Effects of Counterflow Jet on the Performance of a Generic Rocket

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Outline:

- Research goal and introduction
- Description and choice of the body shape
- Previous research results for Mach 6
- Questions posed and answered in summer 2021
- Conclusions

Drag and Average Surface Temperature Equations

$$Drag = D_{skin\ friction} + D_{pressure} + \iint_{jet-exit\ area}(P - P_a)\,dA + \iint_{jet-exit\ area}\left(\rho\, U_{je}^2\right) dA$$

$$D_{pressure} = \left(-\iint_{rocket\ surface}(P - P_a)\,dA\,\vec{n}\right).\vec{\imath}$$

$$D_{skin\ friction} = \left(\iint_{rocket\ surface}\tau\ dA\,\vec{s}\right).\vec{\imath}$$

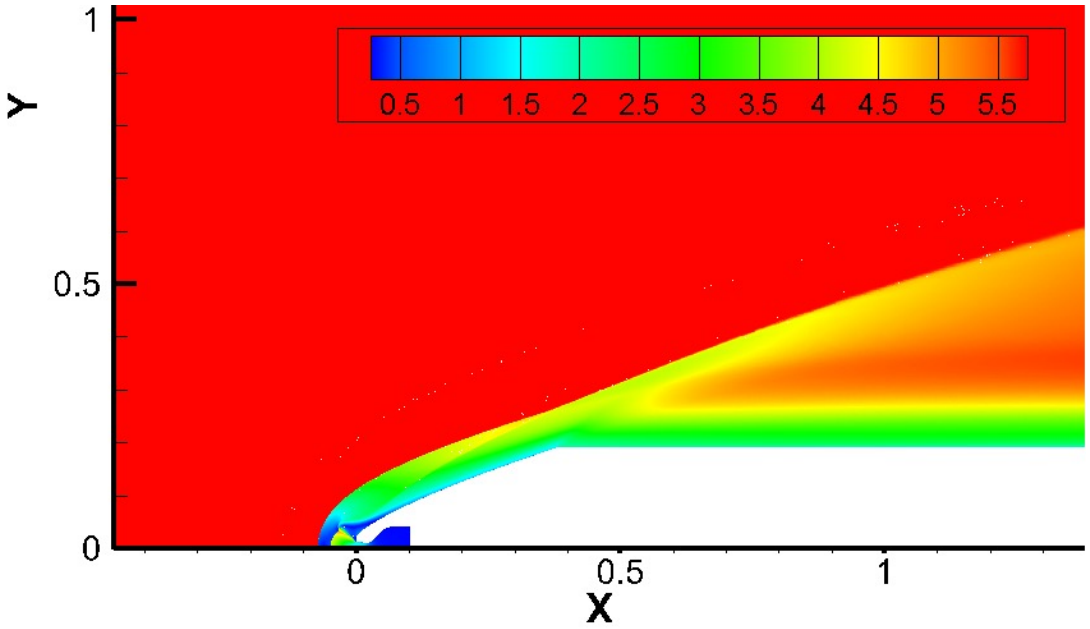
$\vec{n}$:unit vector perpendicular to the surface,

$\vec{s}$:unit vector tangential to the surface,

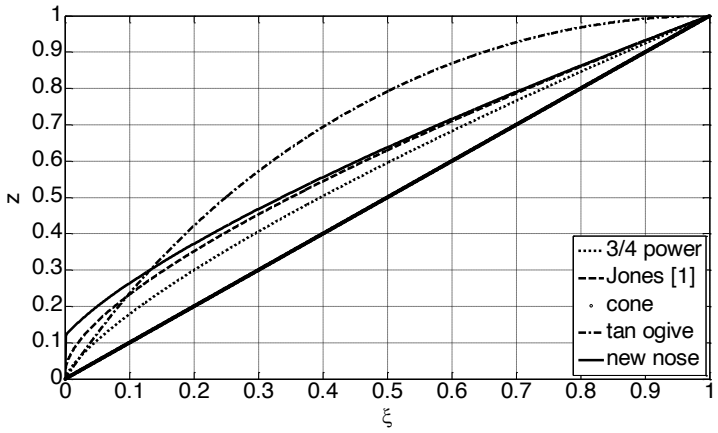
$\vec{\imath}$: unit vector along the axial direction.

Area-weighted average surface temperature :

$$T_{ave} = \frac{\left(\iint_{rocket\ surface} T\ dA\right)}{\left(\iint_{rocket\ surface} dA\right)}$$



Numerical and Experimental Analysis of Projectile Nose Geometry---Schinetsky, Brooker, Treadway, Ölçmen, and Jones
JOURNAL OF SPACECRAFT AND ROCKETS Vol. 52, No. 5, September–October 2015





From left to right: ¾ power series, AMNG, standard cone, tangent ogive, new nose shape. Dia. 1.225”

$$N = \frac{C_D}{2} = 2\alpha^2 \int_0^1 \frac{zz'^3}{1+\alpha^2 z'^2} d\xi = \sum N_i$$

$$z_{i,j+1} = z_{i,j} - C_1 * \left(\frac{\partial N}{\partial z_i}\right)_j$$

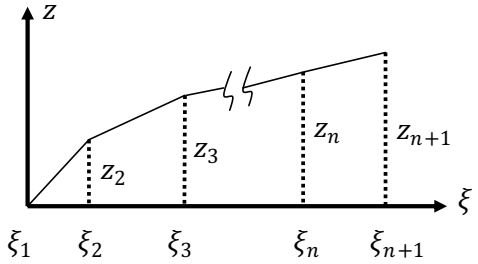
$\alpha = a/b$ =0.5 in this research

a = Nose Radius at the Base

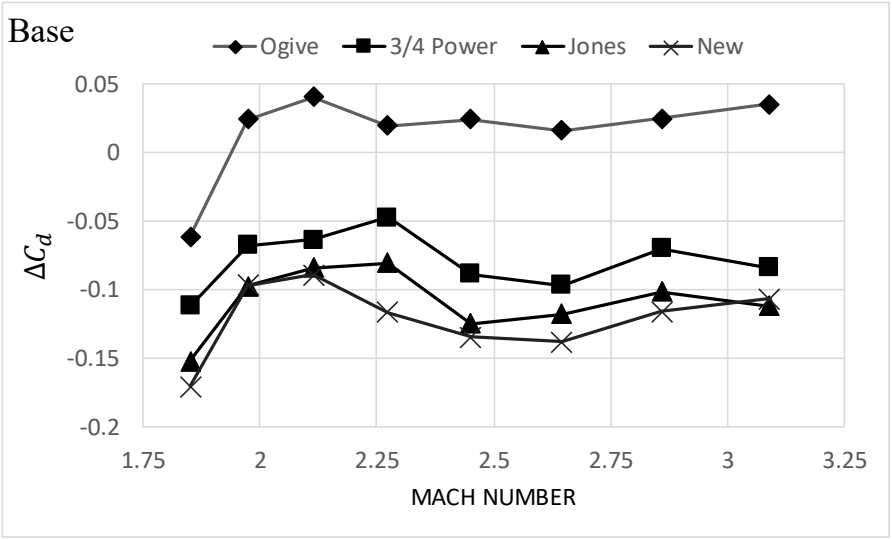
b = Nose Length

$z = y/a$

$\xi = x/b$



Nose shape presented with line segments.

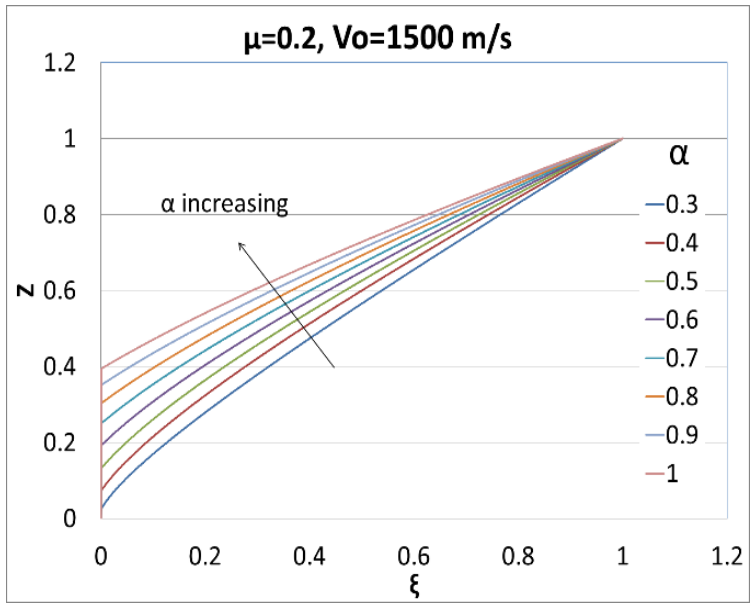


Mach number vs. ΔC_d change in comparison to the conical nose for different nose shapes in supersonic tunnel.

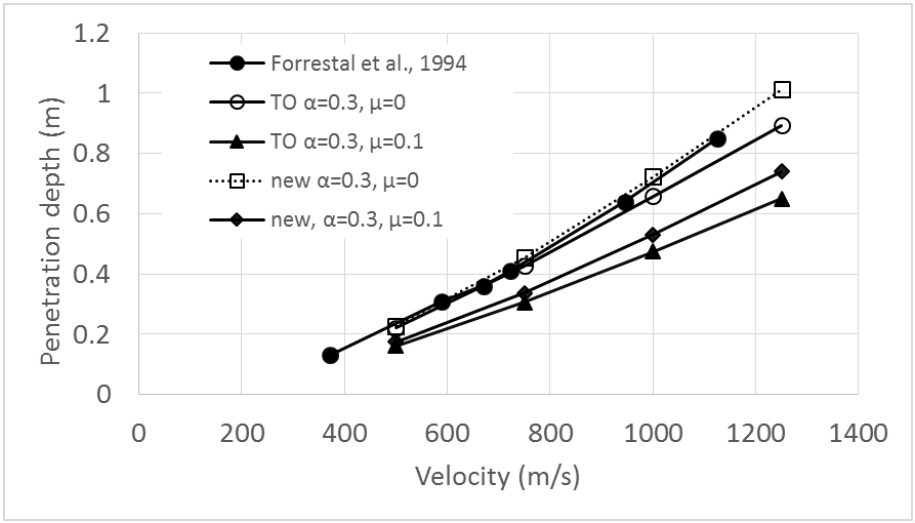
A Numerical Analysis of Projectile Nose Geometry Including Sliding Friction for Penetration Into Geological Targets
Ölçmen, Jones, and Weiner
Proc IMechE Part C: J Mechanical Engineering Science, 2016

$$D_P = 2\pi \int_0^b \left[Av^2 y \frac{y'^3 + \mu y'^2}{1 + y'^2} + B(yy' + \mu y) \right] dx$$

A=Target Density.
B=Target Compressive Dynamic Strength (Pa)
μ= Friction Coefficient

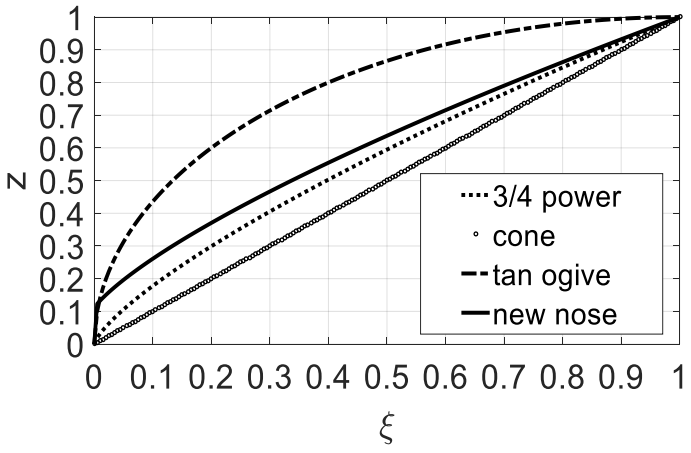


Optimal nose shape variation with different α values at selected μ and v_0 values

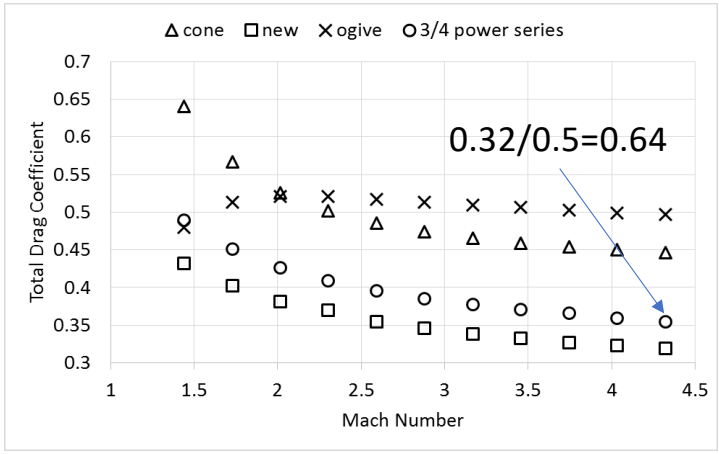


Comparison of penetration depths calculated for tangent-ogive and the optimal nose shapes at different velocities for $\alpha = 0.3$ with $\mu = 0\ or\ 0.1$, and the data by Forrestal et al., 1994.

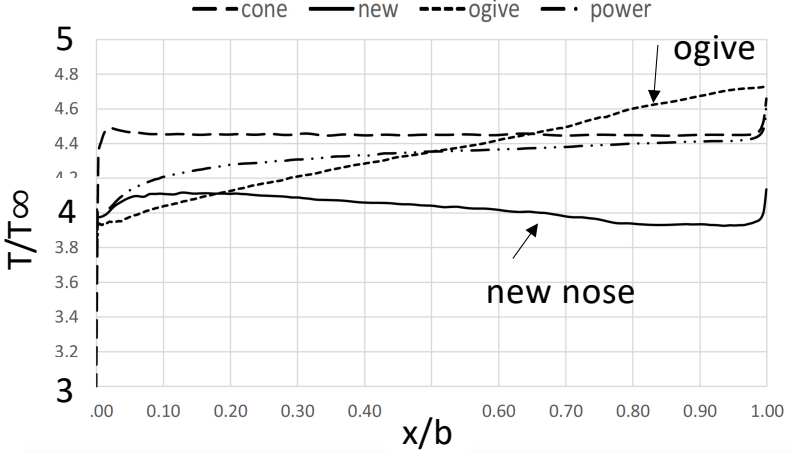
Minimum Drag and Heating 0.3-caliber Projectile Nose Geometry------Ölçmen, Cheng, Branam and Jones
Proc IMechE Part C: J Mechanical Engineering Science 2019, Vol. 233(6) 1990–2000



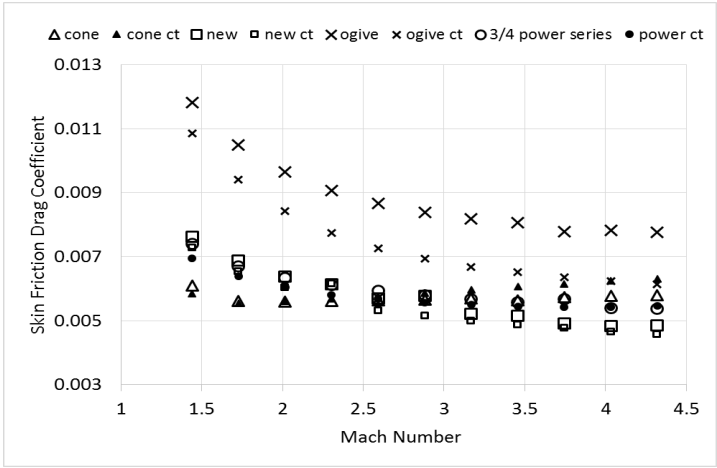
Nose geometries used in the study. b/a = 2 or α = 0.5.



Total drag coefficients for different geometries with adiabatic body assumption.



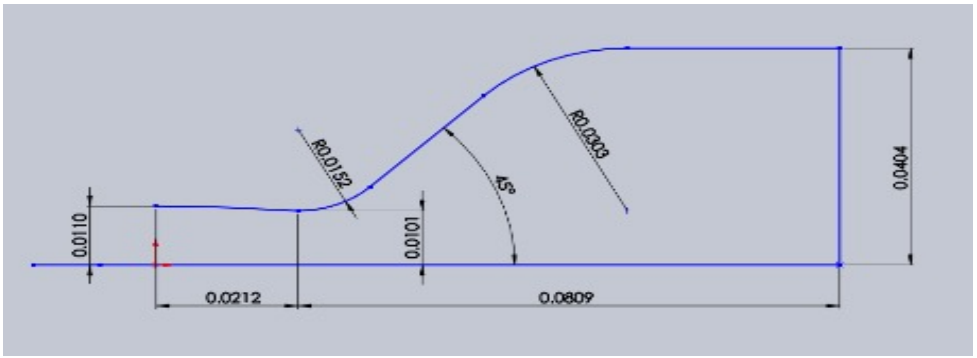
Surface temperature distribution over the nose geometries for the adiabatic body calculations *M* 3.74.

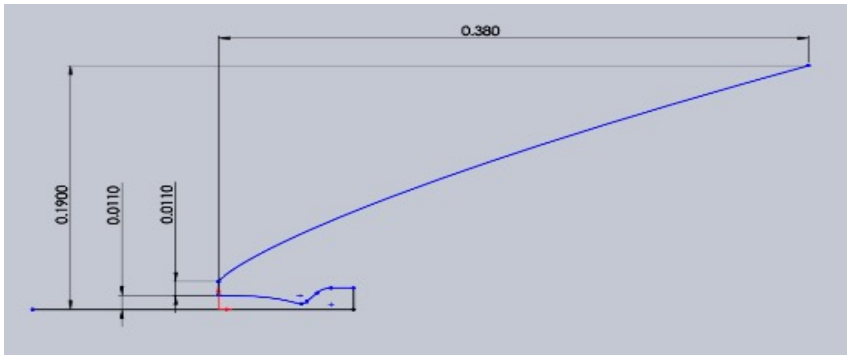


Skin friction contribution to drag coefficients for different geometries. It is about 1.6 % of the

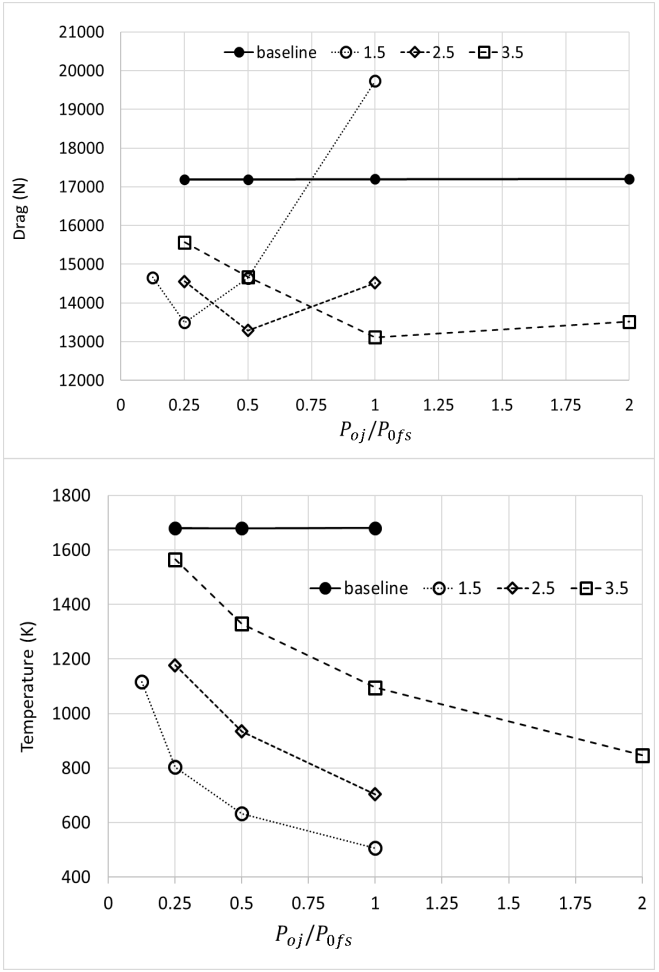
Effects of Counterflow Jet on the Performance of a Generic Rocket
Ölçmen, Cheng, Branam, Baker
Acta Astronautica 182 (2021) 219–229

Freestream, Mach 6 at 40,000 ft. Turbulence model, Transition SST





M_{je} = 1.5 nozzle; top
M_{je} = 3.5 nozzle embedded into the model geometry. The dimensions are in meters. α = 0.5.



Comparisons of drag and average surface temperatures for different jet nozzles.

Questions posed:

1. How much drag reduction could be achieved if the jet total pressure was kept at the value set for the Mach 6, but the flight Mach number was different than Mach 6?

2. How would the area weighted average temperature change if the jet total temperature was different than 500 K at flight Mach 6?

3. What jet total pressure would give the most drag reduction at Mach numbers ranging 4 to 9, while the jet total temperature was kept at 500 K?

The flight conditions during the calculations were kept as same as the previous Mach 6. Calculations were made for 40,000 ft atmospheric conditions.

Methodology:

Density-based, implicit method with axisymmetric and steady flow assumptions, and were iterated until the steady results were obtained.

Gradients were calculated using least squares cell-based approach, and advection terms were discretized using the second-order upwind scheme.

Turbulence model: Transition SST

Mesh for baseline body:
First inflation layer at 1.0 micron away from the wall.
80 inflation layers with a growth rate of 1.1.
Distance between the cells on the surface was 480 microns with a growth rate of 1.01.
500k grid cells in the domain. Grid adaptions were performed as needed.

Mesh for counterjet flow body:
First inflation layer at 1.0 micron away from the wall.
30 inflation layers with a growth rate of 1.2.
Distance between the cells on the surface was 250 microns with a growth rate of 1.01.
864k grid cells in the domain. Grid adaptions were performed as needed.

Summer Research Calculations- All calculations at 40,000 ft atmospheric temperature and pressure.

elevation (m)	absolute pressure (Pa)	gage pressure (Pa)	temperature (K)
12192	18822.69	-82502.7	216.65

Baseline
Mach
4
5
6
7
8
9

Jet-Plenum chamber total temp = 500 K total pressure = 7429683 Pa abs
Mach
4
5
6
7
8
9

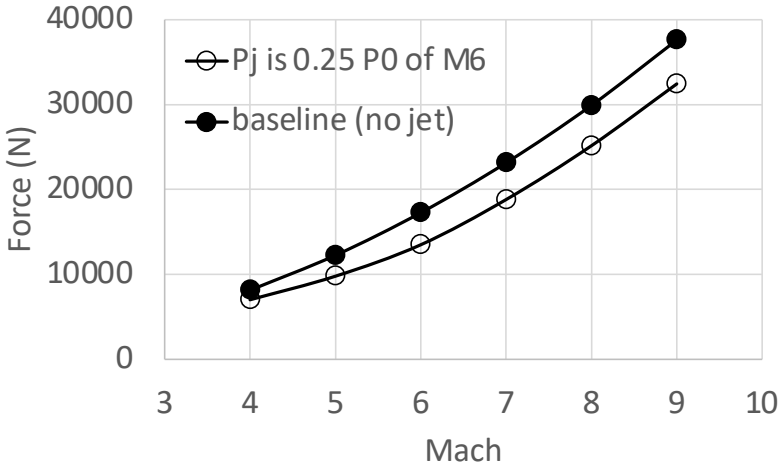
Jet-freestream M 6 total pressure = 7429683 Pa abs
Total temperature (K)
300
400
500
600
700
800
900
1000

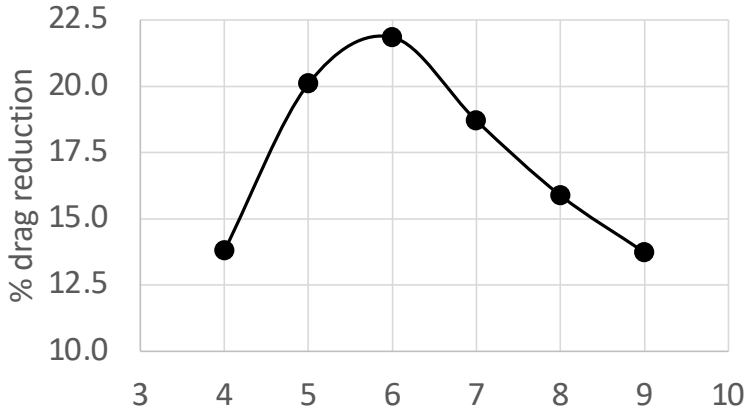
Total of 46 cases

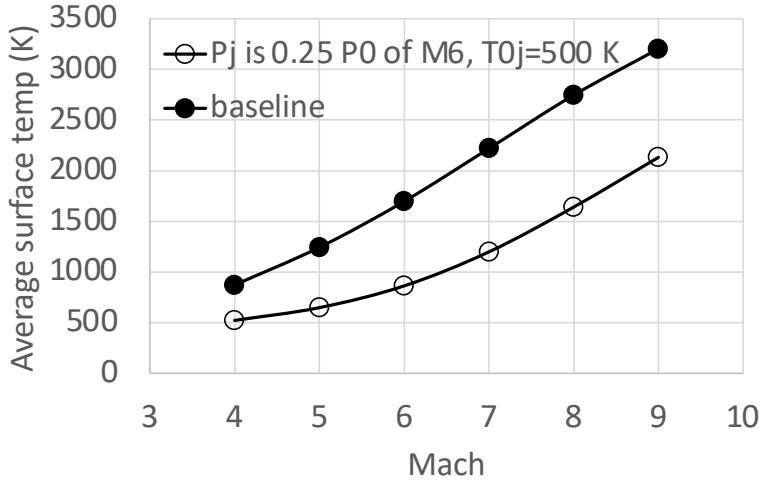
Jet-Plenum chamber total temp = 500 K										
Mach	Jet P0 / freestream P0									
	0.0312	0.0625	0.125	0.25	0.375	0.5	0.75	1	1.25	1.5
4				X		X	X	X	X	X
5				X		X	X			
6			X	X		X		X		
7		X	X	X		X				
8	X	X	X	X	X					
9	X	X	X	X						

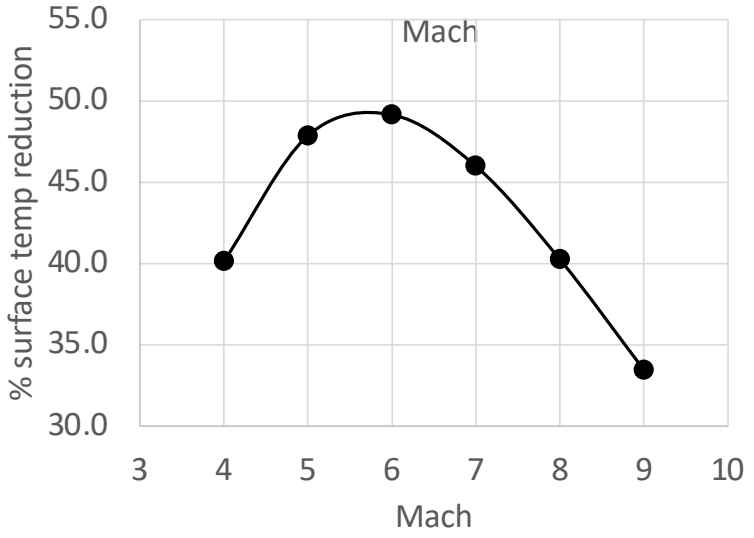
Mach	4	5	6	7	8	9
Total Pressure (Pa abs)	2857947.96	9958896	29718733	77922871	1.84E+08	3.97E+08

Q1. Effect of Using P_{0j} = 0.25 P_{0fs} of M 6 Freestream at Different Mach Numbers

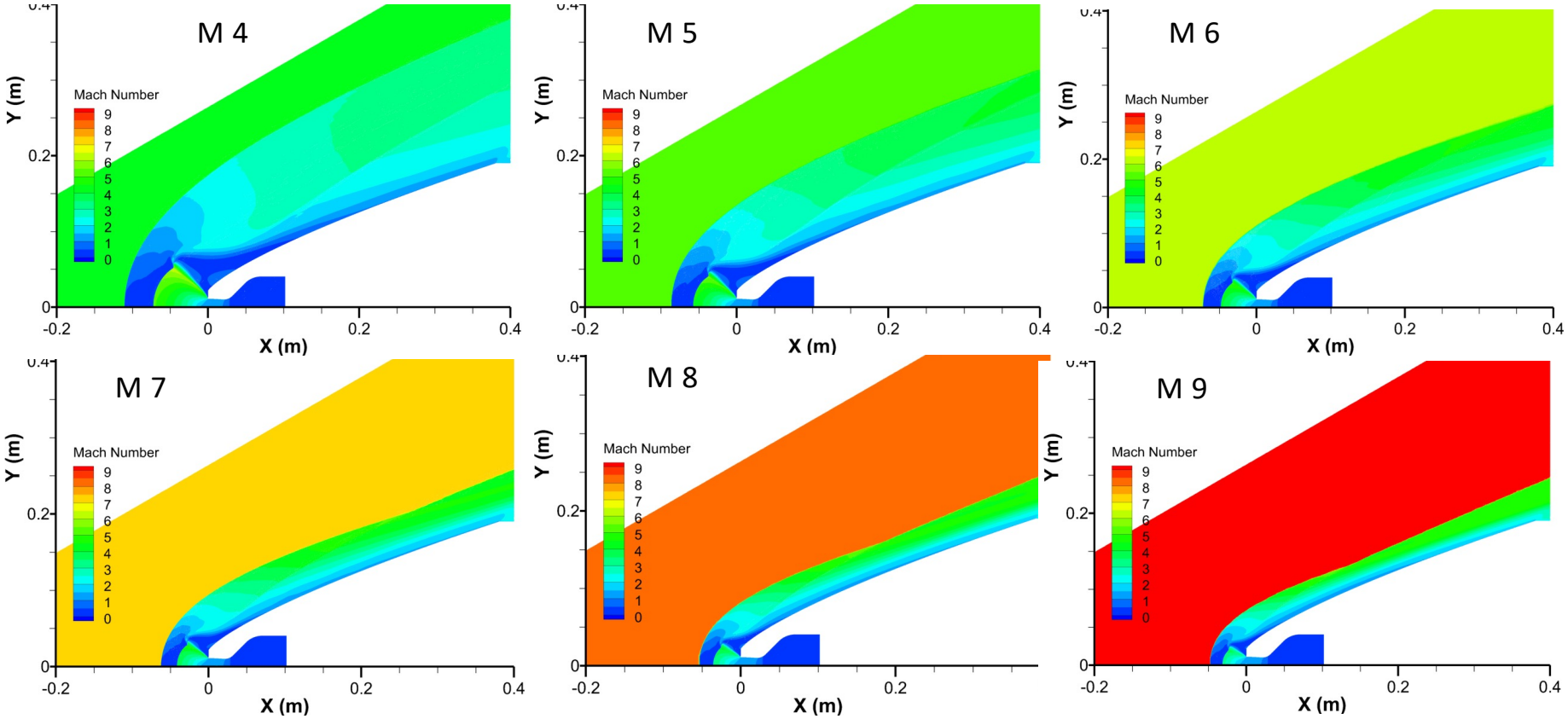




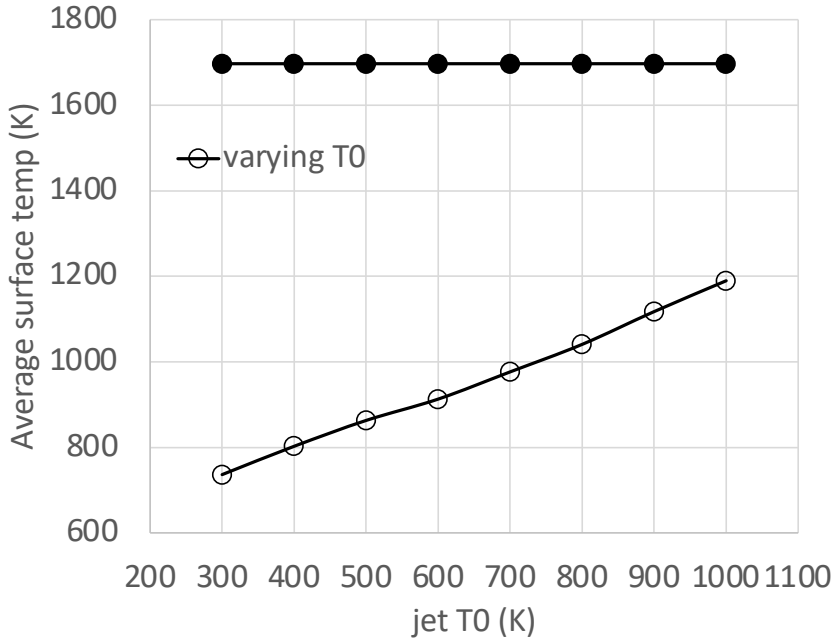


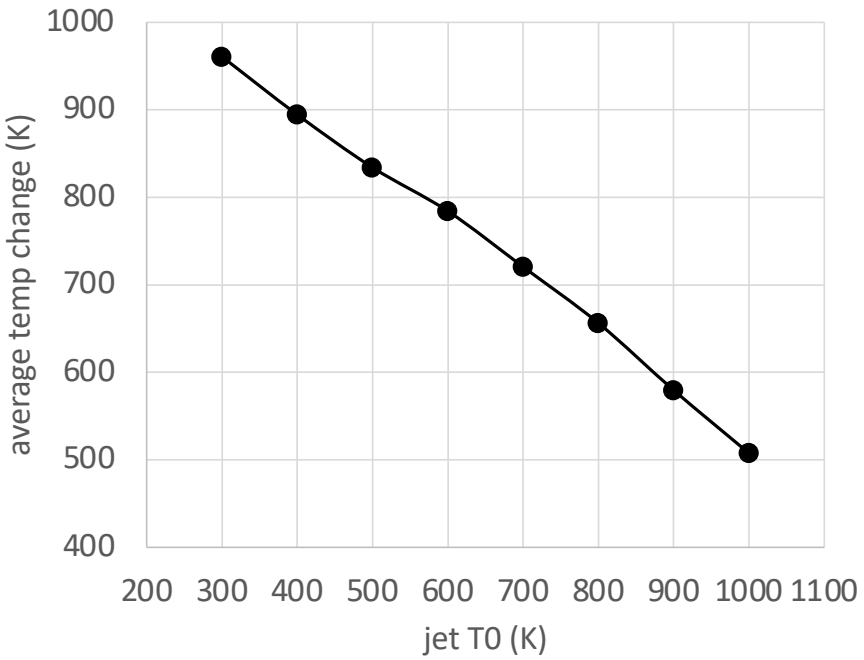


Effect of Using P_{0j} = 0.25 P_{0fs} of M 6 Freestream at Different Mach Numbers

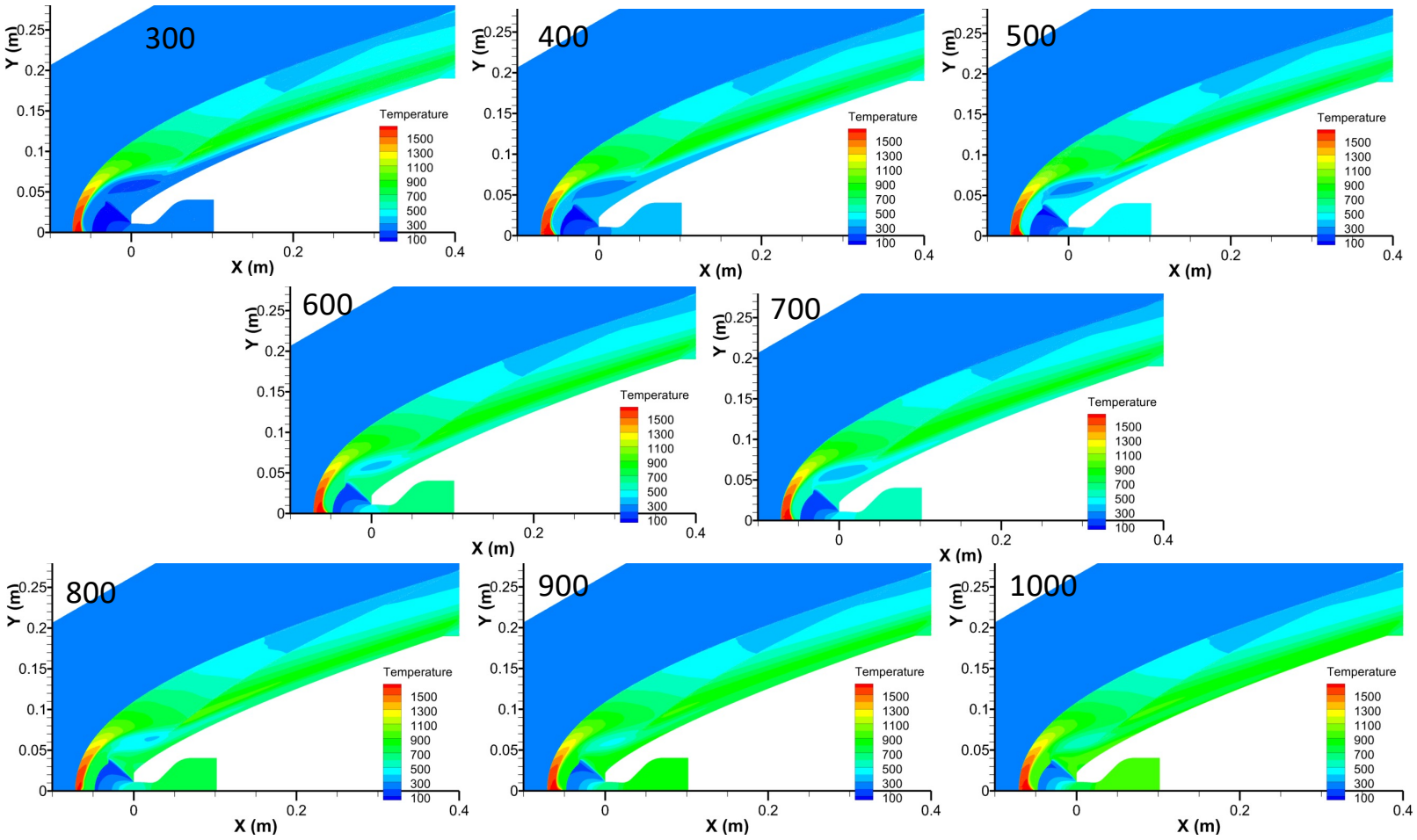


Q2. Effect of Using Different T_{0j} at M 6 Freestream on the Average Surface Temperature

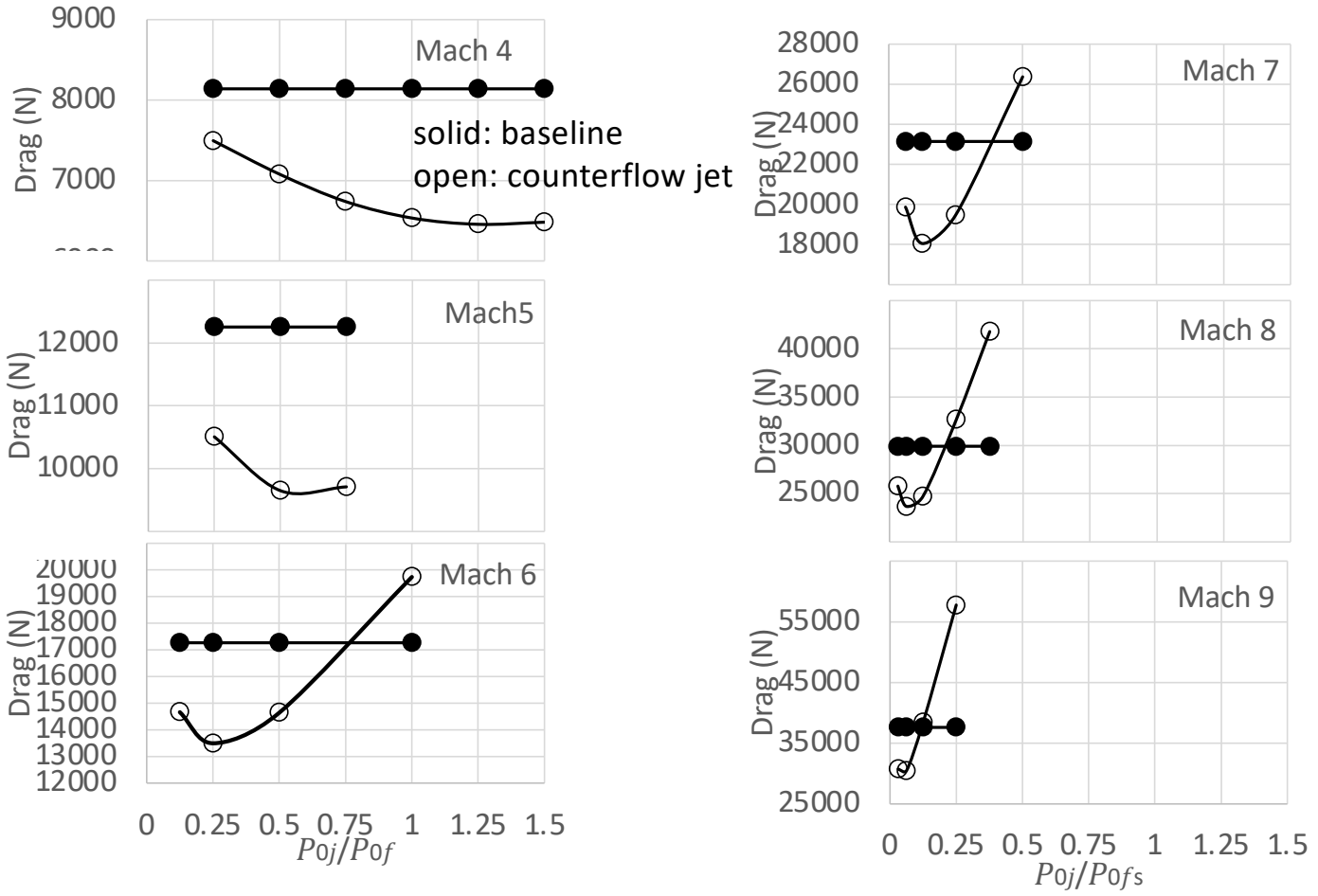




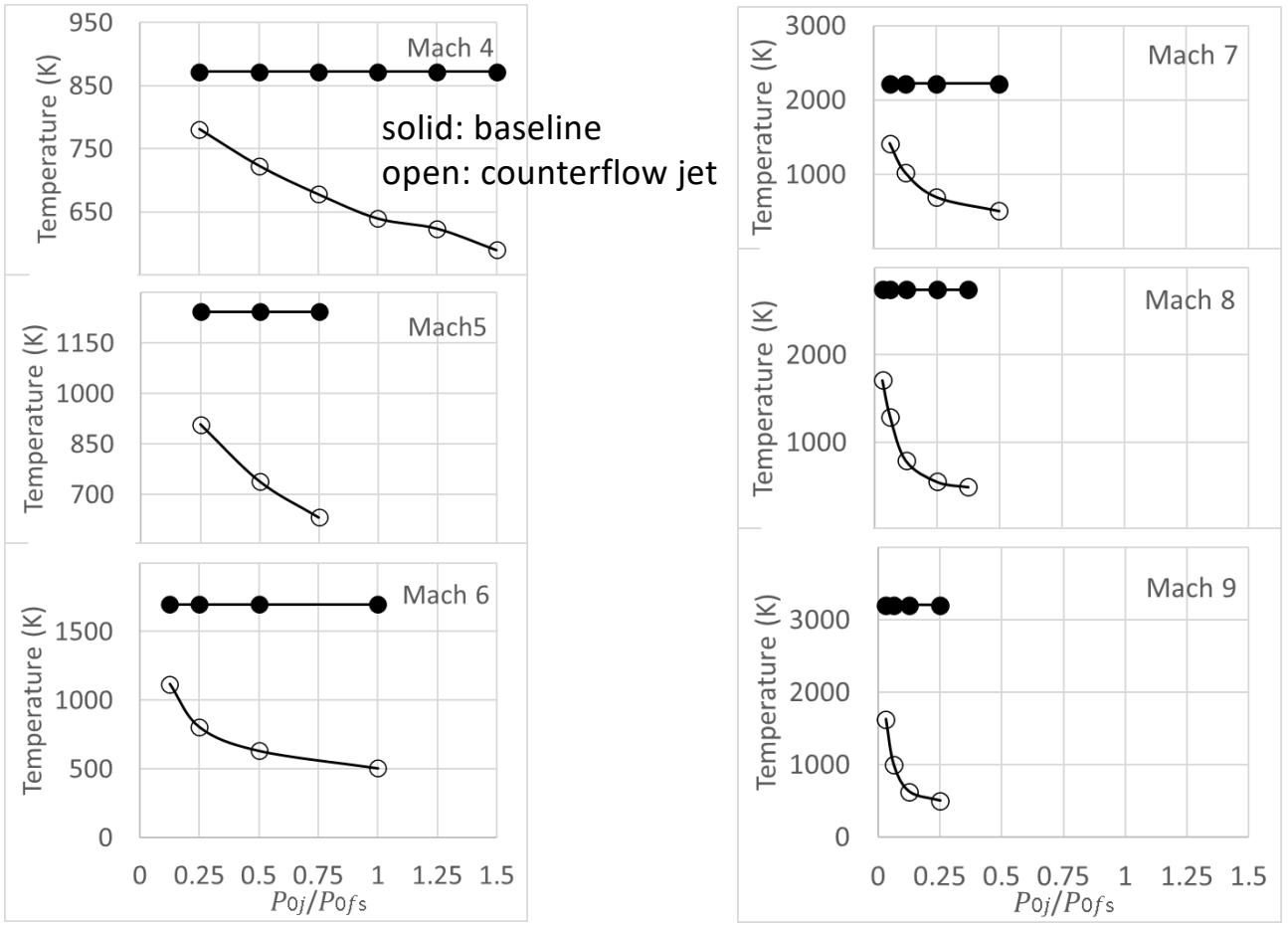
Effect of Using Different T_{0j} at M 6 Freestream on the Average Surface Temperature



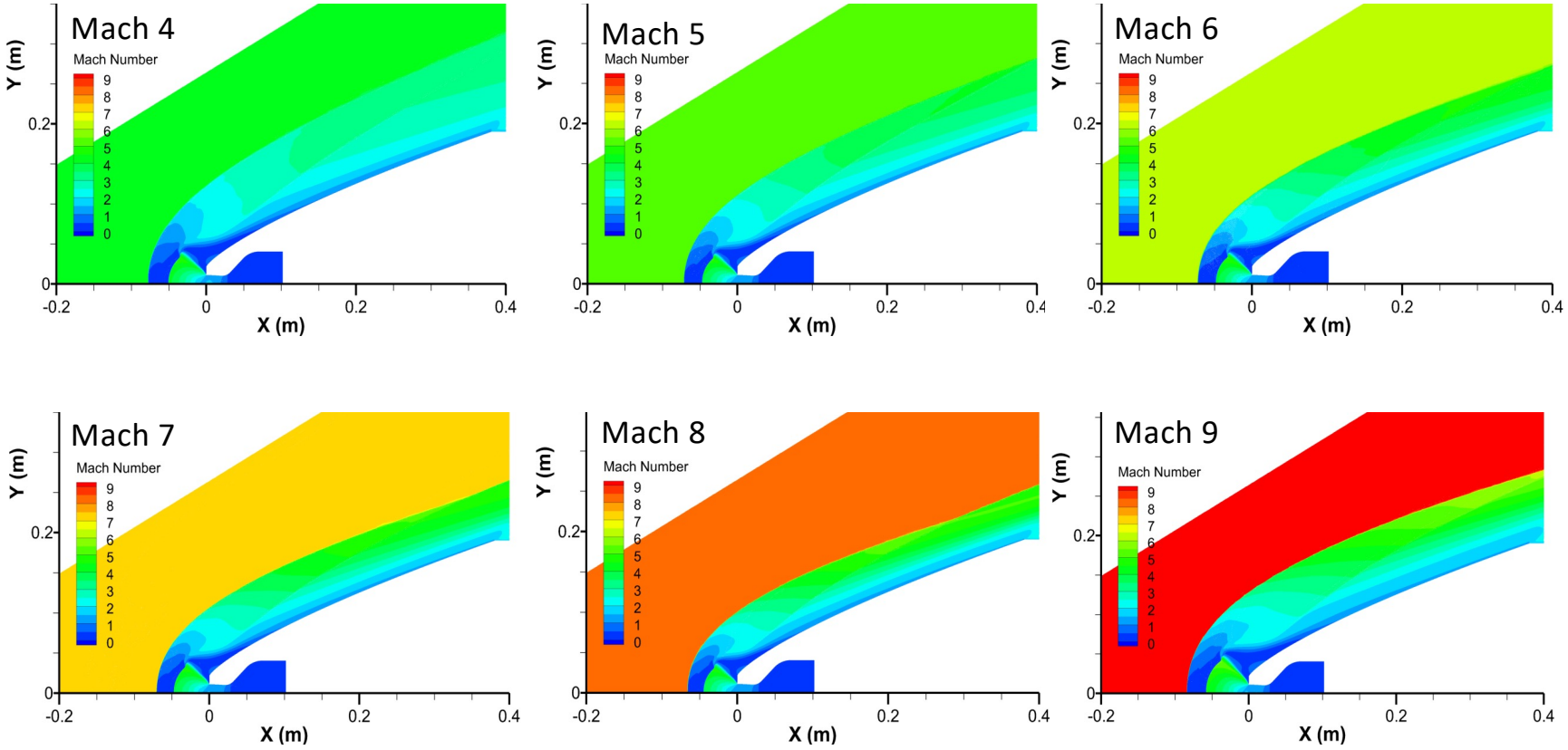
Q3. Determination of the P_{0j} that Results in Least Total Drag for a Given Mach Number

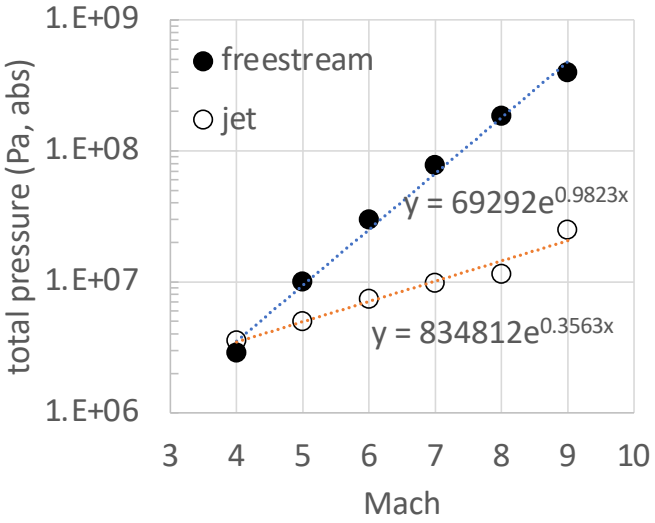


Variation of the Average Surface Temperature with the P_{0j} for a Given Mach Number

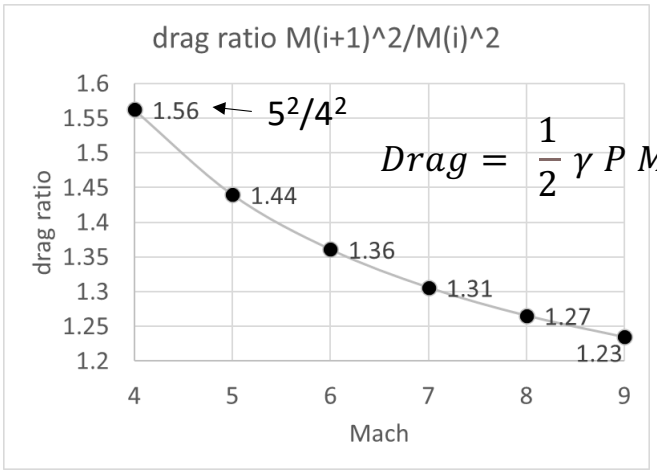


Mach Number Contours for P_{0j} that Results in Least Total Drag for a Given Mach Number



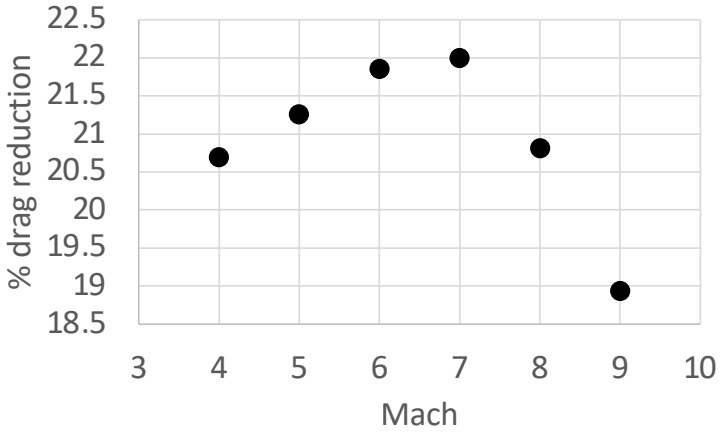


Relation between the freestream and the jet total pressures for the most drag reduction.

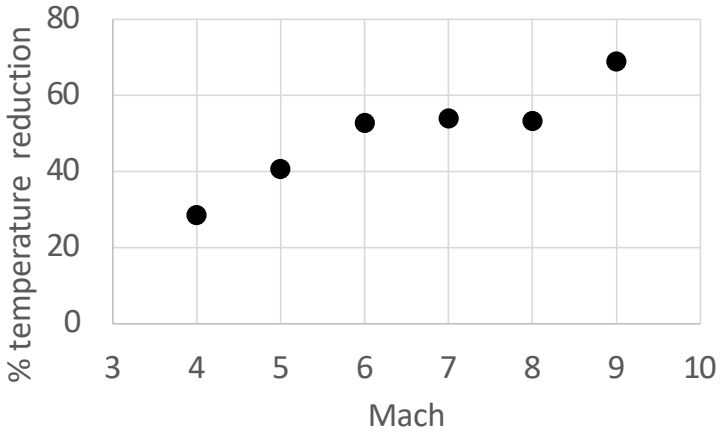


$$Drag = \frac{1}{2}\gamma P M^2 S C_d$$

Drag ratio variation with Mach number.



Percent drag reduction at different Mach numbers with P_{0j} that result in most drag reduction.



Temperature reduction at different Mach numbers with P_{0j} that result in most drag reduction.

Conclusions

- Using P_{0j} = 0.25 P_{0fs} of Mach 6 freestream at different Mach numbers results in drag reduction between %14 and % 22 within the Mach 4-9 range.
- Using P_{0j} = 0.25 P_{0fs} of Mach 6 freestream at different Mach numbers and T_{0j} = 500K results in average surface temperature reduction in between 350 to 1100 K. More temperature reduction is observed as the Mach increases.
- Using P_{0j} = 0.25 P_{0fs} of Mach 6 freestream at Mach 6 with varying T_{0j} between 300 and 1000K indicate that the average surface temperature varies in between 700 to 1200 K almost linearly. The average surface temperature is decreased by 500 K even when the T_{0j} = 1000K.
- The jet total pressures that result in most drag reduction at different Mach numbers, while the T_{0j} = 500K, appear to be a function of the freestream flow total pressure.