Modeling and Simulation of MEMS Microthrusters

Deborah A. Levin,
Associate Professor,
Department of Aerospace Engineering
Penn State University

June 21-25, 2004

Istanbul, Turkey

AFOSR/EOARD Symposium on Energy Conversion Fundamentals

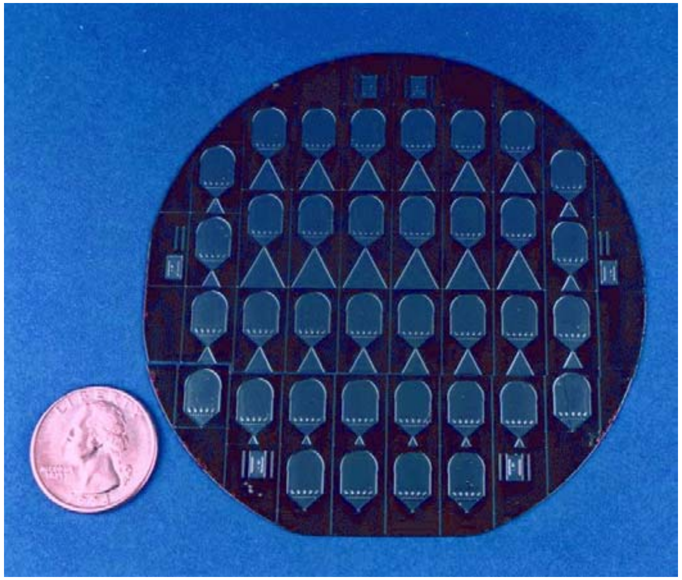
Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

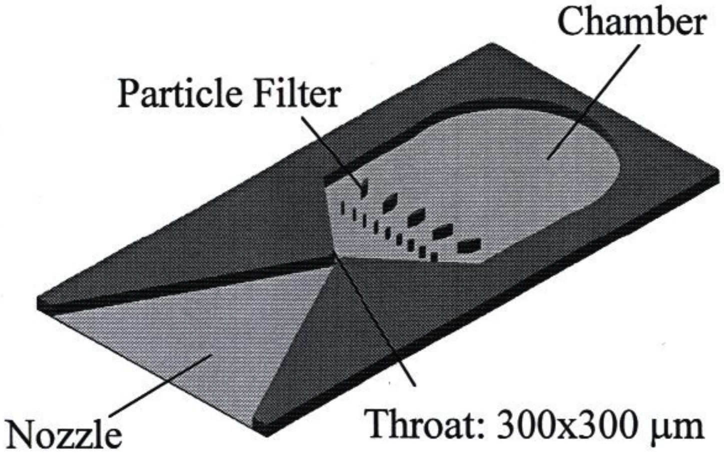
1. REPORT DATE **21 JUN 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Modeling and Simulation of MEMS Microthrusters**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Aerospace Engineering Penn State University**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM001793, International Symposium on Energy Conversion Fundamentals Held in Istanbul, Turkey on 21-25 June 2005., The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**25**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

MEMS-Based Propulsion





- To enable formation flying concept new propulsion systems are needed that can deliver precise impulse bits under strict mass, size and power limitations.
- Various MEM-based propulsion systems are considered for such missions: cold and heated gas, bipropellant, catalytic and solid decomposition thrusters.

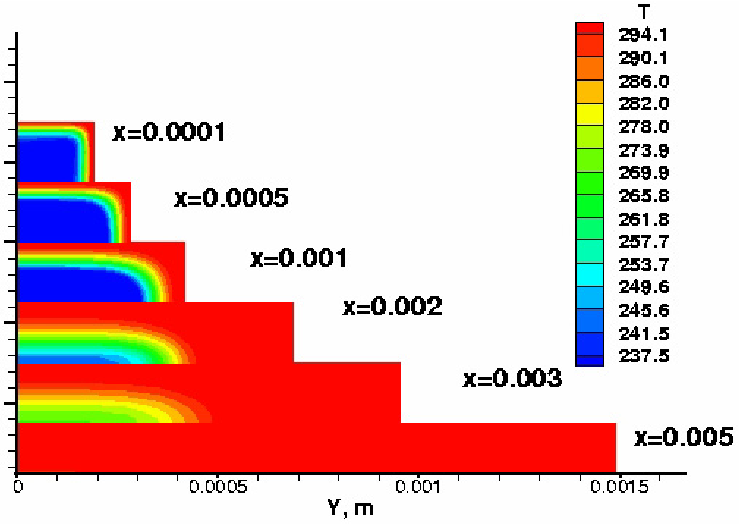
Physics of Micro-nozzle Flows

- **Due to the reduced physical size, frictional surface effects can dominate the gas flow in microthrusters.**

u/u(0)

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

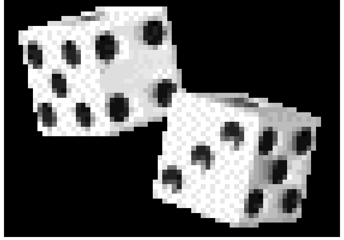
Comparison of boundary layers for traditional axisymmetric vs MEMS flows.



Development of 3D boundary layer in a cold gas flow.

- **In addition, wall temperature, heat transfer, and heat fluxes are major controlling factors for microthruster performance, yet it is often an unknown in the system design.**

The DSMC Method

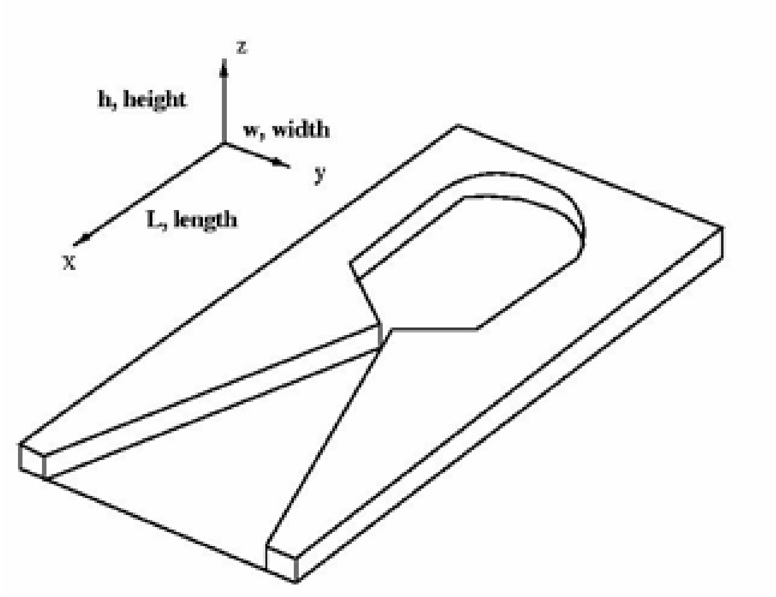


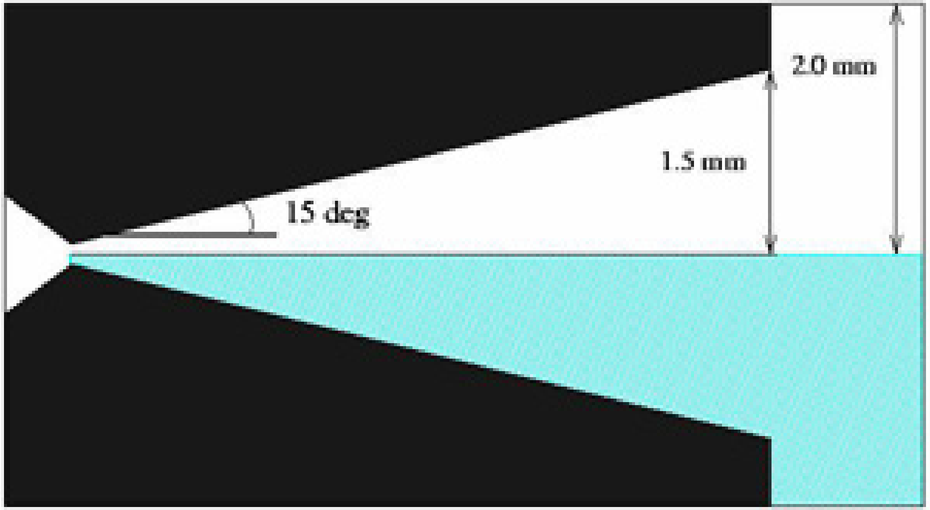
- **A simulation tool for modeling chemically reacting flows in *rarefied/transitional* environments.**
- $Kn = \lambda / l_{ref}$, λ = **mean free path,** l_{ref} = **reference length**
  - **—Continuum: Navier-Stokes, Kn ≤ ~ 0.001**
  - **—Transitional: DSMC , Kn ≥ ~ 0.01**
- **Developed by G. Bird to obtain a solution of the Boltzmann equation,**
  - **— follow the motion of many virtual molecules on a grid, for a series of time steps,**
  - **— calculate particle collisions using Monte Carlo techniques.**
  - **— model gas-surface interactions,**
  - **— using conservation relationships, obtain changes in internal energies and velocities of the components.**
- **Flows around spacecraft and micro-propulsion devices can be modeled by DSMC because they have similar *Kn*.**

Outline of Talk

- Cold gas thrusters - effects of
  - geometry: 3-D , 2-D, axisymmetric,
  - gas surface model,
  - performance.
- Higher temperature gas thrusters - effects of,
  - flowfield dependence on T_o, p_o
  - gas- surface interaction,
  - stagnation conditions and internal energy on performance.
- High-temperature gas thrusters with variable T_{wall},
  - coupled DSMC/FEM method,
  - variable material cooling conditions,
  - time-dependent calculations of thrust and material characteristics.

Cold Gas Thrusters - Geometry





- 3D flat nozzle
  - –XY plane expansion angle α =15°
  - –throat width w = 300 μm
  - –throat height h = 300 μm
  - –Area ratio A_e/A^* = 10
- 2D nozzle, neglect surfaces in x-y plane, for z=0, h

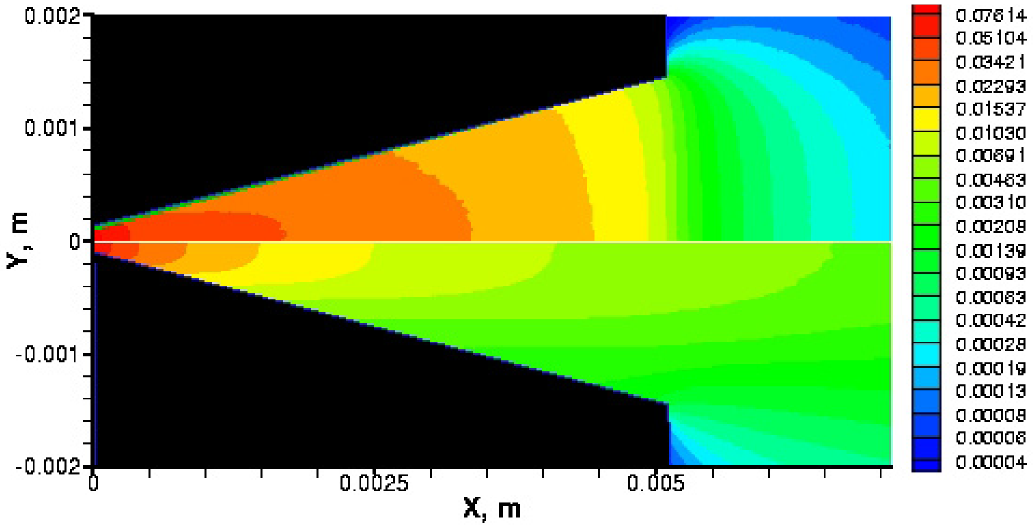
- Axisymmetric
  - –expansion angle α =15°
  - –throat radius R_t = 150 μm
  - –Area ratio A_e/A^* = 100

Cold Gas Thruster - Conditions

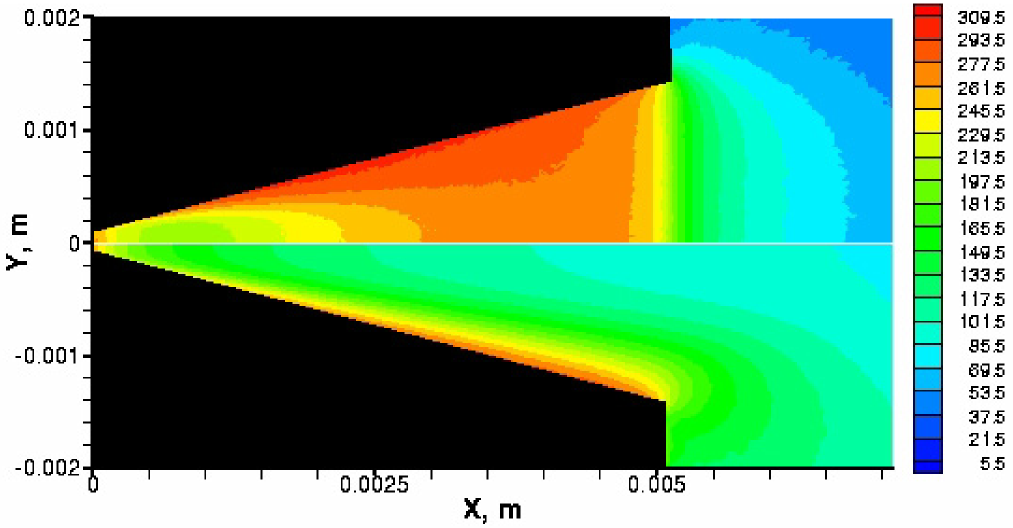
•Test gas	N_2
•Stagnation temperature and pressure	T_c = 300 K, P_c= 10 kPa
•Critical temperature and pressure	T_t = 250 K, P_t= 5.2 kPa
•Wall temperature	T_w = 300 K
•Knudsen number (mean free path/char length)	Kn = $5\text{x}10^{-3}$
•Reynolds number (mom/viscous ratio)	Re = 200

Cold Gas - Effect of Geometry

Top - 3-D, Bottom -2-D



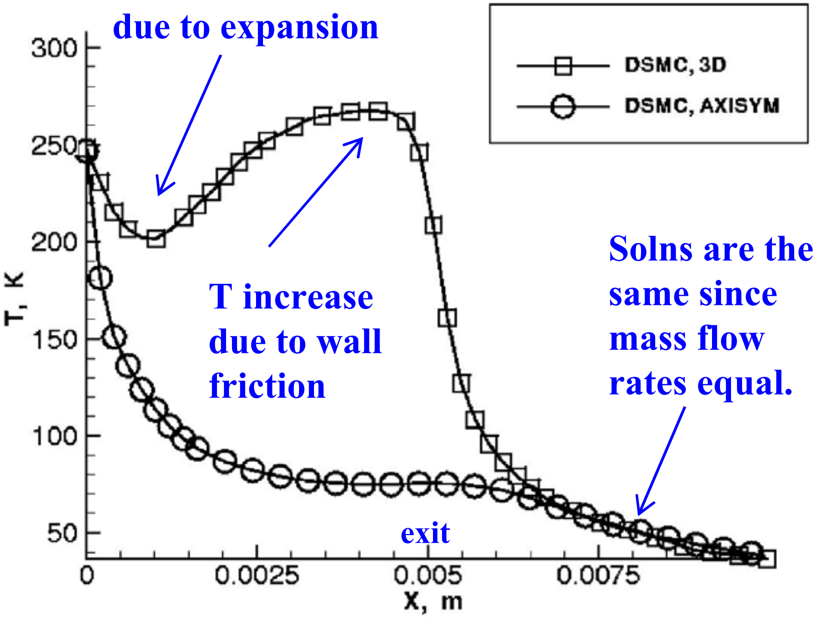
- Density, kg/m^3
- Greater flow expansion in 2-D case.



- T, K
- More heat transfer to the wall in the 3-D case.

Cold Gas - Effect of Geometry

3-D vs. Axisymmetric

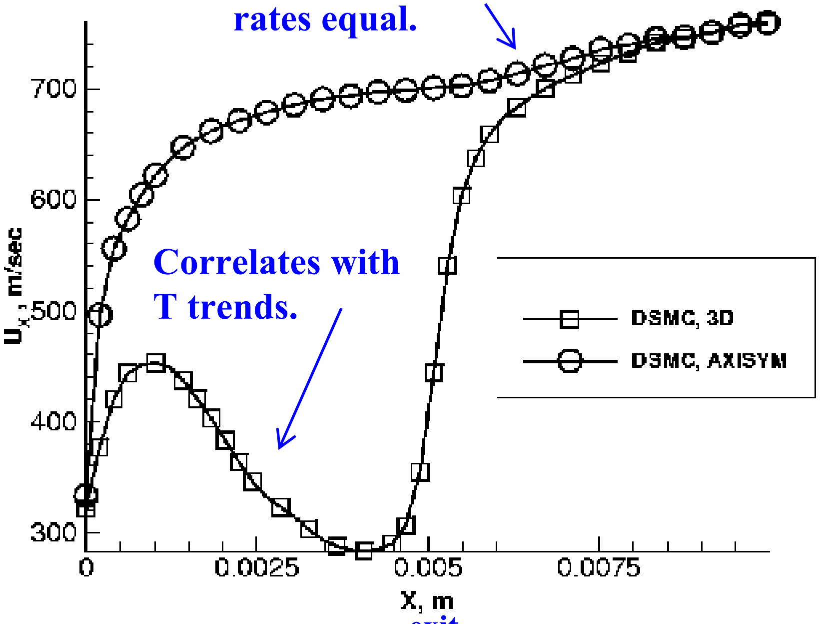


Initial T decrease due to expansion

T increase due to wall friction

Solns are the same since mass flow rates equal.

exit



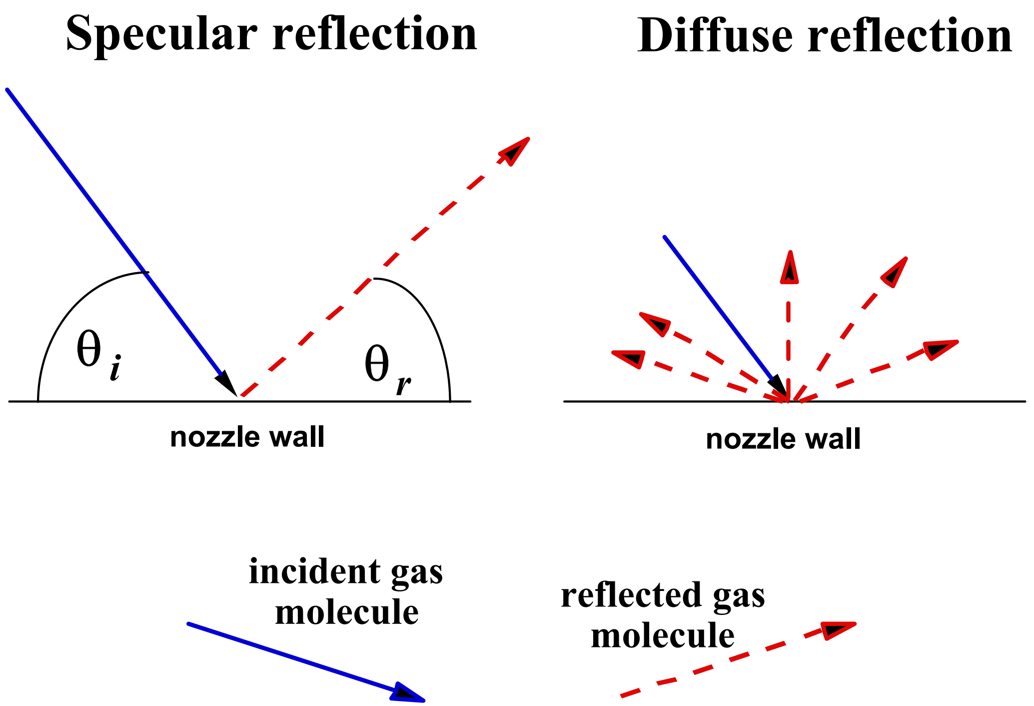
Solns are the same since mass flow rates equal.

Correlates with T trends.

exit

- 3-D vs axisymmetric shows that the degree of wall surface area is important.
- For supersonic nozzle flow into a vacuum, U_x should be a maximum at the exit.
- Instead, extremum U_x is located upstream due to subsonic region at the walls.

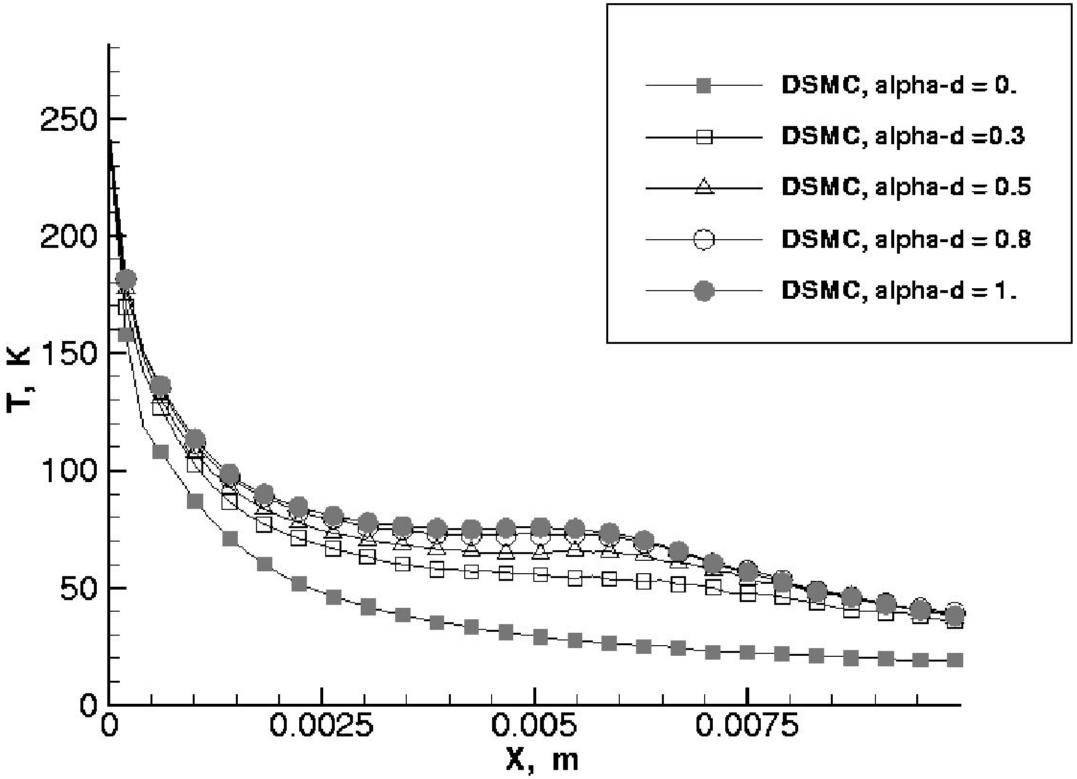
Kinetic, DSMC Gas-Surface Wall Models in Micro-nozzle Flows



- Two types of gas-surface interactions
  - Specular - incident and reflected tangential momentum are the same,
  - Diffuse - all reflected directions are equally probable, wall acts like an emitting source of particles at T_{wall},

- Interaction is specified by with accommodation coefficients for
  - Normal momentum, tangential momentum, and energy (heat transfer)
  - Values between 0,1 and closer to 1 for spacecraft materials.
- Continuum methods are partially corrected with wall slip-jump boundary conditions.
- Accommodation ~ 1 generates large, viscous boundary layers.

Cold Gas Thrusters - Effect of Gas-surface model

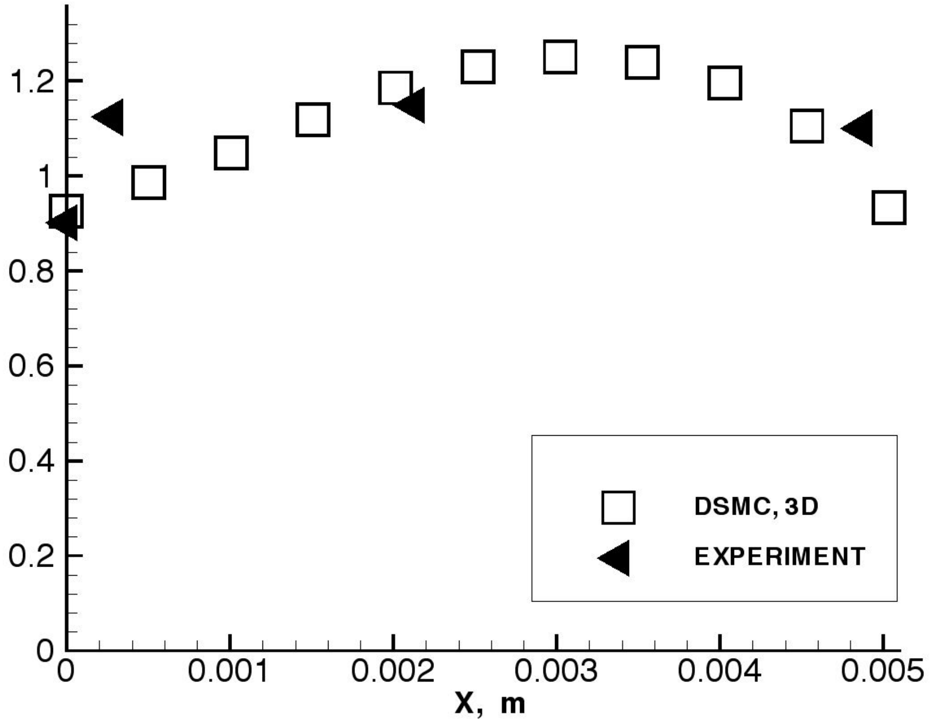


Translational T profiles along the nozzle axis for different α_d in an axisymmetric micronozzle.

- **Definition of tangential momentum accommodation coefficient,**

  $\alpha_d = (P_{\tau i} - P_{\tau r})/ P_{\tau i}$
- **Experiments show that α_d = 0.8 for silicon.**
- **3-D calculations showed only 1% difference for α_d = 0.8 and 1.**

Cold Gas Thrusters - Performance

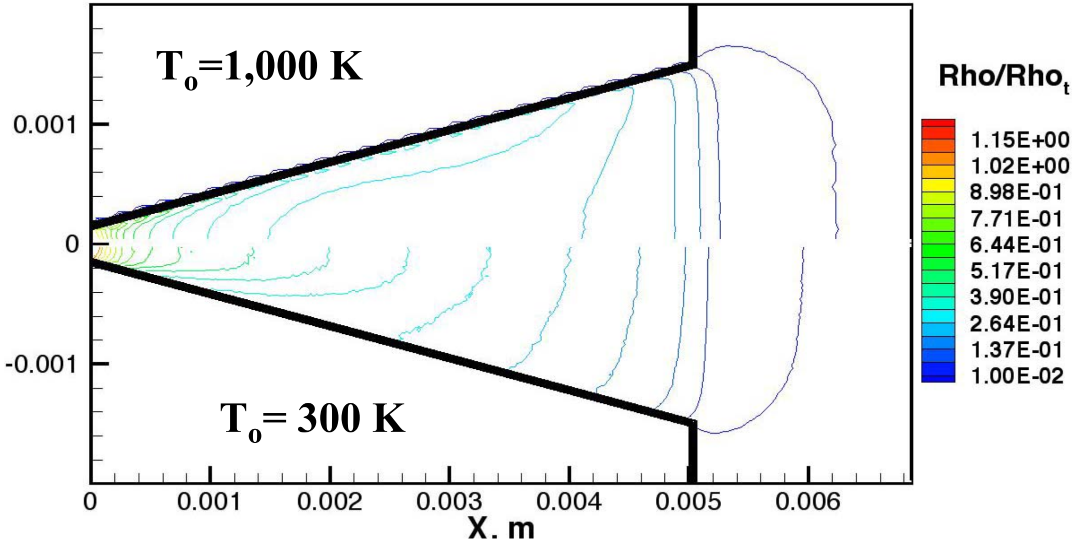


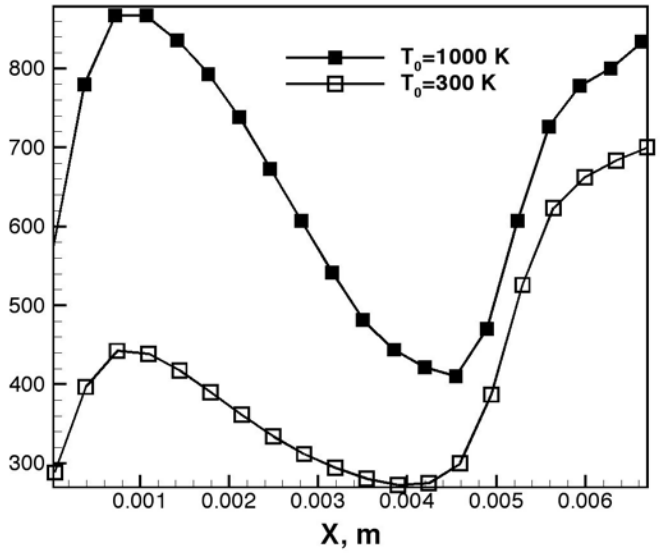
Case	Thrust (mN)	I_{sp}, (sec)
AS NS	1.07	65.62
AS DSMC	1.03	65.5
2D NS	1.17	69.45
2D DSMC	1.10	68.74
3D DSMC	0.93	56.61

- Comparison of 3-D calculations with data show good agreement.
- 2-D assumption is poor and over predicts thrust levels of geometry.
- Wall effects in 3-D case reduce thrust (20%) and specific impulse cf to 2-D.

Higher-Temperature Thruster Flows

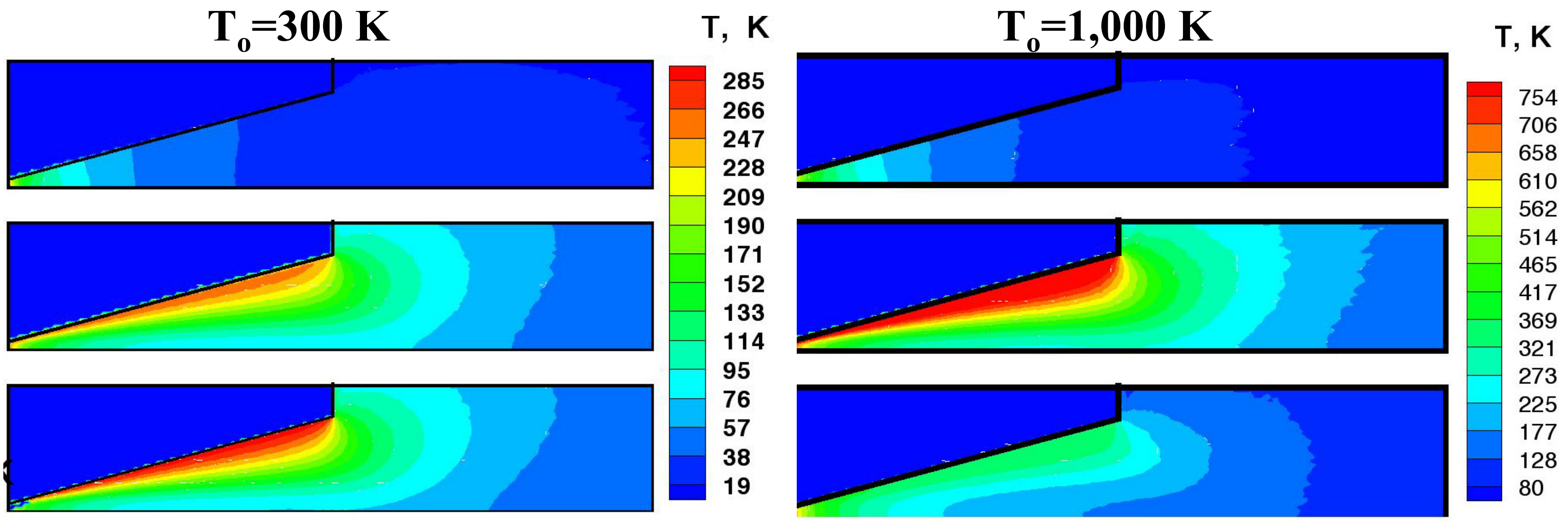
Full wall accommodation, $Re_t \sim 200$, $T_w = 300$ K, 3-D nozzle


Normalized density


U_x along centerline

- •Flows at both temperatures are dominated by surface interactions, but structure is different.
- •I_{sp}= 56.6 and 61.s for T_o=300, 1000 K, respectively.
- •Increase in I_{sp} << than for comparable axisymmetric case due to larger surface-area-volume ratio.

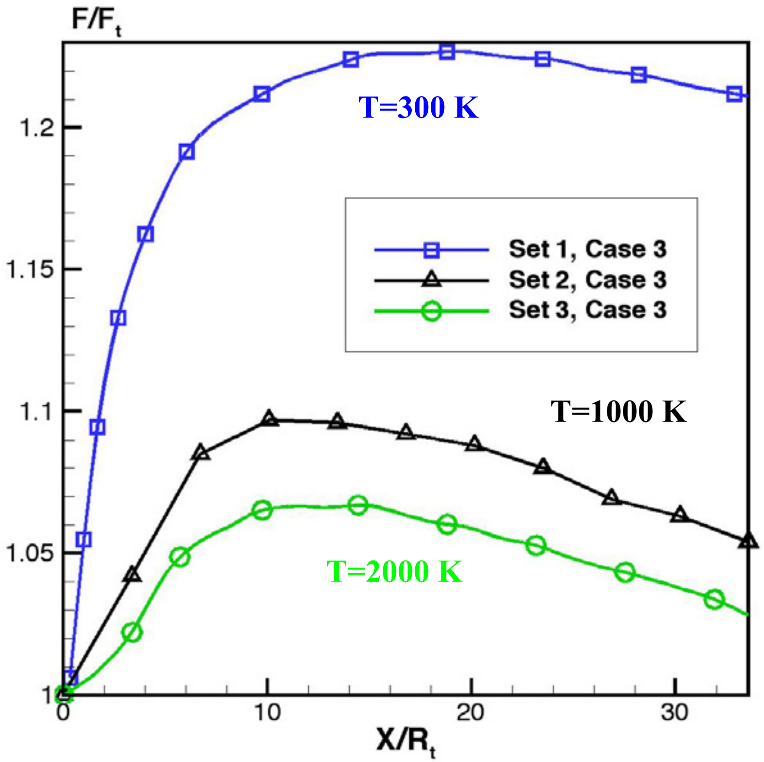
Comparison of Flows for Different Gas - Surface Models and T_0

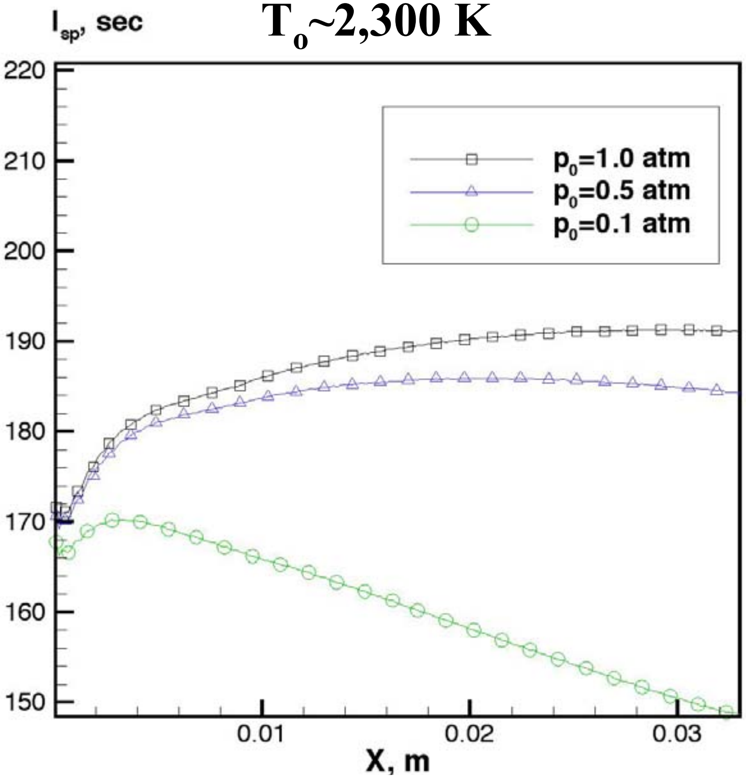


1. "Specular" = ideally smooth, no momentum or energy transfer (TOP),
2. "Diffuse, adiabatic" = av tangential momentum of reflected molecules = 0, no energy transfer with wall (MIDDLE).
3. "Diffuse, T_w=300" = both momentum and energy transfer occurs with wall (BOTTOM).

Effect of T_o and P_o on Performance

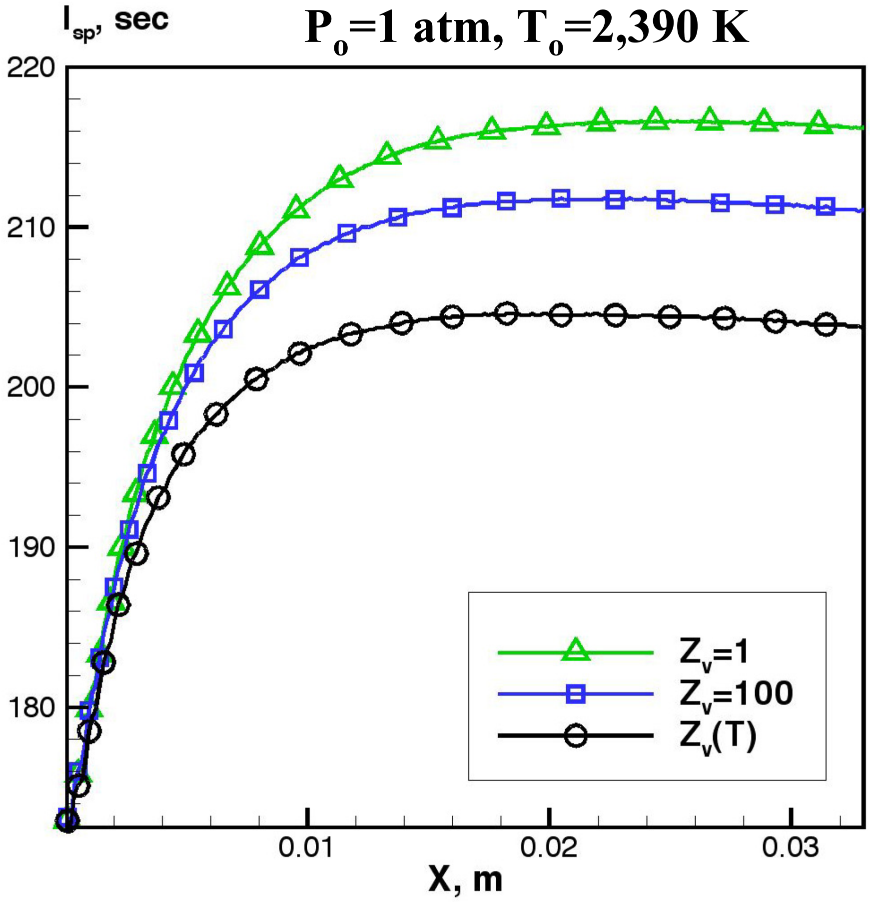
Axisymmetric nozzle, Diffuse wall, T_w=300




T_o~2,300 K

- For high T_o, a shorter nozzle would give better performance at lower Re.
- Need to optimize geometry of high temperature nozzles.
- For lower pressures, the peak value of I_{sp} is closer to the nozzle throat.

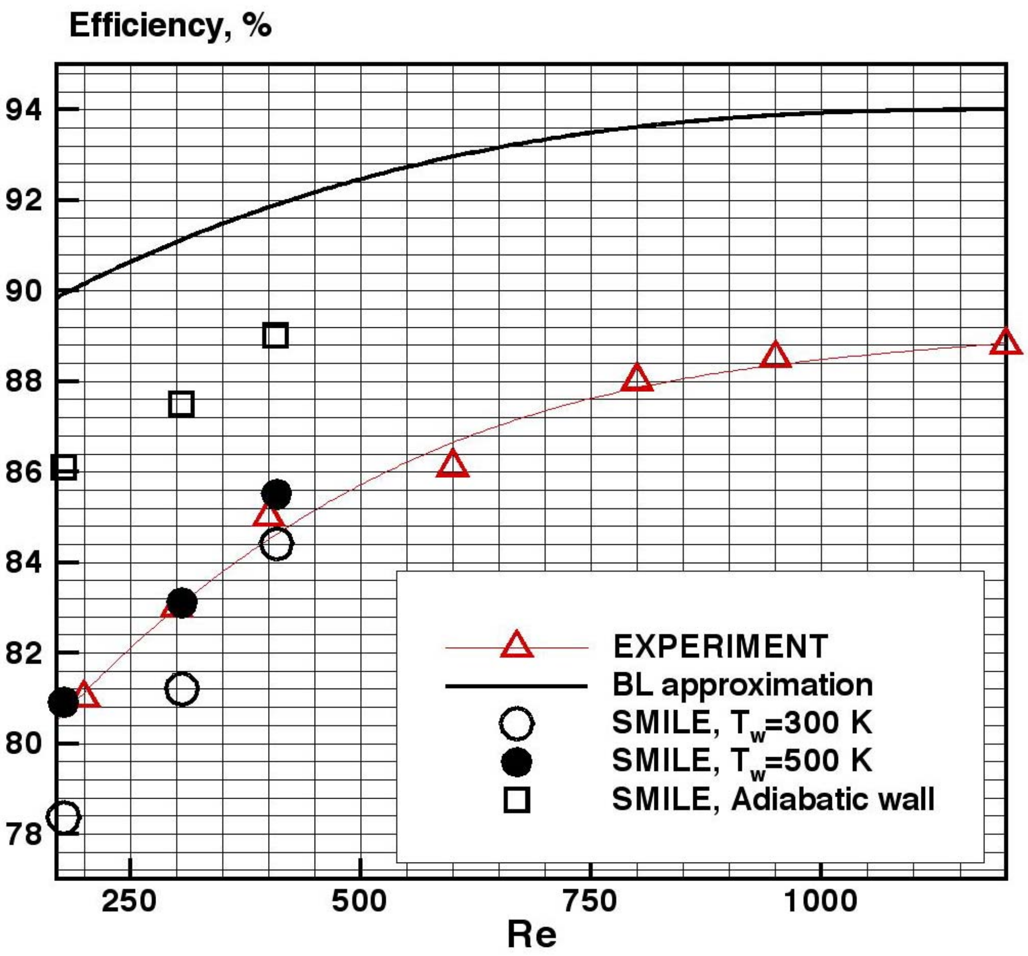
Effect of Internal Energy* on Performance



- Axisymmetric nozzle, hydrogen air mixture ⇒ 66.1% N_2, 32.4% H_2O, and 1.5% H_2
- High T polyatomic gas, VT becomes important.
- Represent VT by Z_v relaxation numbers in Larsen-Borgnakke model:
  1. $10^4 < Z_v (T) < 10^6$
  2. Constant Z_v = 1 and 100.
- Faster VT relaxation increases nozzle performance.

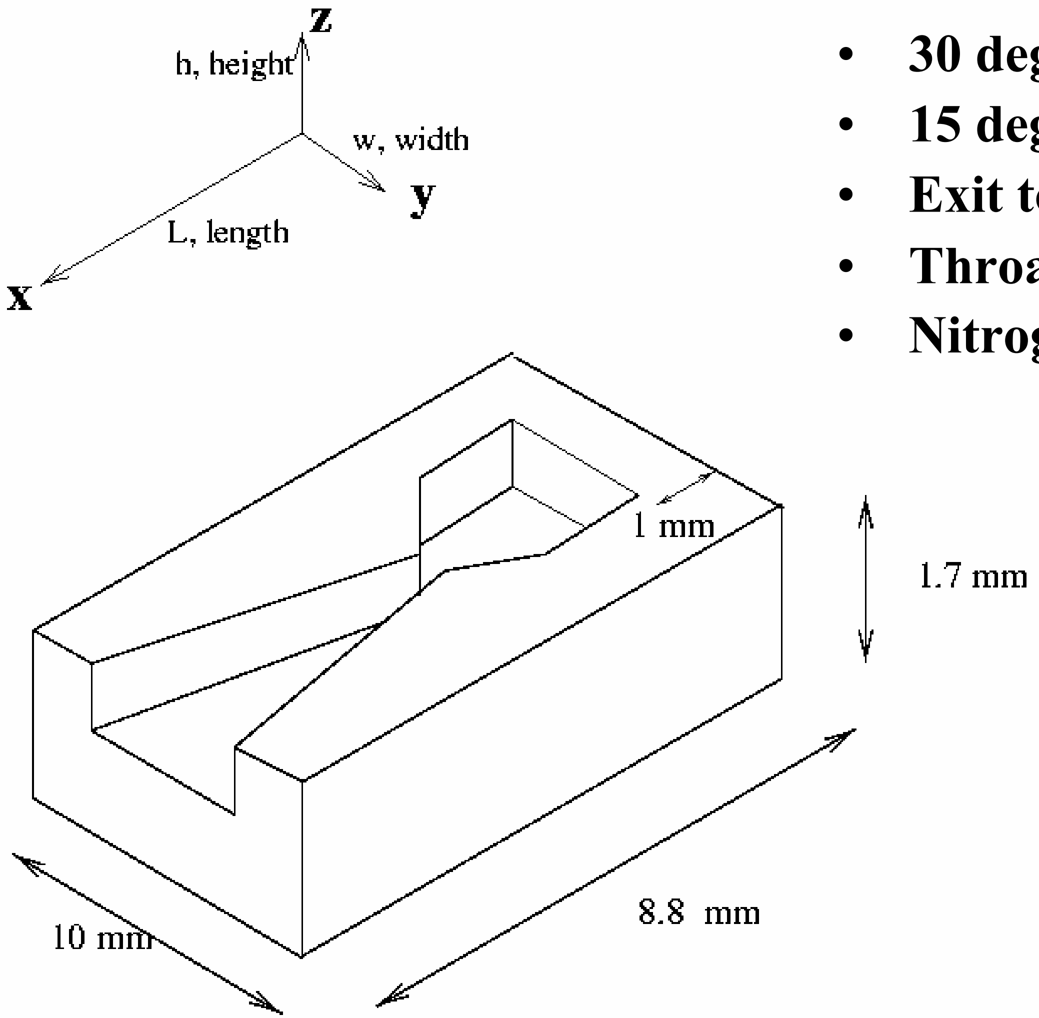
*For cold gas thrusters, TR relaxation is the dominant internal energy transfer mechanism.

Comparison of Calculated and Measured Efficiencies for Axisymmetric Nozzles



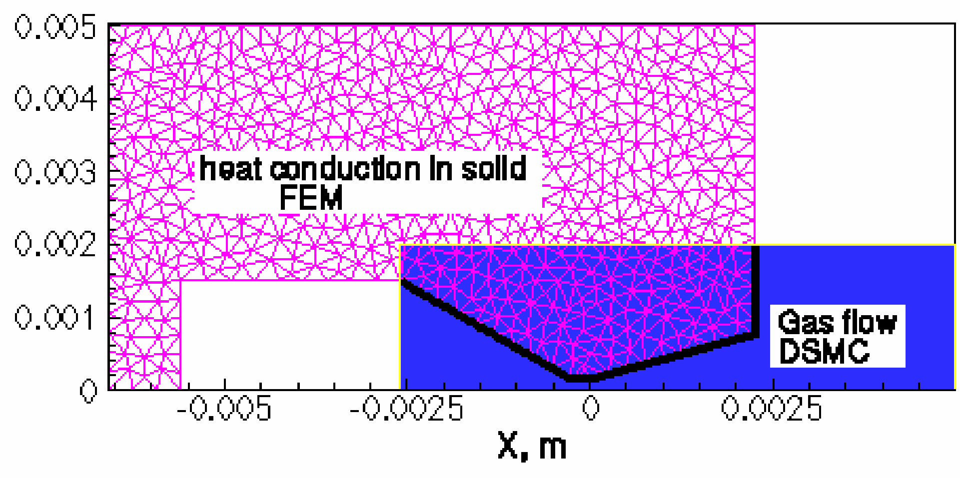
- Experimental data did not specify T_w.
- Good agreement between measurements and modeling for T_w=500 K and complete accommodation.
- I_{sp} sensitive to wall conditions.
- *Need a predictive capability to determine both material and gas properties for micropropulsion devices.*

Geometry and Flow Conditions
Schematic of NASA-Glen Microthruster



- **30 deg converging part**
- **15 deg diverging part**
- **Exit to throat area ratio of 5**
- **Throat: 300μm x 600 μm**
- **Nitrogen flow:**
  - **P_o = 0.1 and 0.5 atm,**
  - **T_o=2000 K,**
  - **Re = 35 and 175, respectively.**

Coupled Thermal and Gas Dynamic Computational Approach



Computational domain for 2D calculations

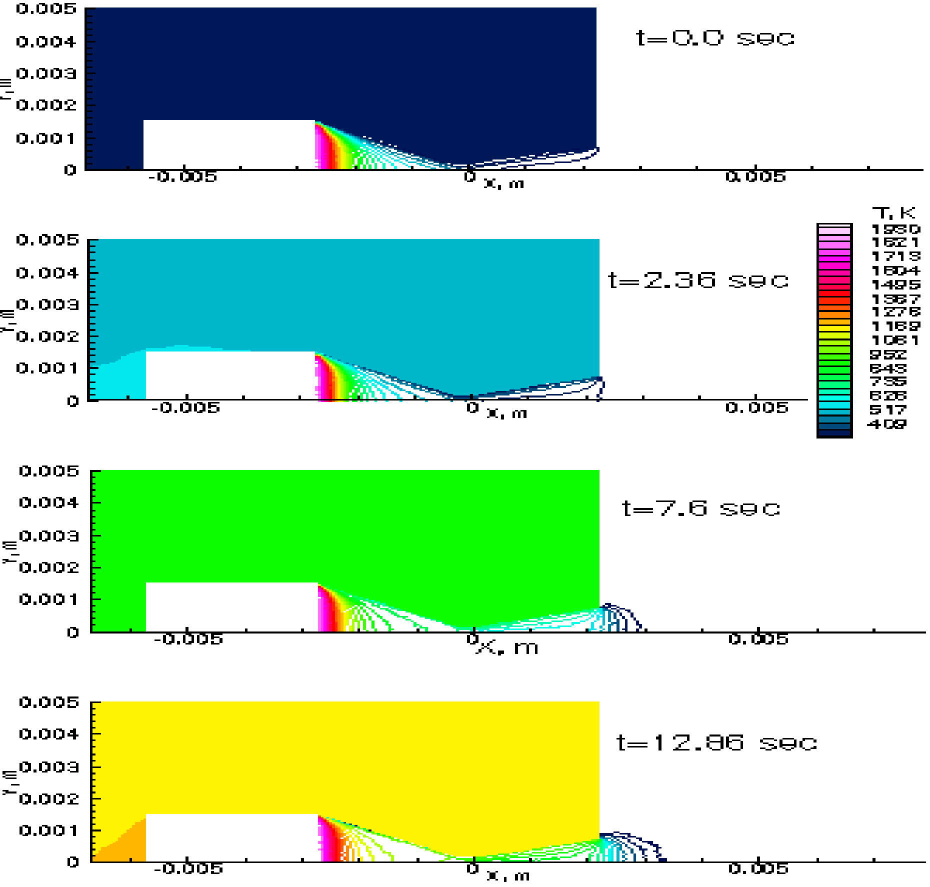
- Based on the solution of the heat transfer problem using finite element method coupled to the DSMC gas flow solution.
- Coupling between material thermal response and flow by using DSMC heat fluxes as the boundary conditions for the heat conduction problem.
- The wall temperature calculated in the heat transfer simulations is, in turn, applied as a boundary condition for DSMC calculations.

PENNSTATE
1855

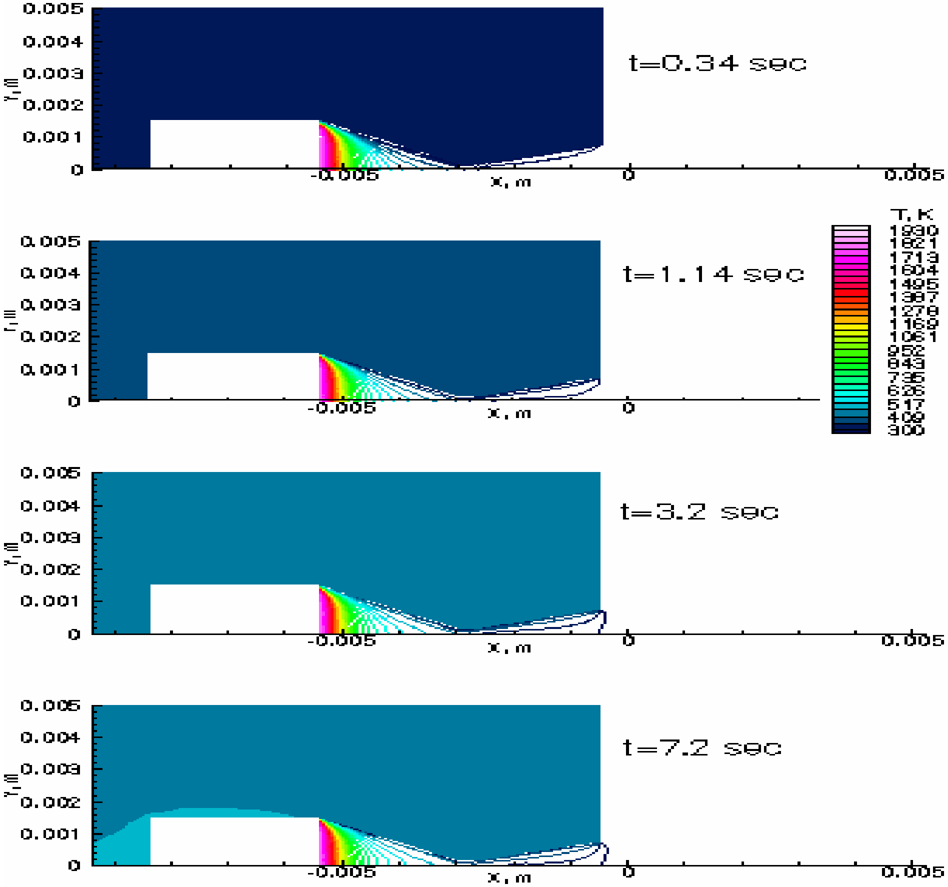
Material thermal response: 3D

Time variation of the temperature fields for 0.1 atm

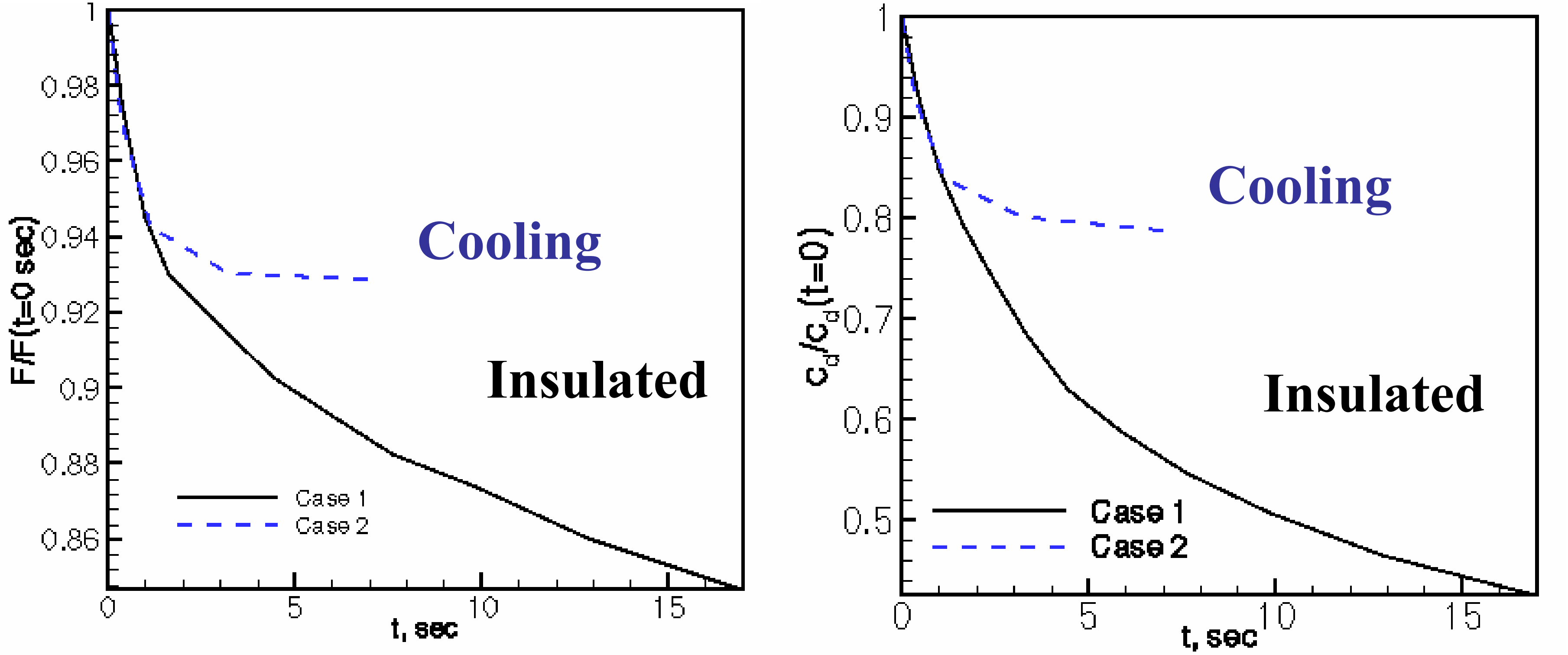
Thermally Insulated



Active Cooling

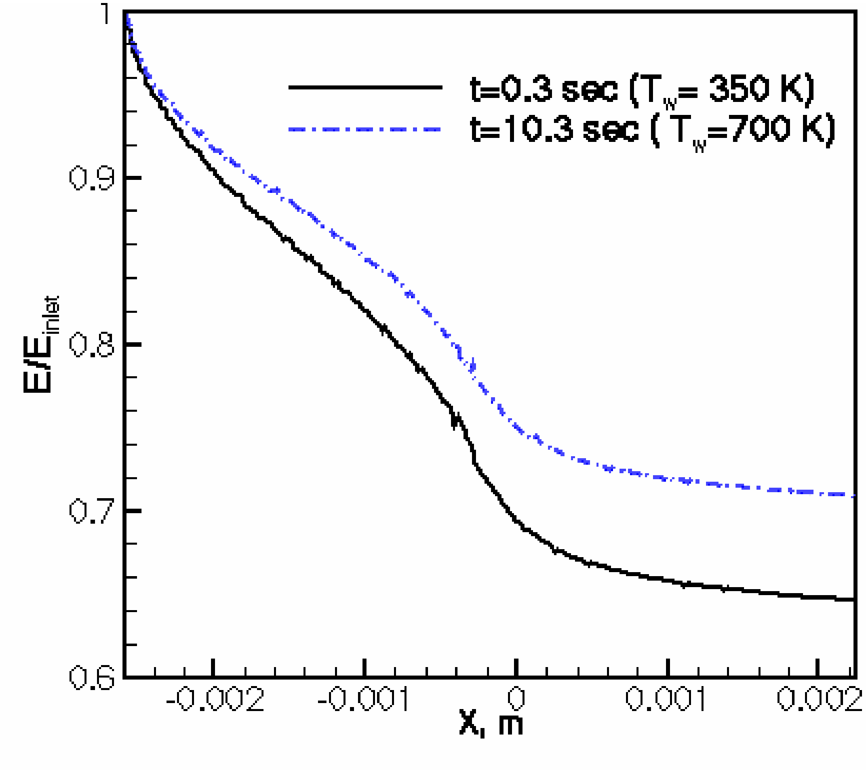


Micronozzle performance $h=600\ \mu m$, $p_o=0.1$ atm, insulated vs cooling



- Final thrust value, F, are 15% and 6% lower than the initial ones for Case 1 and 2, respectively.
- The mass flow degradation is as much as 55% in Case 1.
- Coeff. of mass discharge, C_d, decreases more rapidly than F.

Where does the energy go?



Ratio of gas energy to value at inlet along the nozzle axis.

- 2-D, p_o=0.5 atm, cooling, (AIAA 03-0673).
- Cooling allows heat transfer losses.
- As material heats up, less gas energy is transferred to the wall.
- As material heats up, reduction in thrust will slow down.

Conclusions

- Material thermal response is similar to 2D, but gas flow structure is significantly different due to the side-wall boundary layer.
- For thermal cooling, the steady-state material temperature is 450 K (same as in 2D).
- Higher Re flow results in larger surface heat fluxes and, thus, shorter operational times. However, heat fluxes do not vary proportionally with Re.
- Cooling applied to the outer surface can sustain the material temperature below melting. Cooling results in improved thrust and mass discharge performance.
- The large temporal variation of the thrust, and especially mass discharge coefficient means that the coupling between the gas and material must be taken into account in micropropulsion design.

Related Publications

1. **Alexeenko. A., Fedesov, D., Levin, D., Gimelshein, S., and Collins, R., "Transient Heat Transfer and Gas Flow in a MEMS-based Thruster," submitted to the *IEEE J. of MEMS,* April 17, 2003.**

2. **Alexeenko, A. A., D. A. Fedosov, D. A. Levin, S. F. .Gimelshein, R. J. Collins, "Performance Analysis of Microthrusters Based on Coupled Thermal-Fluid Modeling and Simulation", Submitted to the Journal of Power and Propulsion, Sept., 21, 2003.**

3. **Lempert, W., M. Boehm, N. Jiang, S. Gimelshein, and D. Levin, "Comparison of molecular tagging velocimetry data and direct simulation Monte Carlo simulations in supersonic micro jet flows," *Experiments in Fluids*, 2003 , Vol. 34, pp. 403-411.**

4. **Alexeenko, A.A., D. Levin, S. Gimelshein, R. Collins, G. Markelov, "Numerical Simulation of High-Temperature Gas Flows in a Millimeter-Scale Thruster," *Journal of Thermophysics and Heat Transfer*, January-March, 2002, Vol. 16, No. 1 pp. 10-16.**

5. **Alexeenko, A.A., D. Levin, S. Gimelshein, R. Collins, and B. Reed, "Numerical Modeling of Axisymmetric and Three-Dimensional Flows in MEMS Nozzles," *AIAA Journal*, Vol. 40, Number 5, May 2002, pp .897-904.**

PENNSTATE

1 8 5 5

Acknowledgements

This research was supported by the National Aeronautics and Space Administration, John H. Glenn Research Center under Grant No. NAG3-2590 technically monitored by Mr. Brian D. Reed.

We would also like to thank Dr. Clifton Phillips of SPAWARSYSCEN who provided us with computer time on DoD Maui High Performance Computing Center.