Analysis of Temperature-Constrained Ballute Aerocapture for High-Mass Mars Payloads

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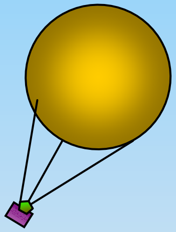

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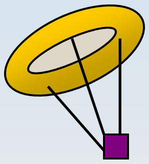

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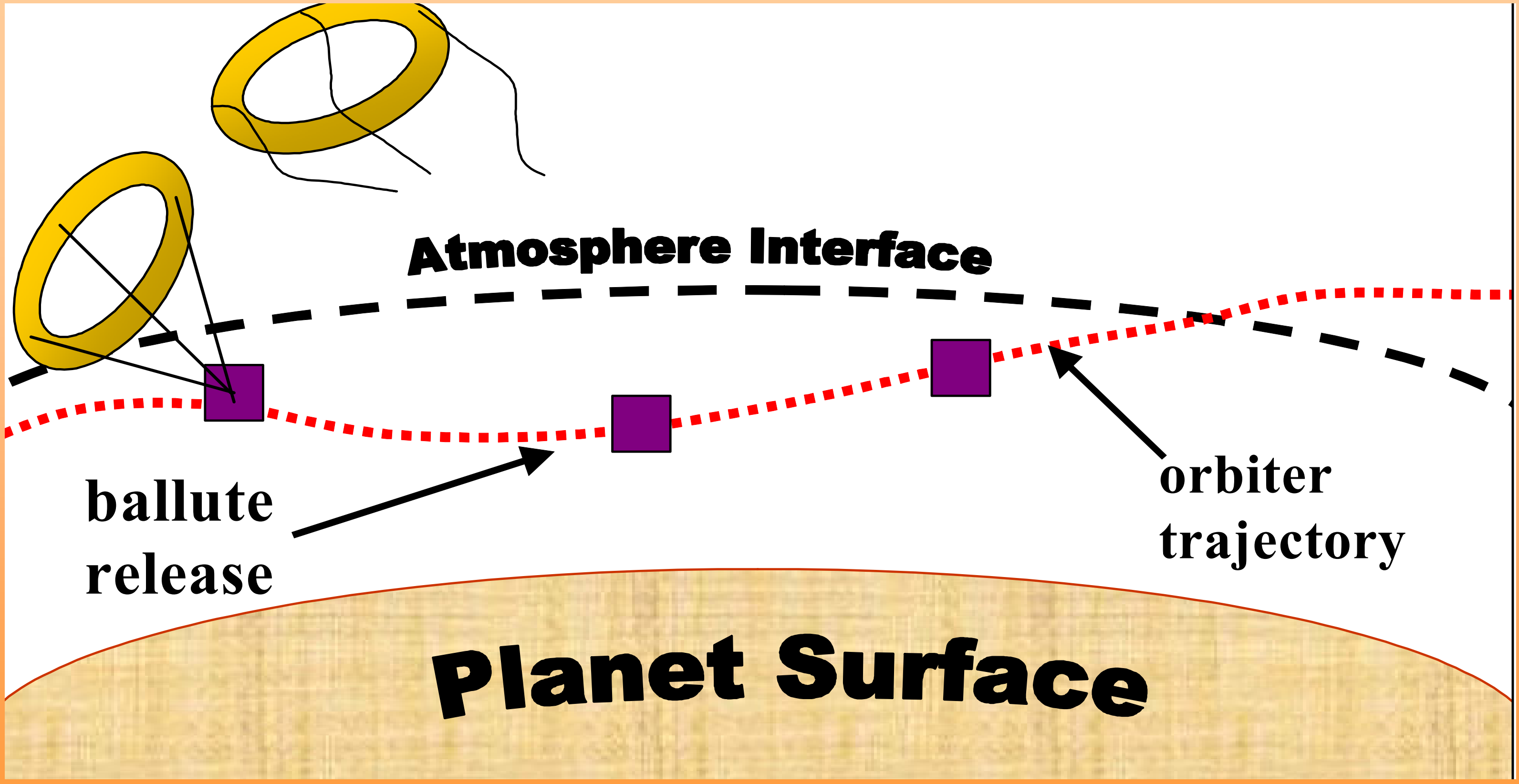
Can towed ballutes be used to capture high mass systems at Mars?



High-fidelity aerothermodynamic analysis must be achieved

Temperature-Constrained Trajectories

for Towed Toroidal Ballute Aerocapture at Mars

Ballute Surface Temperature ≤ 500^oC

(equivalent to Q_s **= 2.01** W/cm^2**)**

Hypersonic Planetary Aeroassist Simulation System (HyperPASS)

- **3DOF trajectory simulations**
- **point-mass vehicle representation**
- **variable C_D model**
- **rotating atmosphere (with planet)**
- **Exponentially interpolated atmosphere (Mars COSPAR90)**

Simulation Parameters

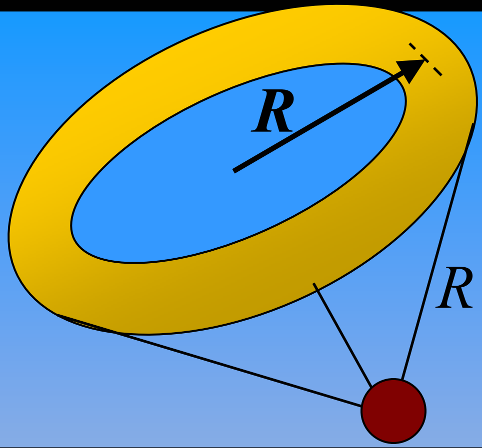
- **Vehicle Mass: 0.1, 1, 10, and 100 tons (sans ballute)**
- **Entry Speed = 6.0 km/s (at 150km)**
- **Target: 4-day Mars parking orbit**
- **$C_{D,ball}$ = 2.00 (varies with Kn)**
  $C_{D,s/c}$ = 0.93 (constant)

Ballute Sizing Results

for Temperature-Constrained Ballute Aerocapture at Mars

Ballistic Coefficient

$$\beta = \frac{m_{s/c} + m_{ball}}{C_{D,s/c} A_{s/c} + C_{D,ballute} A_{ball}}$$

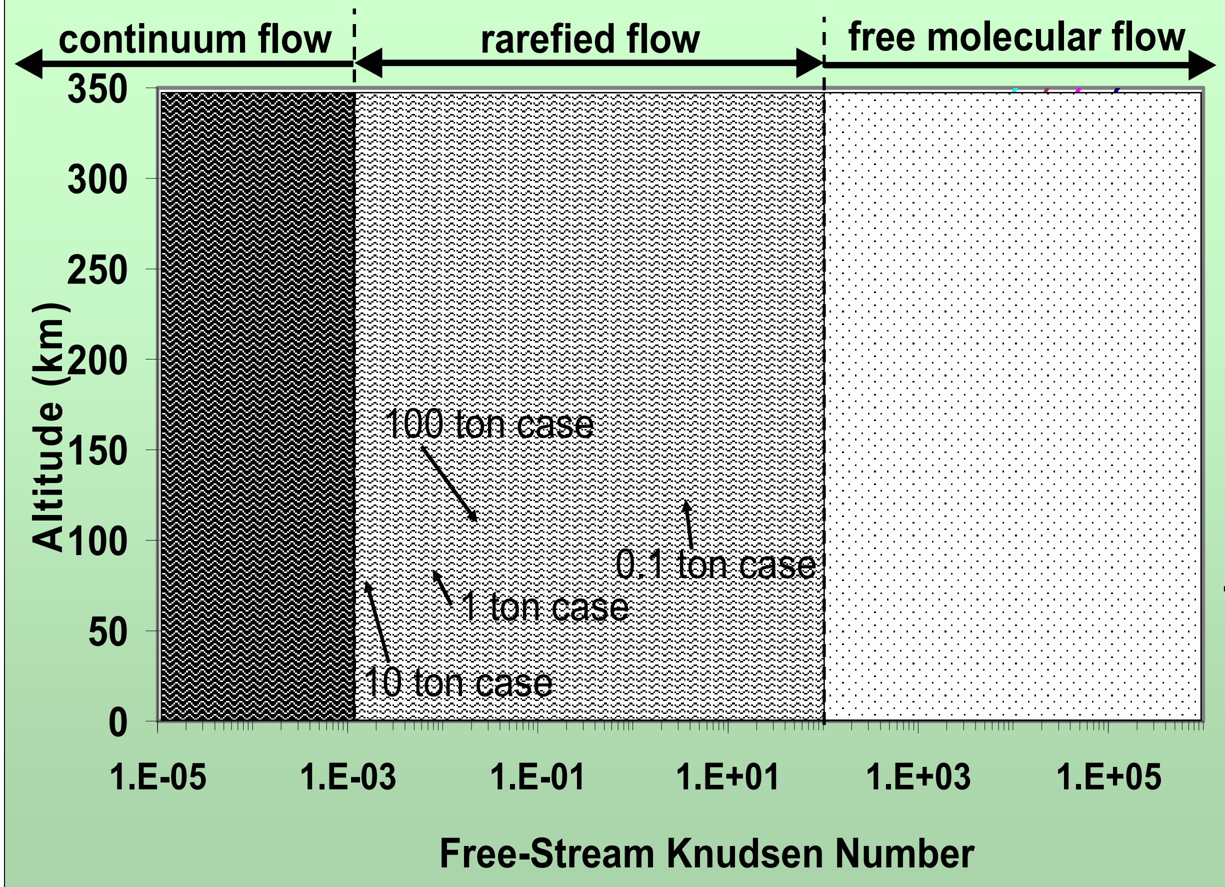


$$r_{ball} = R/4$$

$$R\left[\beta, C_{D,ball}, C_{D,s/c}, A_{s/c}, m_{s/c}, \sigma\right]$$

Parameter	0.1 ton case		1 ton case		10 ton case		100 ton case	
	s/c	ballute	s/c	ballute	s/c	ballute	s/c	ballute
m **[kg]**	**100**	**3.20**	**1000**	**20.9**	**10,000**	**98.2**	**100,000**	**453**
A **[m^2]**	**2.00**	**103**	**5.64**	**669**	**26.1**	**3140**	**121**	**14500**
r **[m]**	**0.80**	**1.43**	**1.34**	**3.66**	**2.88**	**7.91**	**6.20**	**17.0**
R **[m]**	**---**	**5.73**	**---**	**14.59**	**---**	**31.63**	**---**	**67.94**
Initial β **[kg/m^2]**	**0.50**		**0.76**		**1.60**		**3.45**	

Altitude vs. Knudsen Number



$$Kn = \frac{\lambda}{L}$$

Kn > 100: free molecular flow
Kn < 10^{-3} : continuum flow

in between is rarefied and transitional flow

Flow Conditions

at Point of Maximum Heat Flux

Indicates laminar vs. turbulent flow

Indicates rarefied vs. continuum flow regime

CASE	Ballistic Coeff. [kg/m²]	Char. Length [m]	Altitude @ max heating [km]	Knudsen Number	Reynolds Number
0.1 ton case	0.50	2.86	90.99	2.63×10^{-2}	878
1 ton case	0.76	7.31	87.15	6.20×10^{-3}	3745
10 ton case	1.60	15.82	81.40	1.30×10^{-3}	17497
100 ton case	3.45	33.98	75.64	3.00×10^{-4}	81398

rarefied, laminar flow

continuum, turbulent flow

Aerothermodynamic Tools

DSMC

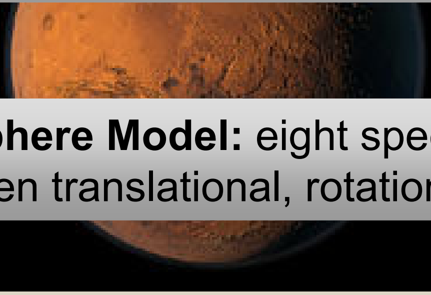
Statistical Modeling In Low-density Environment (SMILE)

- 3D/2D/axisymmetric code
- 3 million simulated molecules
- constant wall temperature assumed
- gas-surface interactions assumed to be diffuse, with full energy accommodation
- variable-hard-sphere molecular model

CFD

Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA)

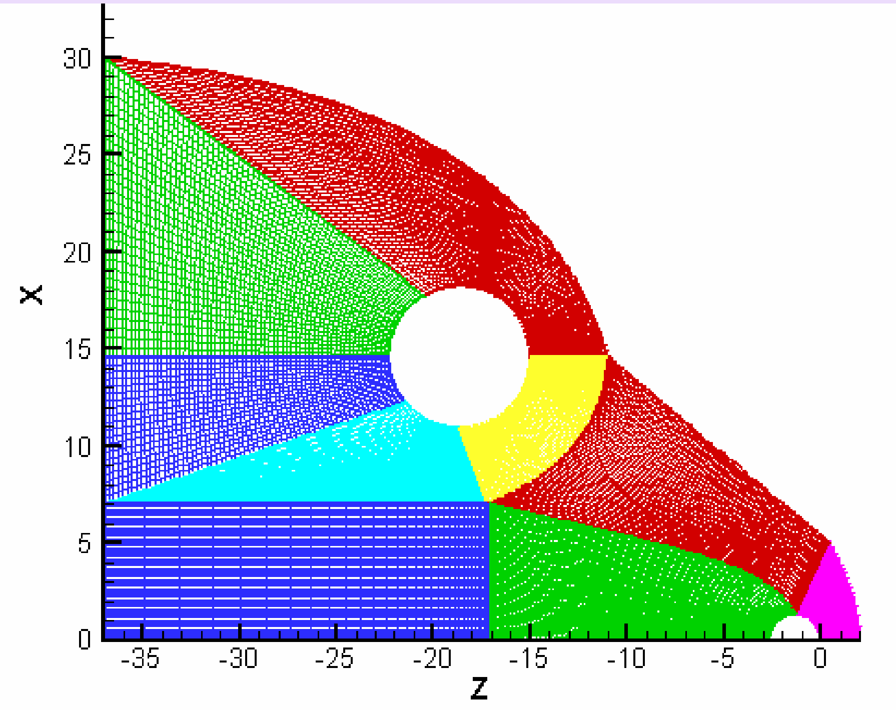
- 3D/2D/axisymmetric code
- grid resolution, ~27500 cells
- radiative equilibrium wall temperature
- super-catalytic wall boundary
- governing equations: Full Navier-Stokes
- laminar flow assumed



Martian Atmosphere Model: eight species gas model with chemical reactions and exchange between translational, rotational, and vibrational modes.

CFD Numerical Issues

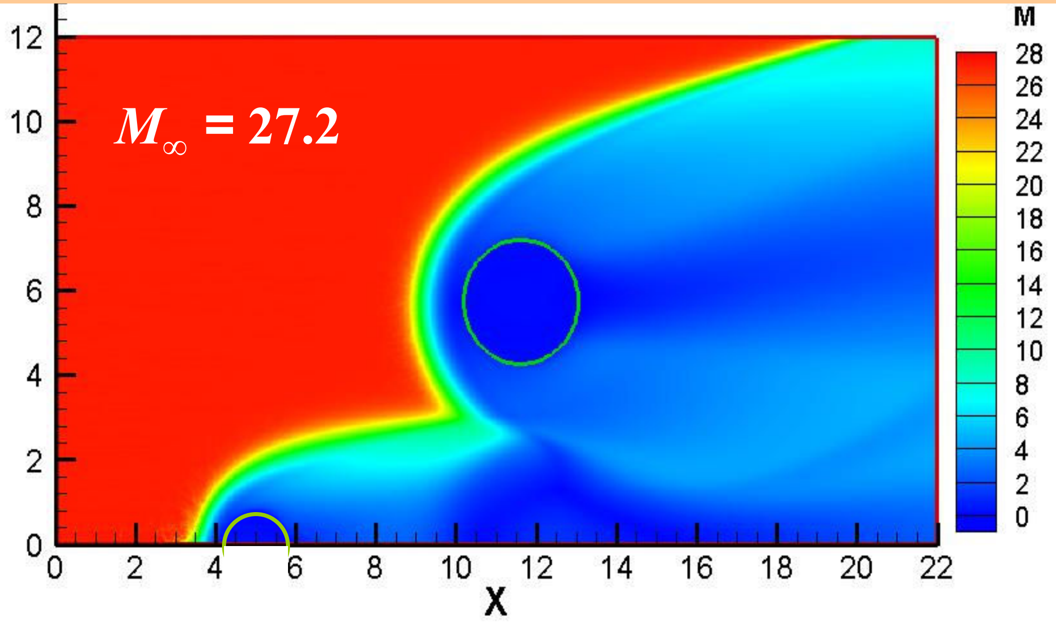
- 9 blocks, 27500 cells
- grid not fully converged
- cell Reynolds number
  - minimum cell Re = 0.03
  - maximum cell Re = 13.06
- Convergence residual
  - minimum residual = 10^{-5}
  - maximum residual = 10^{-3}

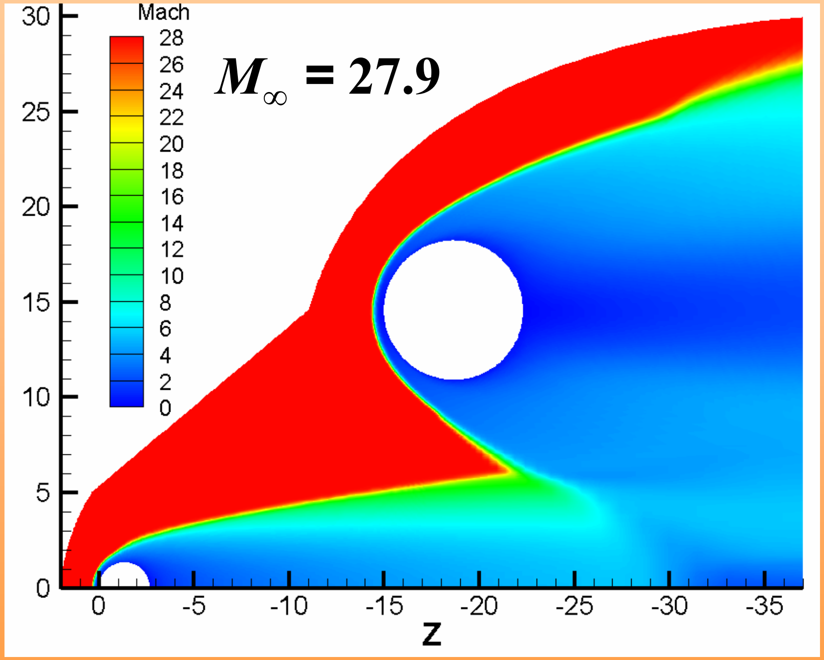


Mach Number

0.1 ton payload, β = 0.50 (DSMC results)
Kn = 2.63E-2, V_∞= 5.38 km/s

1 ton payload, β = 0.76 (CFD results)
Kn = 6.20E-3, V_∞= 5.39 km/s





Complex hypersonic flow, combining normal and oblique shock waves around the spacecraft and ballute.

0.1 ton Pressure & C_D (DSMC)

$$C_D = \frac{2D}{\rho V^2 A}$$ ← **Sum of surface pressure and friction forces in the x-direction**

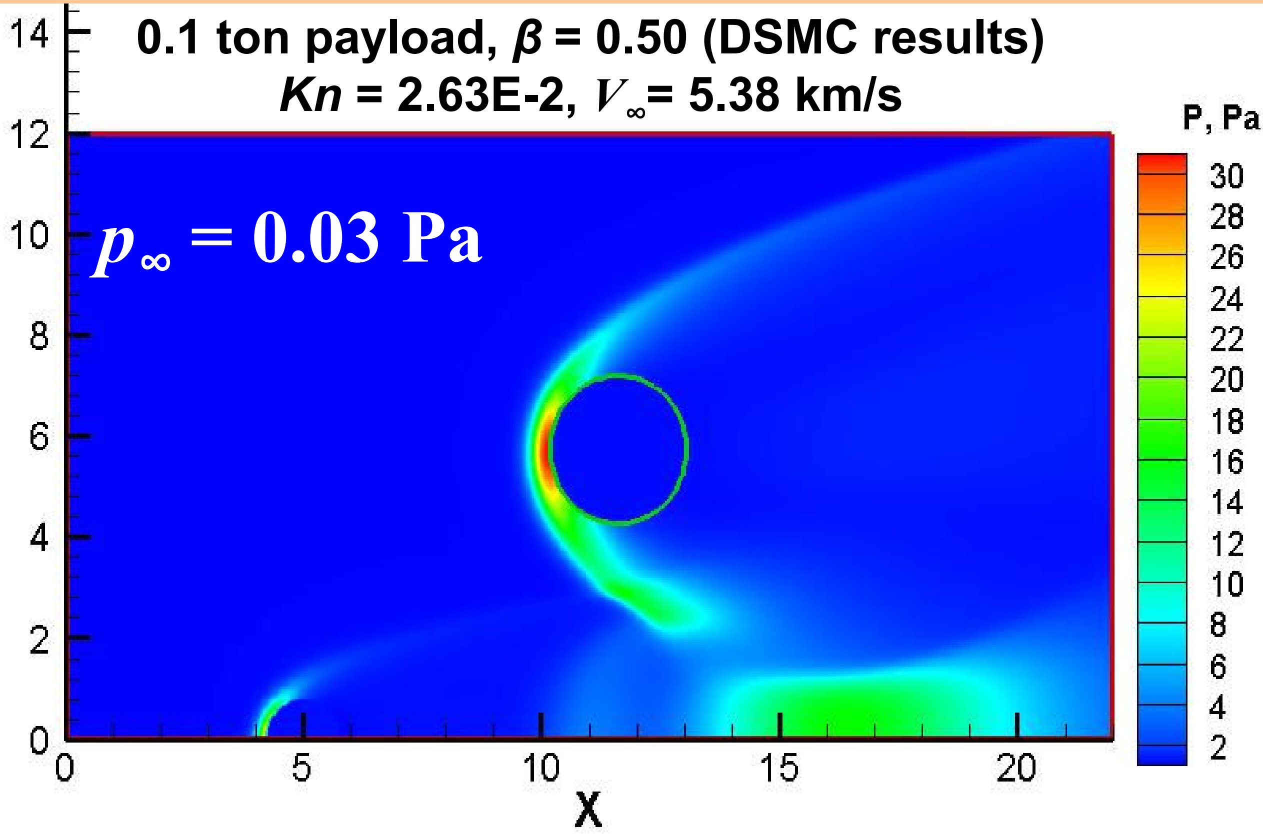
Based on Moss' DSMC calculations for air:

$$C_D = 1.32$$

DSMC results for Mars:

$$C_D = 1.48$$

(12% higher)



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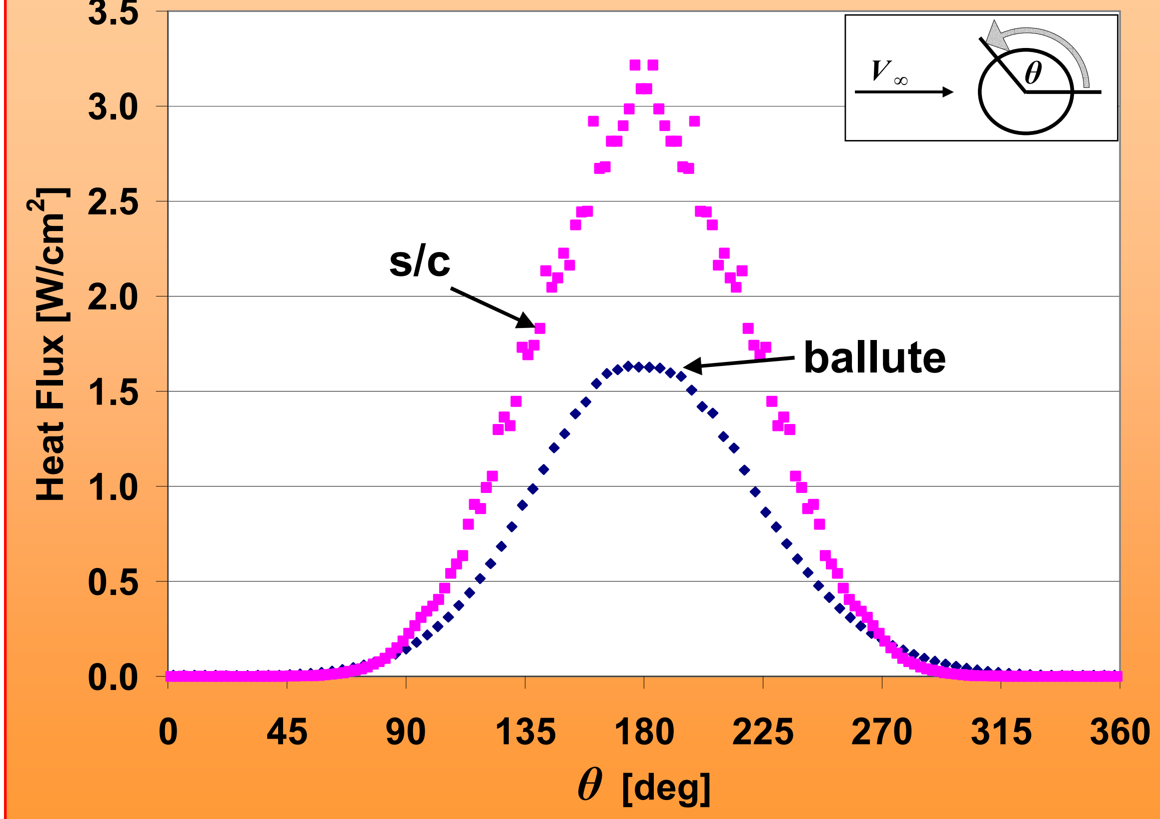
0.1 ton Surface Heating (DSMC)

0.1 ton payload, β = 0.50 (DSMC results)
Kn = 2.63E-2, V_∞ = 5.38 km/s



$$Q_{stag} = Cv^3\sqrt{\frac{\rho}{R_n}}$$

<u>Sutton-Graves model</u> :

assuming C = 2.62x10^{-8} kg$^{1/2}$/m

Q_s = 2.47 W/cm^2 ballute

Q_s = 3.31 W/cm^2 orbiter

<u>DSMC results</u>:

Q_s = 1.63 W/cm^2 ballute
(34% lower)

Q_s = 3.09 W/cm^2 orbiter
(6% lower)

1 ton Pressure & C_D (CFD)

Based on Moss' DSMC calculations for air:

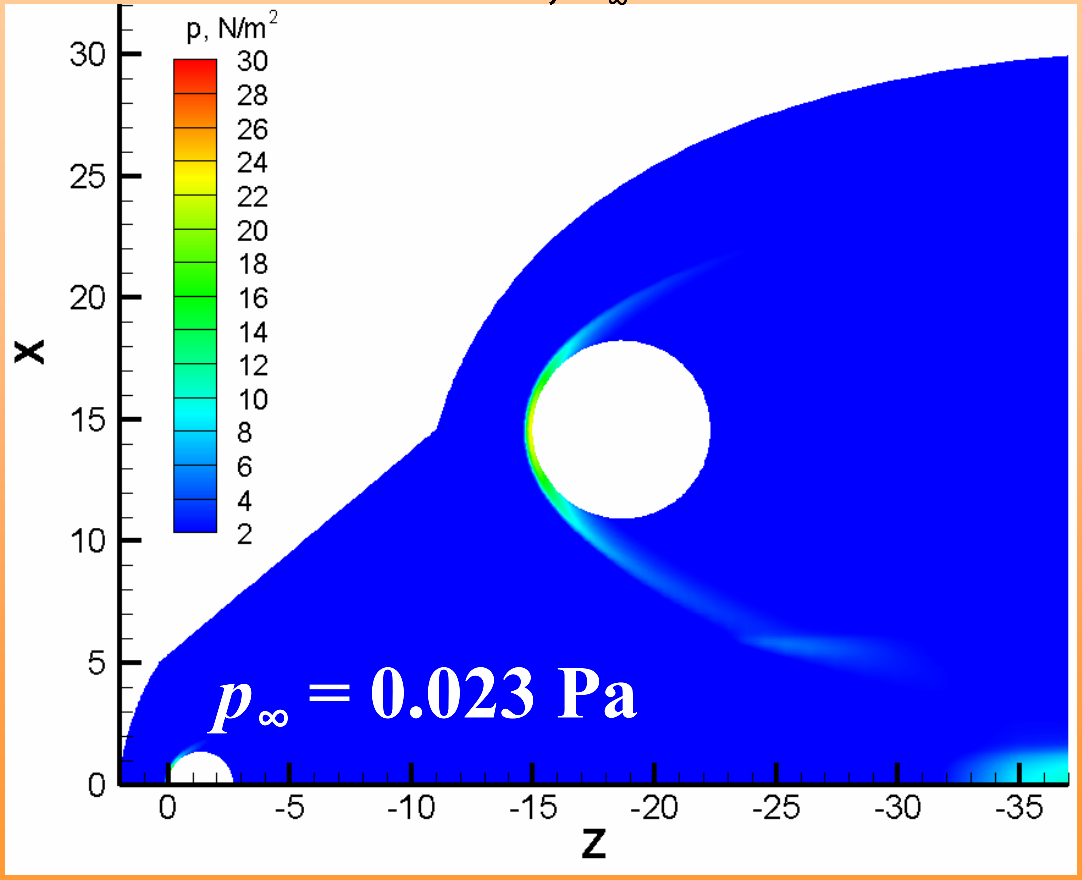
$$C_D = 1.32$$

Preliminary CFD results for Mars:

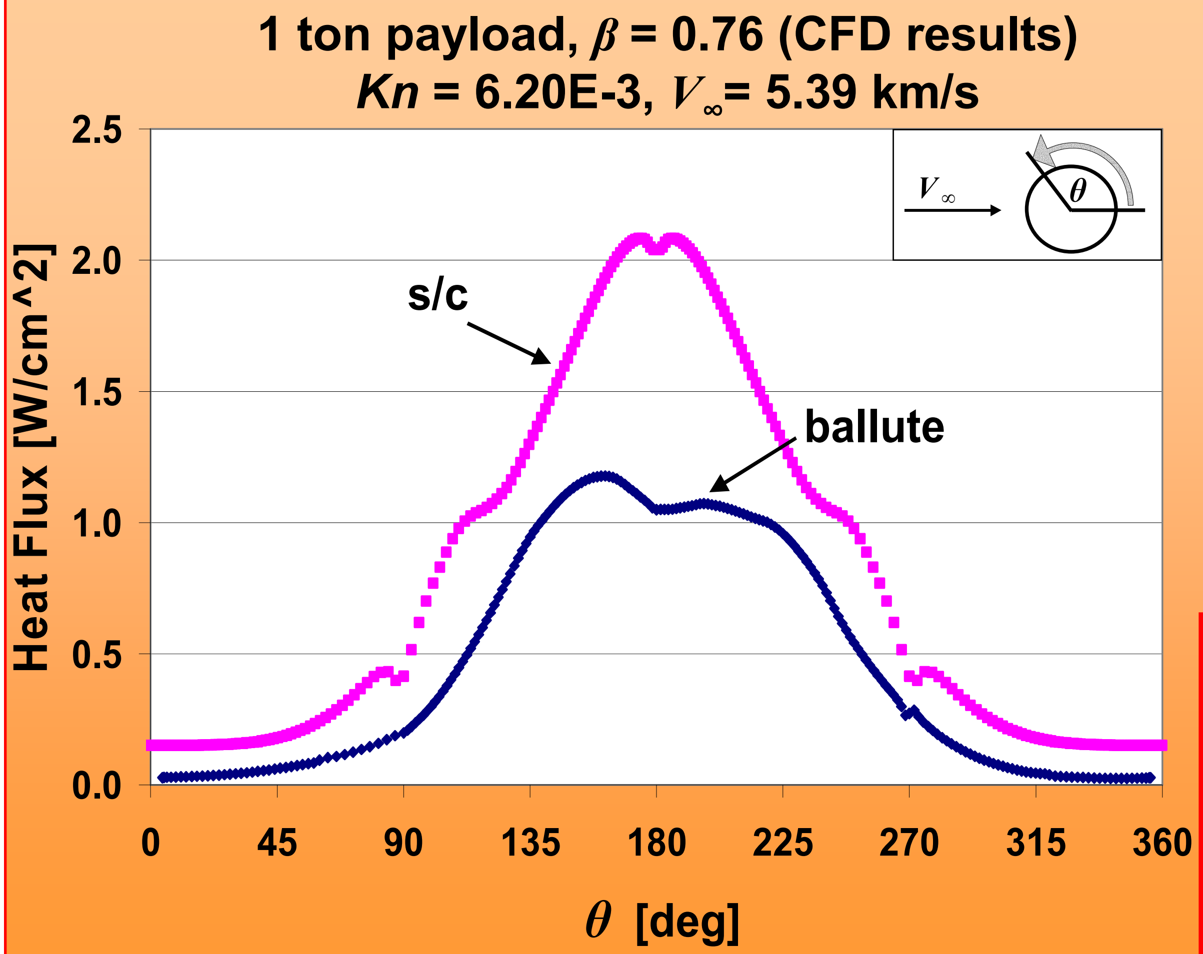
$$C_D = 1.52$$

(expected to be lower when fully converged)

1 ton payload, β = 0.76 (CFD results)
Kn = 6.20E-3, V_∞ = 5.39 km/s



1 ton Surface Heating (CFD)



$$Q_{stag} = Cv^3 \sqrt{\frac{\rho}{R_n}}$$

$\downarrow$

Sutton-Graves model :

assuming C = 2.62E-8 kg$^{1/2}$/m

Q_s = 2.01 W/cm^2 ballute

Q_s = 3.32 W/cm^2 orbiter

Preliminary CFD results:

Q_s = 1.18 W/cm^2 ballute (41% lower)

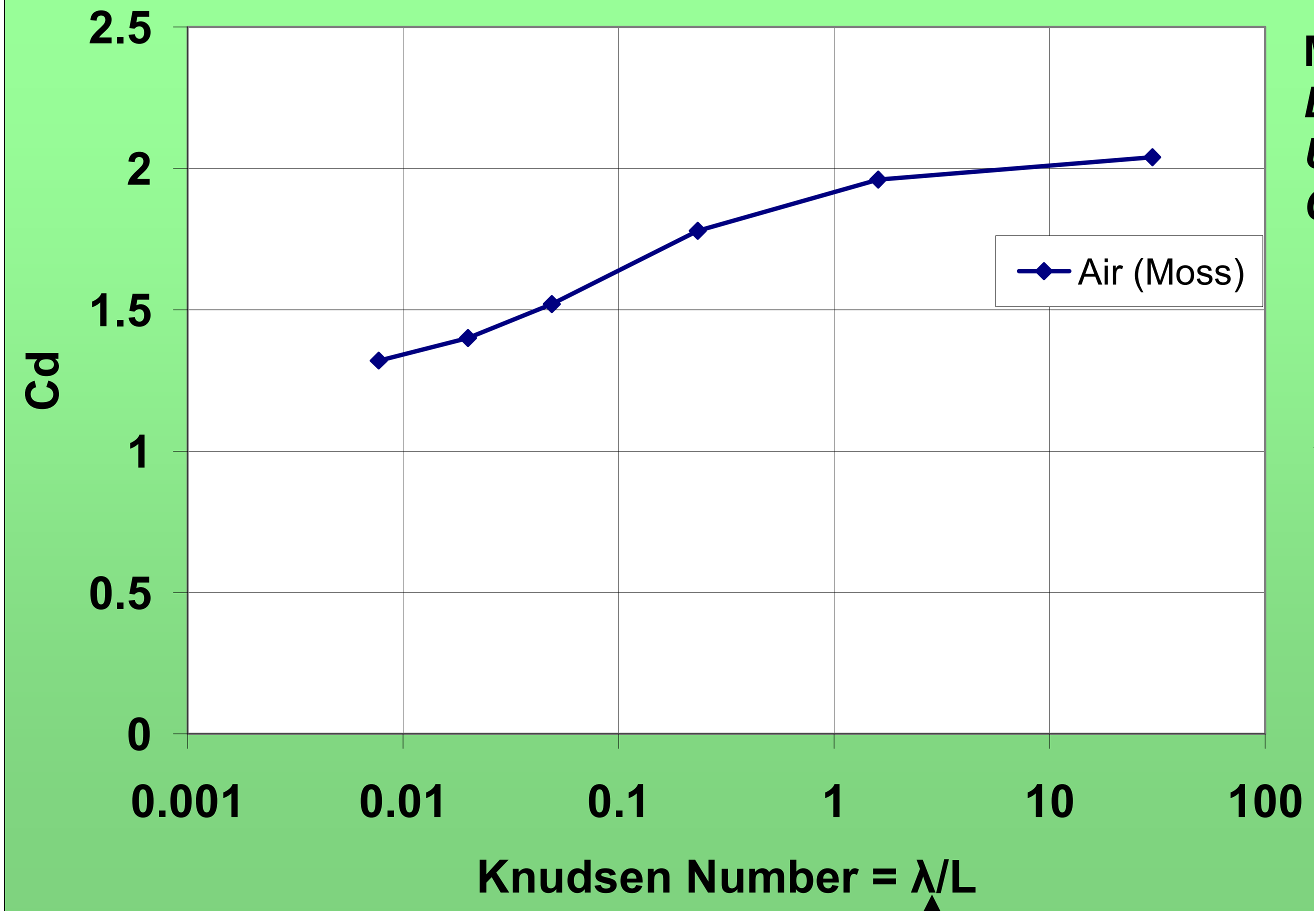
Q_s = 2.08 W/cm^2 orbiter (37% lower)

Conclusions

- Aerothermodynamic analysis indicates that C_D for Mars is higher than the C_D calculated for air at the same Knudsen number (as expected).
- Aerothermodynamic analysis (both DSMC and preliminary CFD) predict a lower ballute heat flux than estimated by Sutton-Graves model (34 % lower for the 0.1 ton case and 41% lower for the 1 ton case).
- Heating results suggest that ballute-spacecraft systems with larger ballistic coefficients (than predicted by the Sutton-Graves model) are feasible for Mars aerocapture.

Back-up Slides

DSMC Predictions for C_D vs. Kn (Earth)



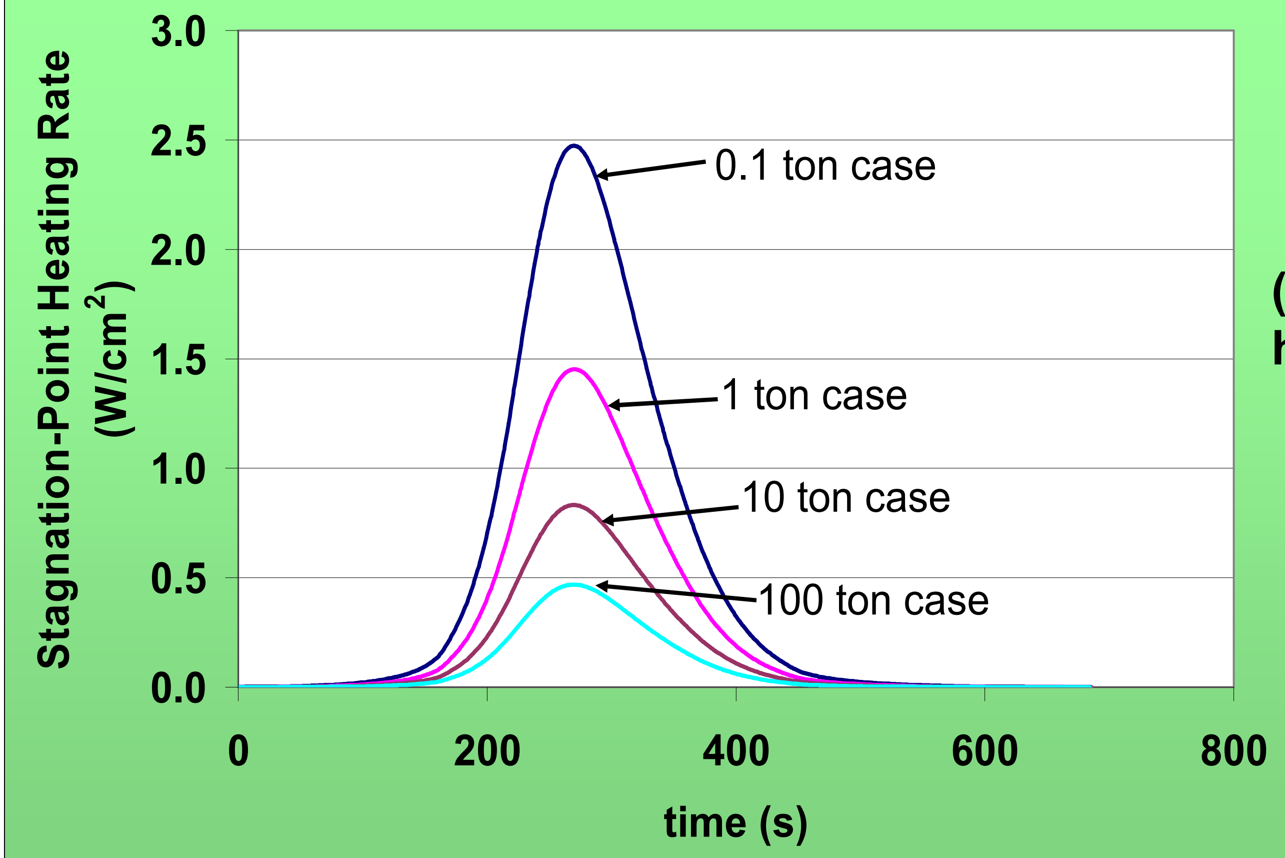
Moss, "*DSMC Simulations of Ballute Aerothermodynamics Under Hypersonic Rarefied Conditions*", AIAA 2005-4949.

$$D = \frac{1}{2}\rho V^2 A \underset{\uparrow}{C_D}$$

function of Kn

Mean free path, λ, is a function of altitude

Stagnation Point Heating Rate



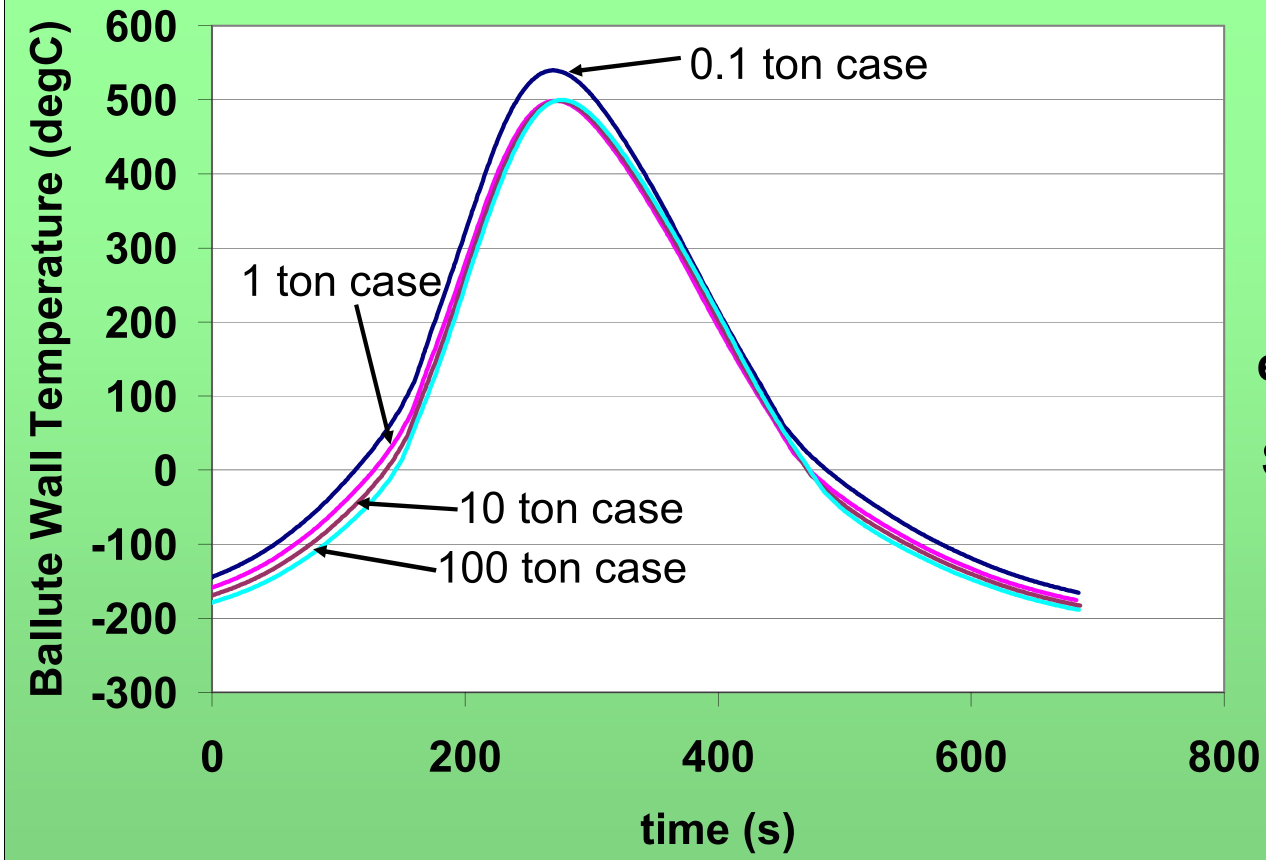
$$Q_s = \frac{C\rho^{0.5}V^3}{\sqrt{R_n}}$$

(based on Sutton-Graves heating approximation)

Larger ballute = lower heating rate at a given altitude

$$\text{for Kapton: } T_{w,\max} = 500^\circ C \rightarrow Q_{s,\max} = 2.01\ W/cm^2$$

Stagnation Point Heating Rate



$$T_w^4 = \frac{1}{2\varepsilon\sigma} Q_s$$

emissivity ($\varepsilon = 0.5$)

Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}\ kg/s^3/K^4$)

0.1 ton: β = 0.50

1 ton: β = 0.76

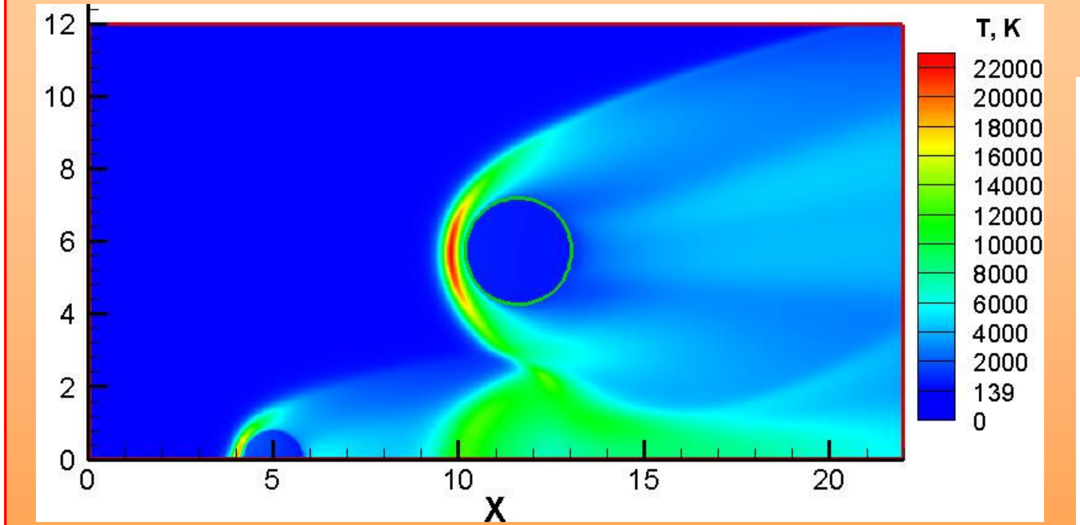
10 ton: β = 1.60

100 ton: β = 3.45

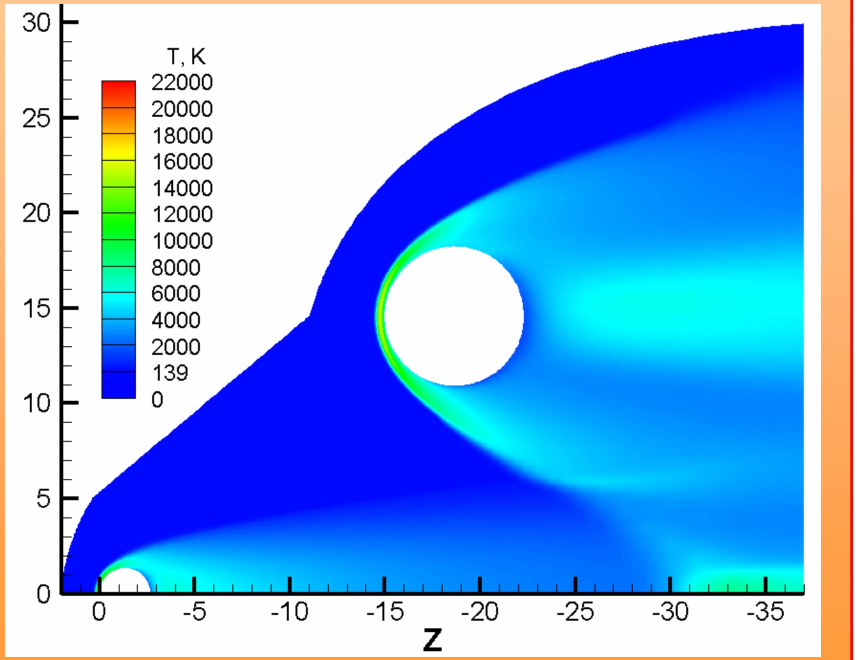
for Kapton: $T_{w,\max} = 500^\circ C \rightarrow Q_{s,\max} = 2.01\ W/cm^2$

Temperature

0.1 ton payload, $\beta = 0.50$ (DSMC results)
$Kn = 2.63E\text{-}2$, $V_\infty = 5.38$ km/s



1 ton payload, $\beta = 0.76$ (CFD results)
$Kn = 6.20E\text{-}3$, $V_\infty = 5.39$ km/s



$$T_\infty = 139\ \text{K}$$

High temperature leads to CO_2 dissociation, which causes chemical reactions.

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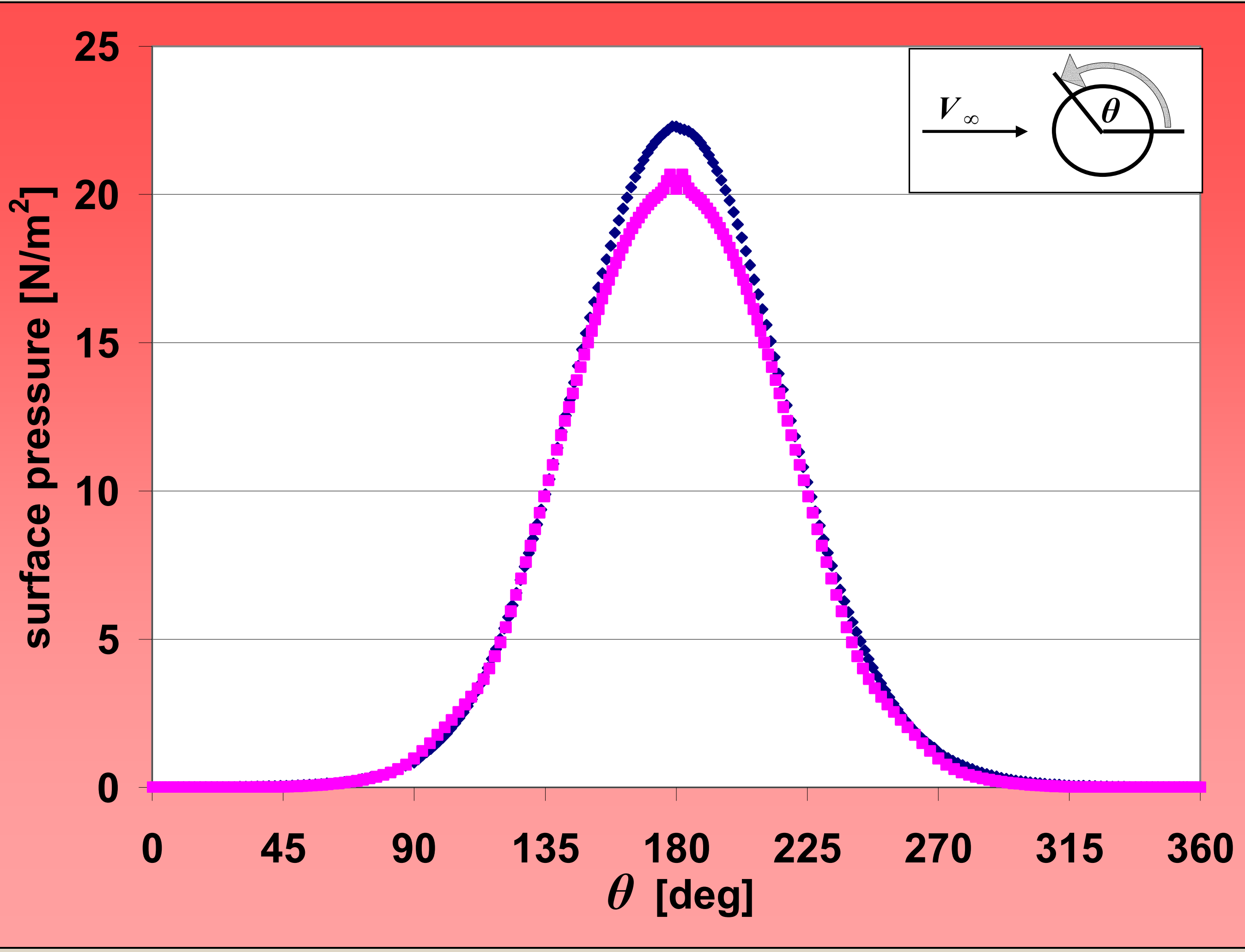
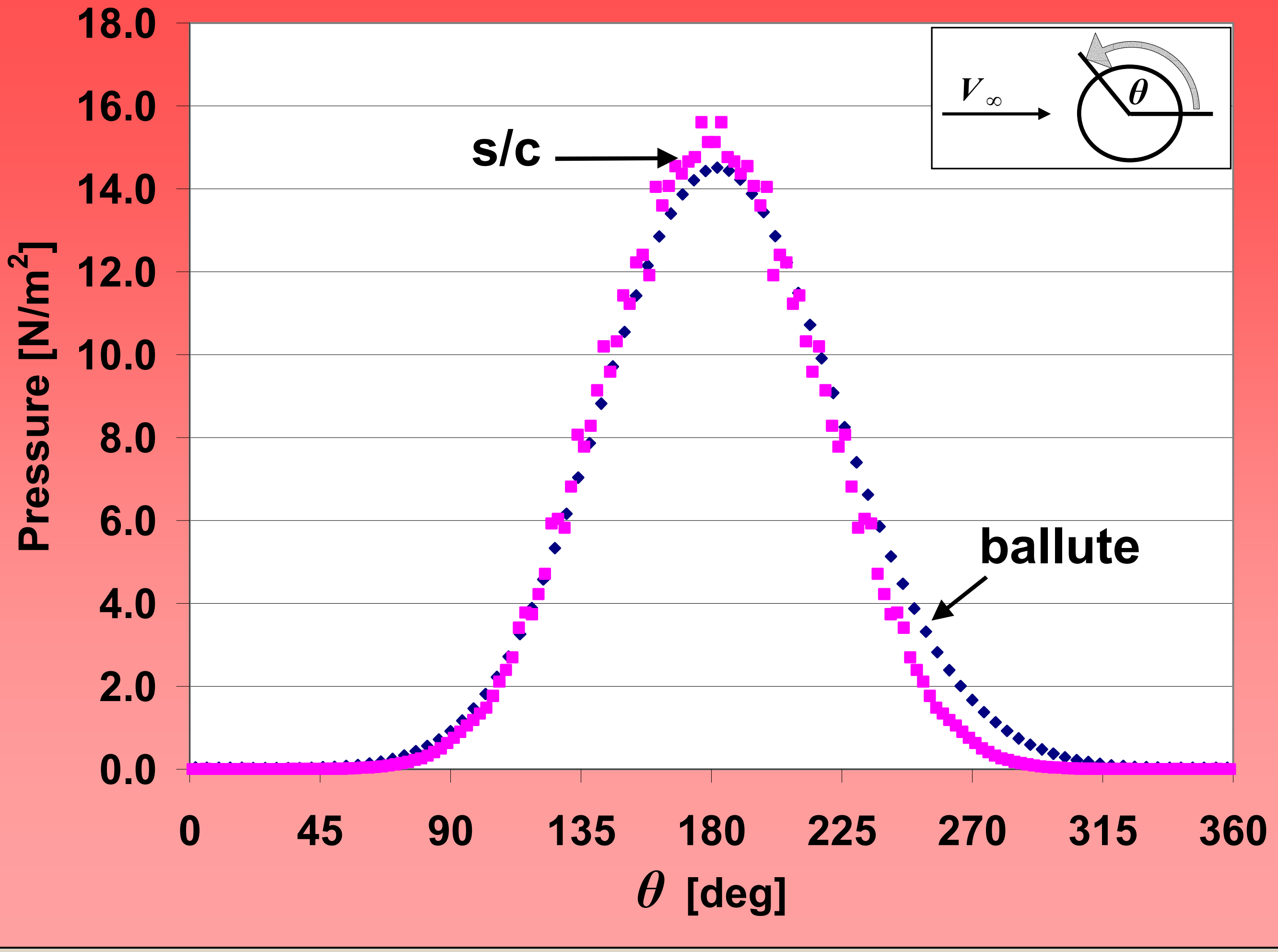
Surface Pressure (1 ton, CFD)



Surface Pressure (0.1 ton, DSMC)



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Surface Temperature (0.1 ton, DSMC)