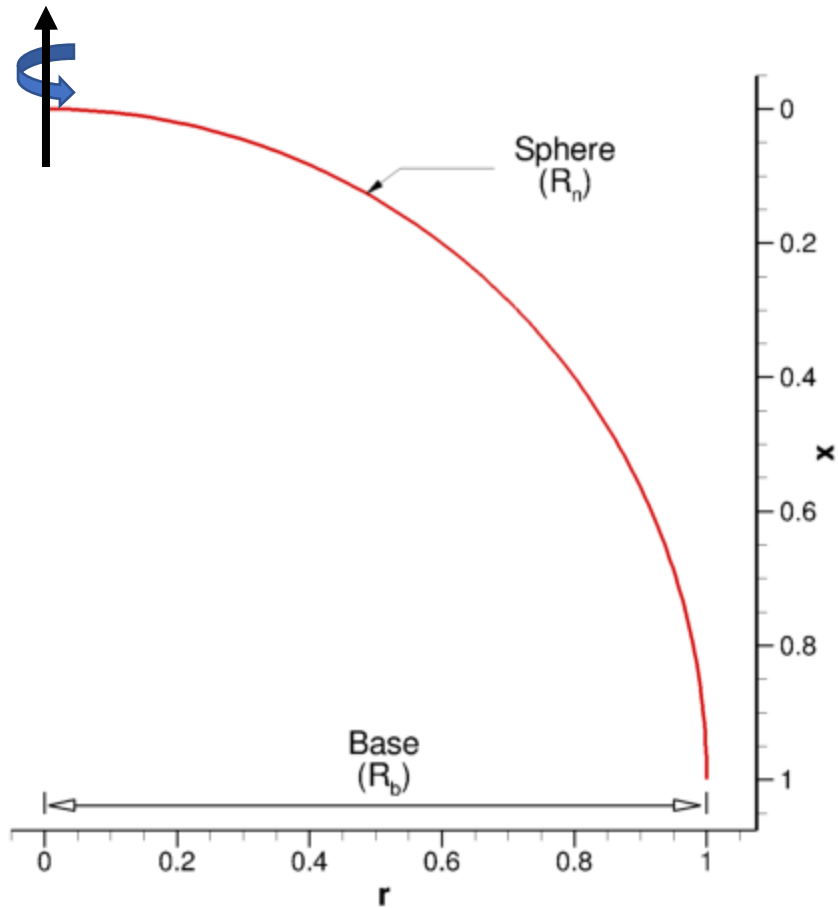
- Only 6 elements – C, H, O, N, He, Ar, free electrons (e⁻), and compounds made up of these elements need to be considered
- Bond dissociation enthalpy (BDE) is the *average* energy required to break a molecule into its constituent elements

Geometries (1/5)



TYPE 1 GEOMETRY

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



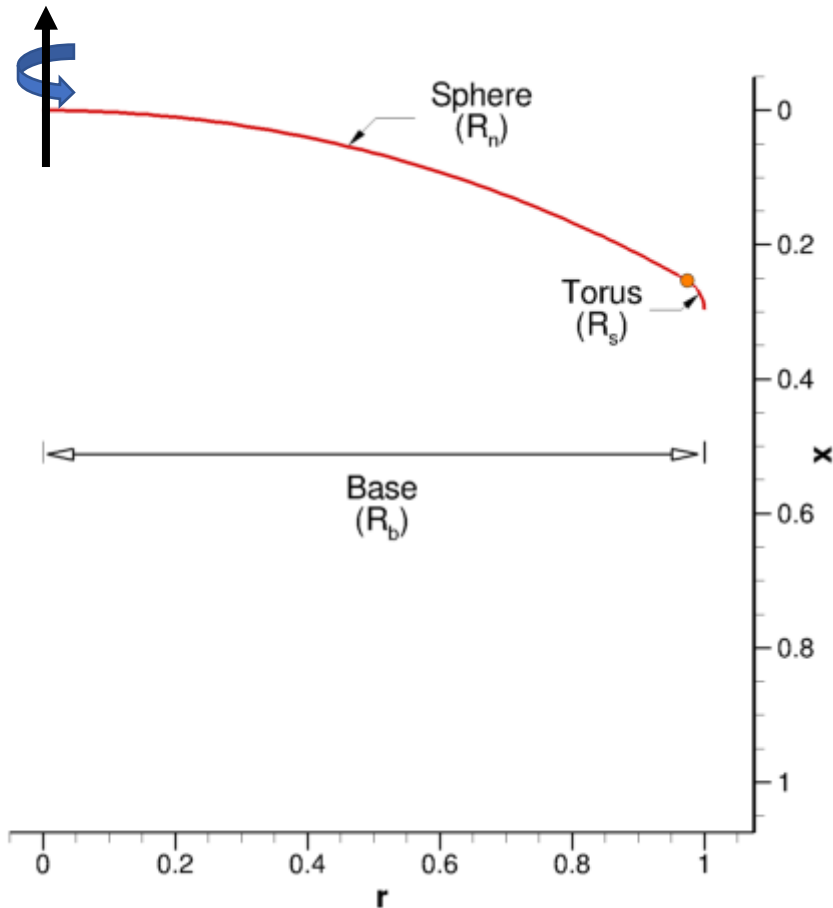
- Any conic section will have smooth curvature
- 2 parameters (R_b, R_n) needed for analytical description
 - For a hemisphere: $R_b = R_n$
- A hemisphere is the simplest geometry
- Basis for stagnation point theory
- Reference geometry for arc jet calorimetry
- Only one known instance of atmospheric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

Geometries (2/5)



TYPE 2 GEOMETRY

[Generatrix: 1 Discontinuity in Curvature]



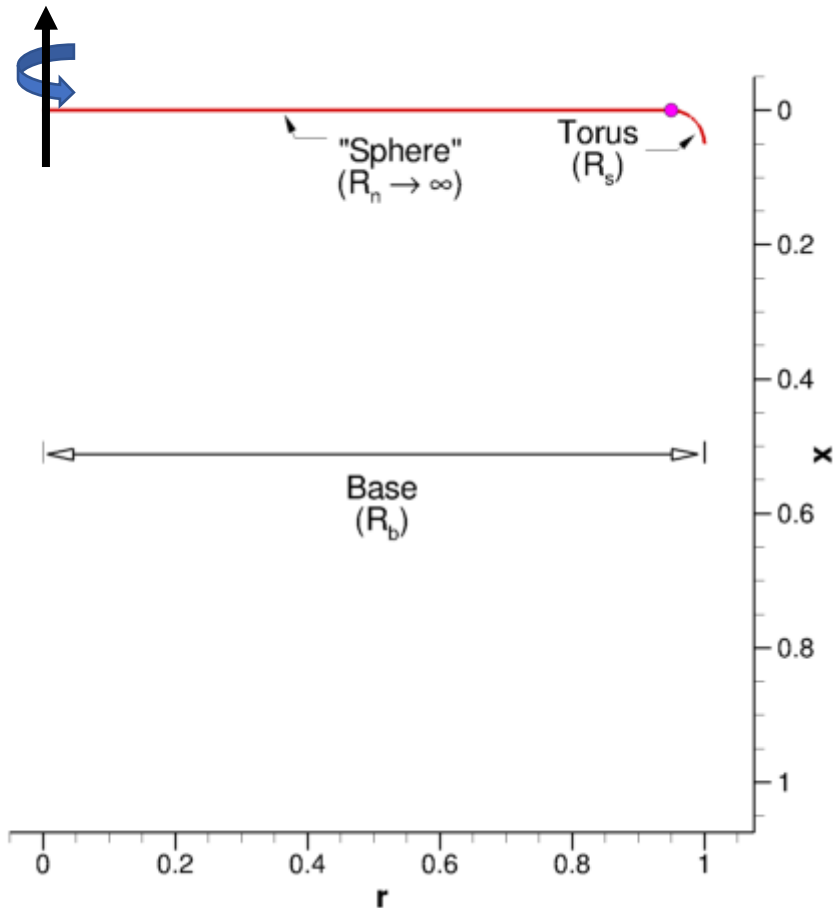
- Any conic section will have smooth curvature
- 3 parameters (R_b, R_n, R_s) needed for analytical description
 - For an iso-q: $R_n = 2R_b$
- An iso-q geometry is the preferred geometry for materials testing in an arc jet
- The spherical section shape is almost exclusively used for human missions and 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]



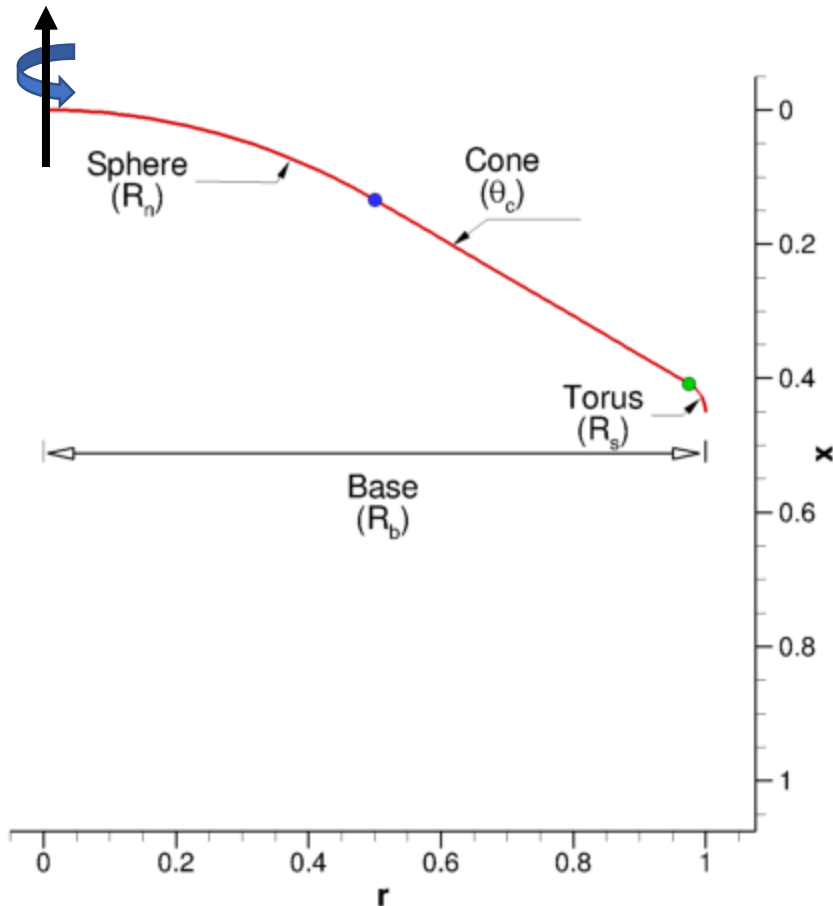
- Strictly, only 2 parameters (R_b, R_s) needed for analytical description
 - $R_n \rightarrow \infty$
- A flat-faced cylinder geometry is also an often-used geometry for materials testing in an arc jet
 - Stagnation region experiences “uniform” pressure and heat flux (at low shear) over the test face
- 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, θ_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)



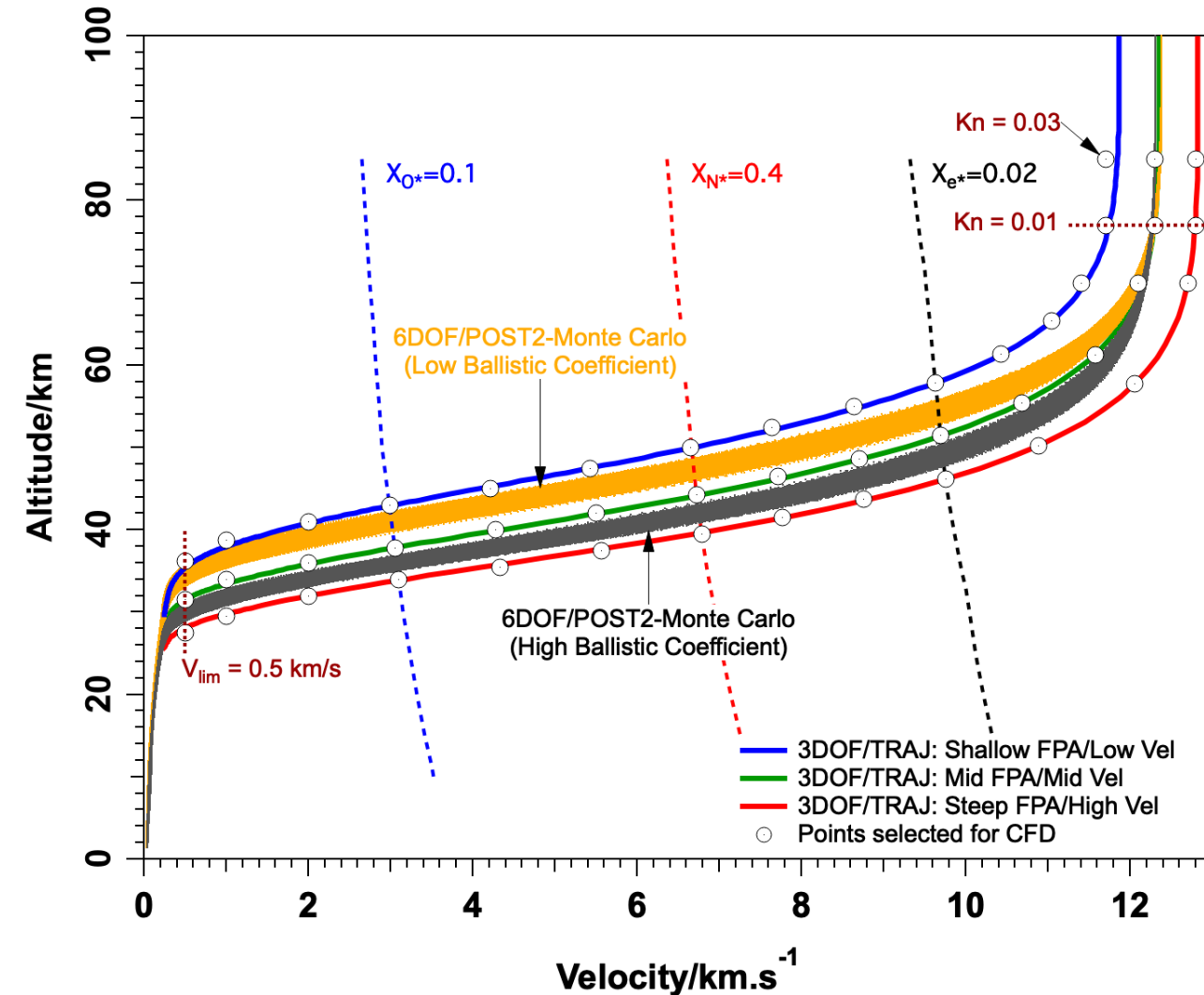
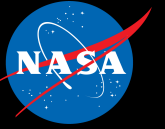
- Two additional geometry types are:
 - Type 4 – Asymmetric blunt bodies with bilateral (pitch) symmetry
 - Geometry can be described analytically
 - No flight heritage, although AFE (Aeroassist Flight Experiment) came close
 - Note: A rotationally symmetric geometry with added features such as a trim 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
 - $L/D \approx 1$
 - 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 $V_{\infty} = V_E \exp\left(-\frac{1}{6}\right) \cong 0.85V_E$
 - Peak stagnation pressure ($\propto \rho_{\infty} V_{\infty}^2$) occurs when $V_{\infty} = V_E \exp\left(-\frac{1}{2}\right) \cong 0.61V_E$
 - 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 (2nd?) 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 ρ_{∞} - V_{∞} space could have several angles of attack!
- Impose upper and lower limits ρ_{∞} - V_{∞} space
 - Upper limit – Knudsen number cutoff
 - $Kn = \lambda/R_n \leq 0.01$
 - λ 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



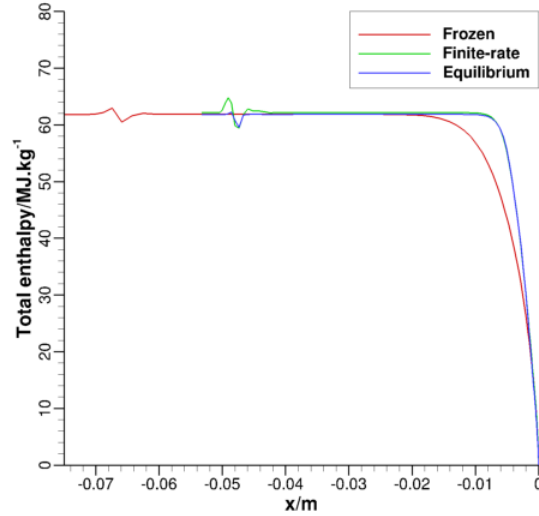
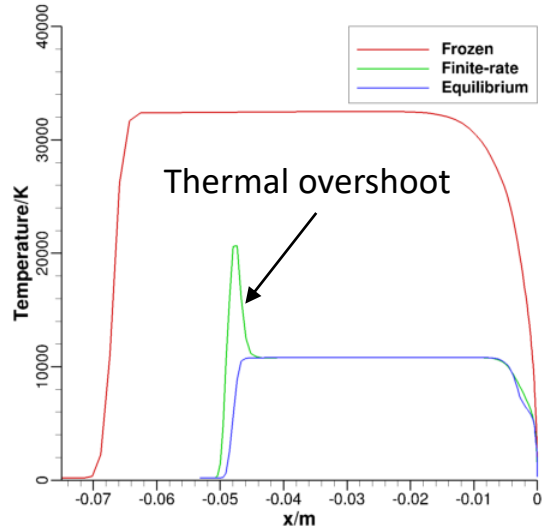
- Chemistry
 - Reaction mechanism & rates
- Thermodynamic properties – curve fits or analytical expressions
 - Atomic species and their ions (if necessary) – Translational energy (continuous) & electronic energy (discrete/quantal)
 - Molecular species and their ions (if necessary) – Translational energy (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

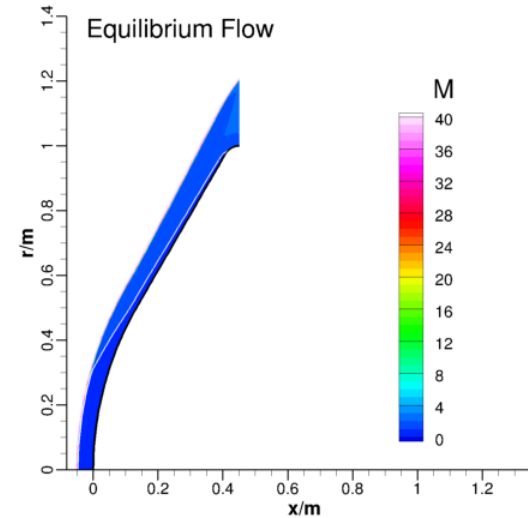
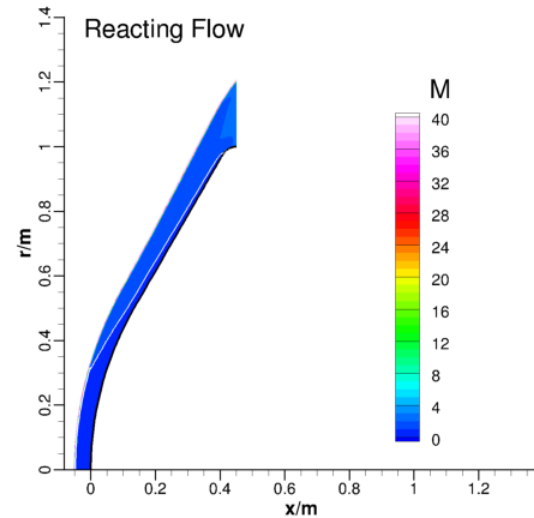
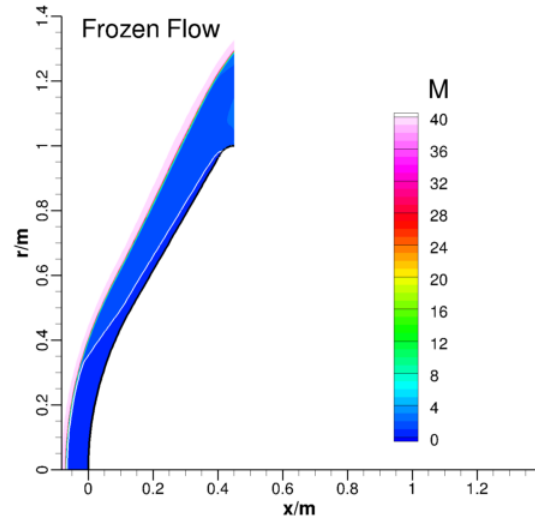


- Three types of walls
 - Cold wall – wall temperature fixed at 298 K (usually), but species chemistry allowed to float
 - Hot wall – wall temperature AND species chemistry allowed to float, usually conduction into the material is ignored
$$q_{\text{thermal}} + q_{\text{chemical}} = \epsilon_w \sigma (T_{\text{wall}}^4 - T_{\text{sink}}^4)$$
 where $\epsilon_w = \epsilon(T)$ is the emissivity and σ 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. $\text{O}_2 + \text{M} \leftarrow \text{O} + \text{O} + \text{M}$ $[\Delta H_r^\circ = -498.458 \frac{\text{kJ}}{\text{mol}}]$
 2. $\text{N}_2 + \text{M} \leftarrow \text{N} + \text{N} + \text{M}$ $[\Delta H_r^\circ = -944.87 \frac{\text{kJ}}{\text{mol}}]$
 3. $\frac{\partial}{\partial n} Y_s = 0, s \neq \text{N or O}$
 - 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 γ ; $\gamma = 1$ 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_{wall} and T_{wall} (fixed or floating)
 - Works well in most cases except for CO_2 flow over a cold wall – $\text{CO} + \text{O}$ has a significant thermal barrier

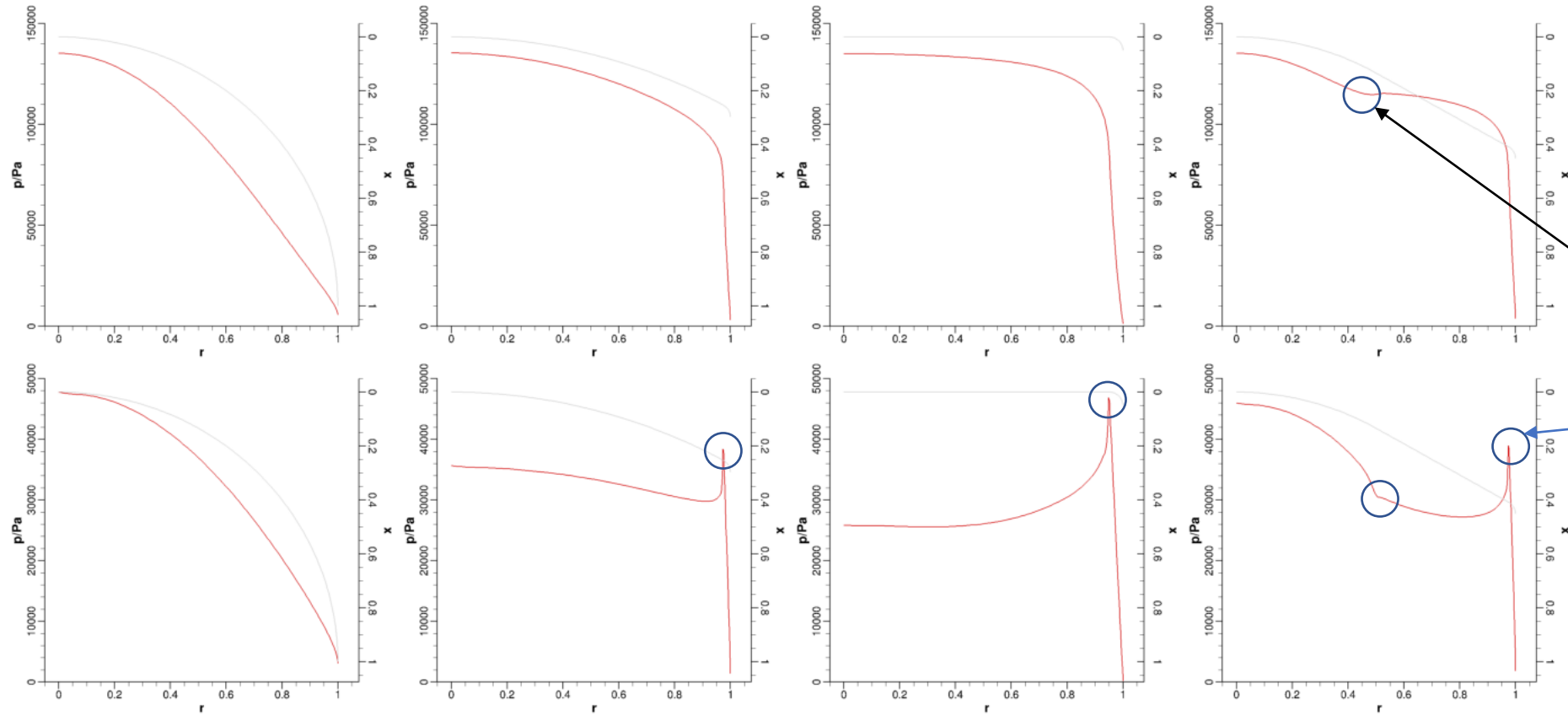
Warm up Exercise 1



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



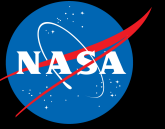
Warm up Exercise 2



Influence
of curvature
discontinuity

- $V_\infty = 1.1 \text{ km}\cdot\text{s}^{-1}$, $\rho_\infty = 0.118 \text{ kg}\cdot\text{m}^{-3}$, $T_\infty = 57.5 \text{ K}$
- 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

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

- $R_{\text{aerothermal}}$ is a characteristic length scale/aerothermal radius/effective radius
 - ρ_{∞} is ambient atmospheric density
 - V_{∞} 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

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

- 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_{∞} 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

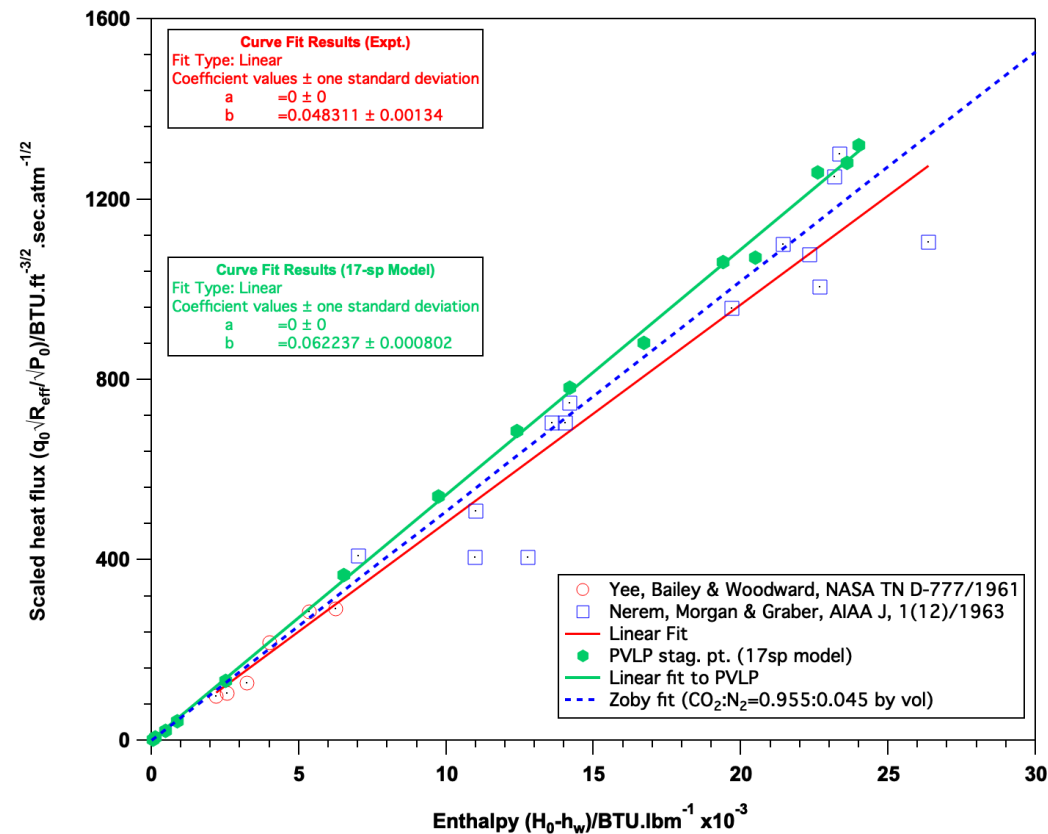
$$q_{\text{stag}} = K \frac{\sqrt{p_{\text{stag}}}}{\sqrt{R_{\text{aerothermal}}}} (H_{\text{edge}} - h_{\text{wall}})$$

- 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 CO₂ shown below



- The experimental data and fits shown (red line and dashed blue line) are for pure CO₂, the flow computations are for a Venus mixture (CO₂:N₂=0.965:0.035, by volume)

Stagnation Point Environments: Conv. Ht. Flux



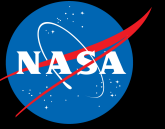
- Scaling law for convective film coefficient is then

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

- 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

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

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_{Hemi}
 - If the heat flux at the stagnation point of the arbitrary blunt body is known (from experiment or CFD), then

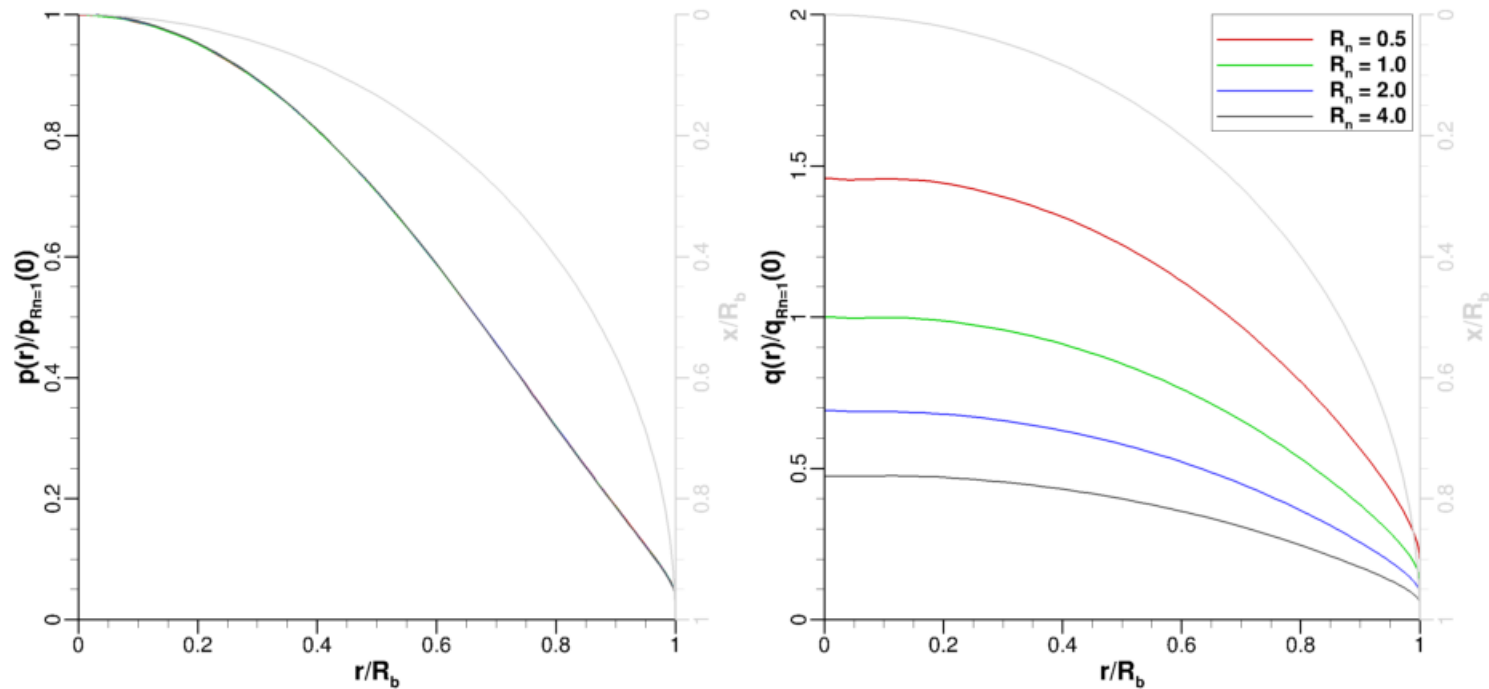
$$\frac{q_{\text{stag, BB}}}{q_{\text{stag, Hemi}}} = \frac{\sqrt{R_{\text{Hemi}}}}{\sqrt{R_{\text{BB}}}} \Rightarrow R_{\text{BB}} = \left(\frac{q_{\text{stag, Hemi}}}{q_{\text{stag, BB}}} \right)^2 R_{\text{Hemi}}$$

- 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_{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



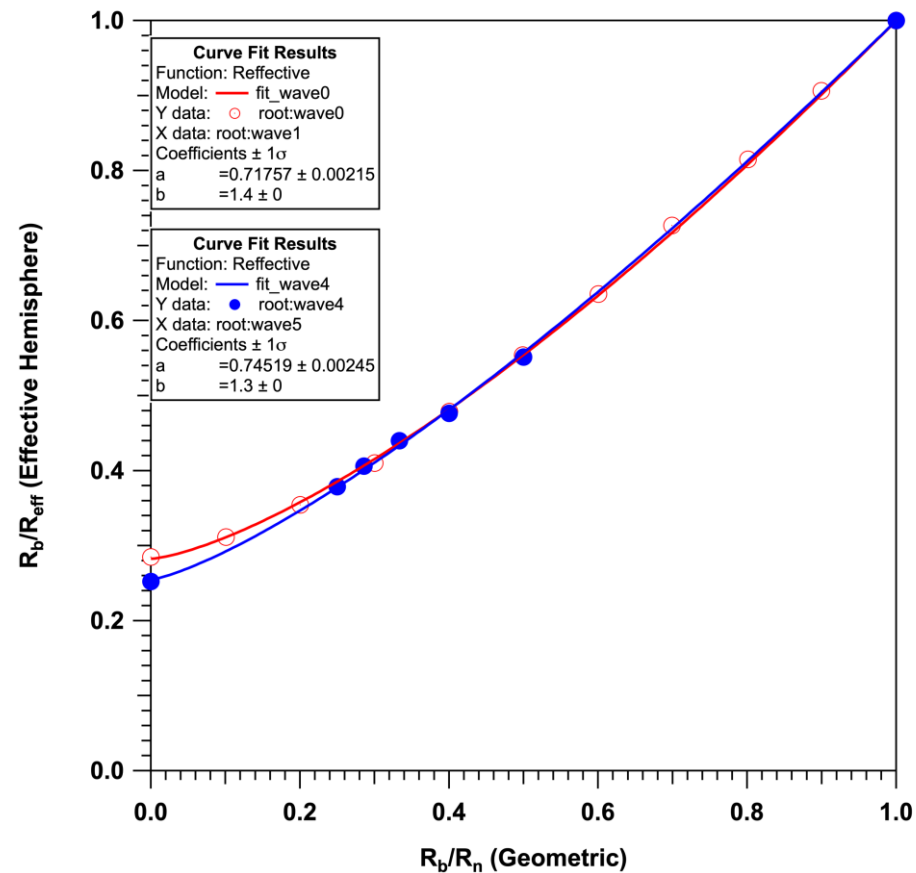
- That convective heat flux goes at the inverse square root of the aerothermal radius (same as the geometric radius in the case of a hemisphere) is shown below



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_{CFD} ($\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-3/2}\cdot\text{atm}^{-1/2}$)	$K_{\text{Sutton-Graves}}$ ($\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-3/2}\cdot\text{atm}^{-1/2}$)	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	

^aPure CO₂ value quoted from Sutton and Graves report.

^bComposition assumed is 85% H₂ and 15% He (by volume)

^cProbably 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 $\sqrt{R_{\text{aerothermal}}}$ 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

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

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

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

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

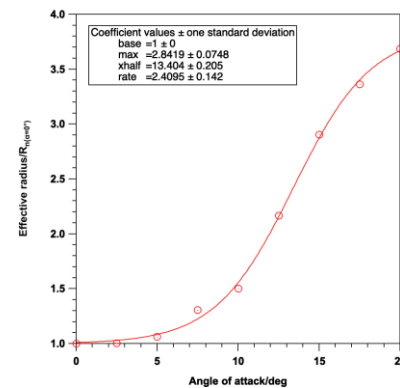
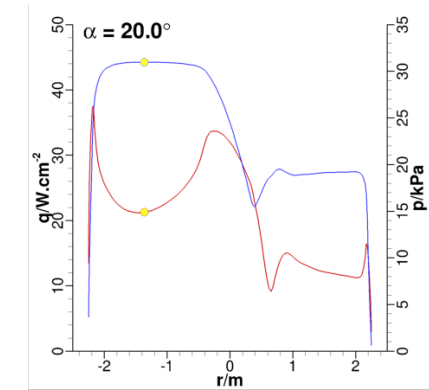
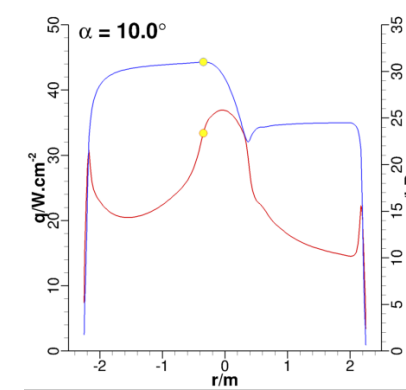
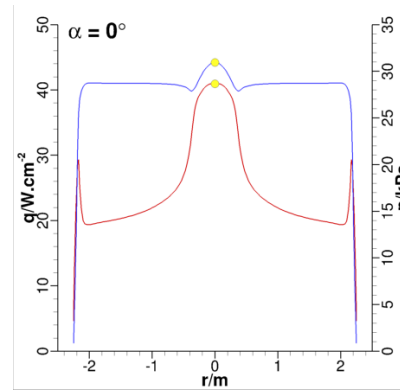
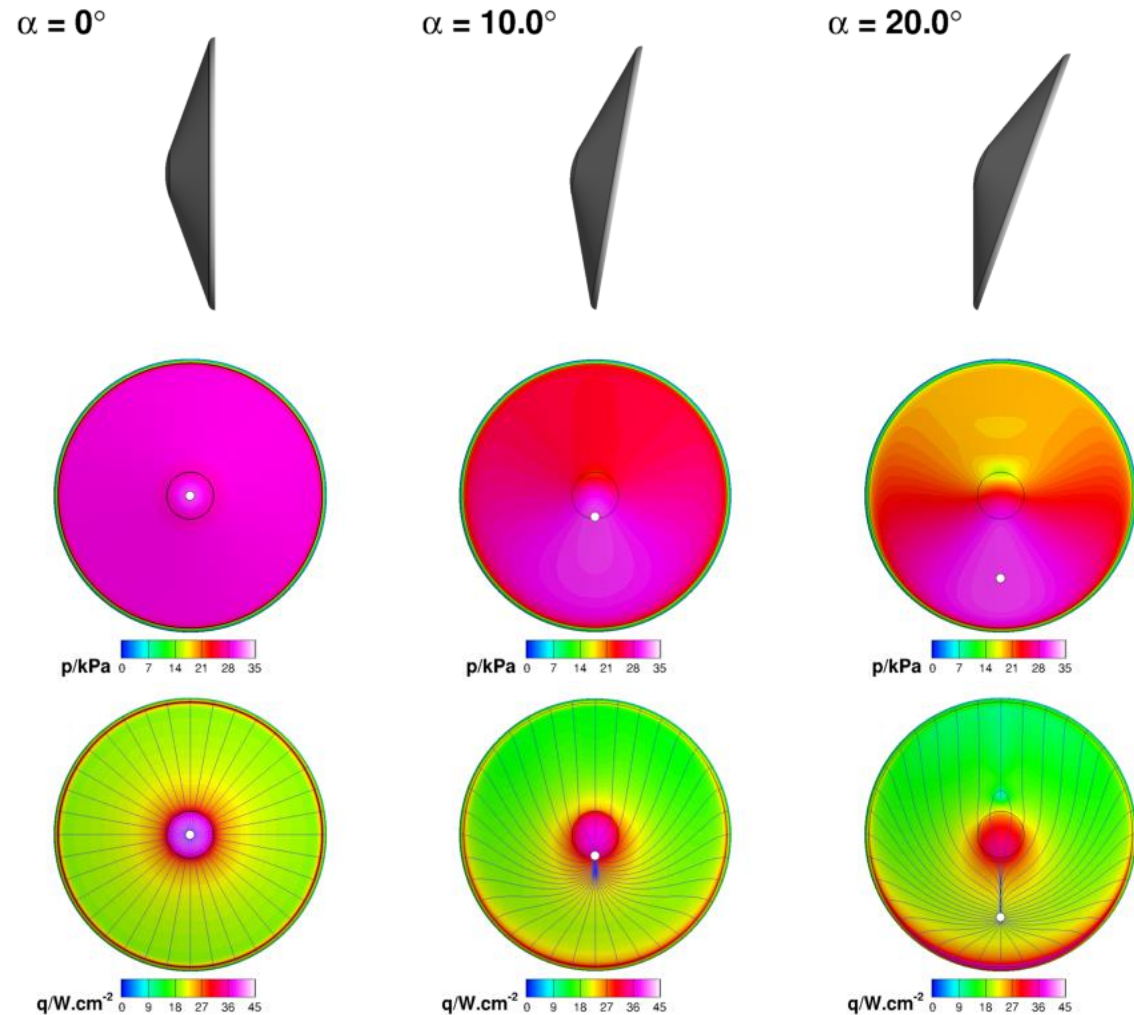
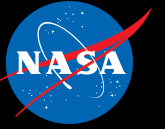
We have accomplished what we set out to do, at least for the stagnation point. What about 3D?

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 $\alpha = 0^\circ$ 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 $\alpha = 0^\circ$ to the conical frustum for $\alpha > \alpha_{crit}$

Example



- $V_\infty = 4.2 \text{ km.s}^{-1}$, $\rho_\infty = 1.8 \cdot 10^{-3} \text{ kg.m}^{-3}$, $T_\infty = 178.4 \text{ K}$, 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

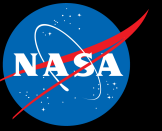
$$q_{\text{stag}} \cong K_2 \frac{\sqrt{\rho_{\infty}}}{\sqrt{R_{\text{ref}}}} V_{\infty}^3$$

- $H_e \gg h_w$ implies a *cold wall*, which is fine for most cases except CO₂ flows – CO₂ and CO have large $\Delta_f^0 H$
 - 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 (1st-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

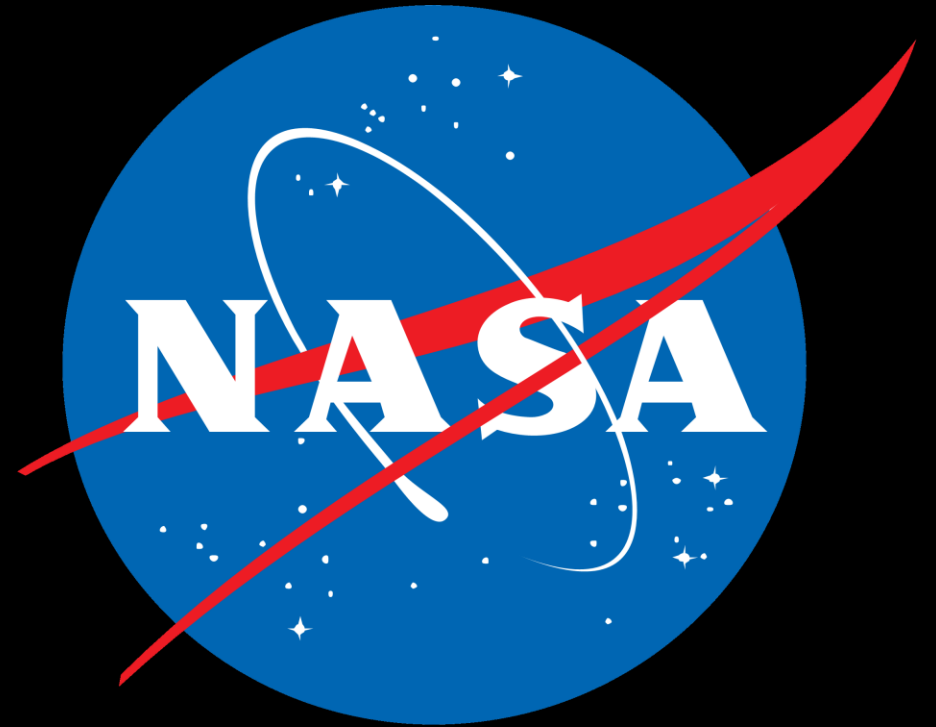


- One could (should?) use a heat flux-based methodology
 - Obviates the need for boundary layer information in materials response
 - Wall boundary condition will matter
 - Cold-wall BC, while enforceable from a physics/chemistry viewpoint, is probably not useful
 - Hot-wall BC would mean including material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