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GAS TRANSPORT BY THERMAL TRANSPIRATION IN MICRO-CHANNELS— A NUMERICAL STUDY

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ABSTRACT

A reliable micro gas pump is an essential element to the development of many micro-systems for chemical gas analyses. At Sandia, we are exploring a different pumping mechanism, gas transport by thermal transpiration. Thermal transpiration refers to the rarefied gas dynamics developed in a micro-channel with a longitudinal temperature gradient. To investigate the potential of thermal transpiration for gas pumping in micro-systems, we have performed simulations and model analysis to design micro-devices and to assess their design performance before the fabrication process. Our effort is to apply ICARUS (a Direct Simulation Monte Carlo code developed at Sandia) to characterize the fluid transport and evaluate the design performance. The design being considered has two plenums at different temperatures (hot and cold) separated by a micro-channel of 0.1 micron wide and 1 micron long. The temperature difference between the two plenums is 30 Kelvin. ICARUS results, a quasi-steady analysis, predicts a net flow through the micro-channel with a velocity magnitude of about 0.4 m/s due to temperature gradient at the wall (thermal creep flow) at the early time. Later as the pressure builds up in the hot plenum, flow is reversed. Eventually when the system reaches steady state equilibrium, the net flow becomes zero. The thermal creep effect is compensated by the thermo-molecular pressure effect. This result demonstrates that it is important to include the thermo-molecular pressure effect when designing a pumping mechanism based on thermal transpiration. The DSMC technique can model this complex thermal transpiration problem.

NOMENCLATURE

J	Collision term in the Boltzmann equation
P	Pressure
Q	Reduced mass flow rate
Q_P	Coefficient representing pressure contribution to flow
Q_T	Coefficient representing temperature contribution to flow

T	Temperature
a	Radius or half of the equivalent diameter
f	Particle distribution function
k	Boltzmann constant
m	Mass of molecule
q	Collision kernel
t	Time
v, w	Particle velocity before collision
v', w'	Particle velocity after collision
x	Longitudinal coordinate
δ	Rarefaction parameter
γ	Exponent for pressure-temperature ratio relationship
λ	Mean free path
μ	Shear viscosity
1	Subscript for the colder region
2	Subscript for the hotter region

INTRODUCTION

Recent advances in micro-science and technology have led to the development of many micro-systems for biological or chemical analyses. These micro-analyzers, in turn, can substantially affect our daily life. A micro pump for gas transport is an essential element to many of these micro gas analyzers. However at present, there is not a good, reliable, and proven micro gas pump available in the market¹. Different pumping mechanisms have been investigated for gas transport; these include positive displacement pumps that utilize diaphragms and various actuation mechanisms, such as electrostatics and thermo-pneumatics². Diaphragm pumps have a drawback as the size decreases³. Most existing micro diaphragm pumps have difficulty producing a flow rate useful for general applications. This happens because at the length scale of microns, the deflection of a diaphragm will be smaller for a given applied pressure. It does not scale linearly. Thus a much higher pressure is needed to deflect the diaphragm to achieve a given degree of deflection. Hence most

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diaphragm pumps do not work as well at the microscale as at the mesoscale. This drawback leads us to explore a different gas pumping mechanism.

As the size decreases, it becomes more difficult to move fluid through a micro-channel. Inertia effect at the micron scale diminishes and surface friction begins to dominate^{4,5}. Relying on pressure head to drive fluid along a micro-channel may not be that efficient; pressure loss per unit length, for a given flow velocity, is inversely proportional to the square of the channel diameter. Thus other driving mechanisms to move fluid in micro-channels should be explored. For liquid transport, one example is to apply electro-osmotic pumping to move liquid in micro-channels in the micro bio/chemical analyzers⁶. For gas transport, our effort at Sandia, is to investigate a different pumping mechanism, gas transport by thermal transpiration. In theory, gas pumping by thermal transpiration can be very efficient at the micron or submicron length scale because of the rarefied gas dynamics effect. In addition, this type of pump will have an advantage of no moving parts.

THERMAL TRANSPIRATION

The phenomenon of thermal transpiration, also known as thermal creep flow, was first studied by Reynolds⁷, Maxwell⁸, and Knudsen⁹ in the early 20th century. It refers to a rarefied gas dynamics phenomenon that occurs in a passage with a longitudinal temperature gradient. When a temperature gradient exists in a channel connecting two plenums and the channel diameter is comparable to the mean free path of the gas molecules, to maintain the temperature difference between the plenums, the gas begins to move from the cold plenum to the hot plenum when the pressure in both plenums are equal. If this is a closed system, a pressure head will be established between the plenums. This pressure head will induce a gas flow opposite to the thermal creep flow near the surface. In a steady state condition, this counter-current flow components will compensate with each other, leading to a zero net mass flow in the micro-channel. Our goal is to develop a pumping design that is an open system so that one-directional continuous flow will occur in the system.

In the past, researchers have studied the thermal transpiration phenomenon for different reasons. It has many applications; for example, studying small gas leakage in a vacuum chamber^{10,11} and analyzing thermal heating in space-crafts¹². Exploring the use of thermal transpiration as a gas pumping mechanism in a micro-system is relatively new. Muntz and his team have designed and tested a micromechanical Knudsen compressor¹³. They have demonstrated a design concept and concluded that more work including Direct Simulation of Monte Carlo (DSMC) analysis are recommended. Sone and his team have applied DSMC technique to analyze rarefied flow through channel configurations with rectangular ditches¹⁴. However, the temperature gradient in their analysis is relatively high, i.e. a temperature ratio of three, which is difficult to achieve in a micro-system. Our present study is to focus on a much smaller temperature ratio.

PREVIOUS ANALYSES

Reynolds carried out the first experimental and theoretical work on thermal transpiration⁷. He derived the pressure-temperature relationship by considering the extreme case with a very low pressure, in the free-molecular flow regime. Under the steady state condition, it requires that the number of molecules entering the channel from both plenums are equal. This gives the following relationship:

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{0.5} \quad \text{Eq. (1)}$$

In the other extreme with a relatively higher pressure, in the continuum viscous flow regime, the pressure at both ends will be the same no matter what their temperatures may be. Hence in this case the exponent has a value of zero.

Since then, many experiments^{11,15} have been performed to investigate the thermal transpiration phenomenon for different gas media and wall surface interactions and further develop a better pressure-temperature relationship to cover transition from the continuum flow to molecular flow regime. Results can be summed up by the following empirical correlation:

$$\frac{P_2}{P_1} = \frac{f(X) + \sqrt{T_2/T_1}}{f(X) + 1} \quad \text{Eq. (2)}$$

$f(X)$ is a monotonous function of pressure and can be expressed as

$$f(X) = A^* \cdot (X/T^*)^2 + B^* \cdot (X/T^*) + C^* \cdot (X/T^*)^{1/2} \quad \text{Eq. (3)}$$

with $T^* = (T_1 + T_2)/2$. The parameter X characterizes the ratio of channel diameter d to mean-free-path length and is given as: $X = P_2 d$. The parameters A^* , B^* , and C^* depend on the gas species and were determined empirically¹⁶.

In modeling, most work involves solving the linear Boltzmann equations and developing different forms of analytical solutions¹⁷. An example is to consider a rarefied monoatomic gas dynamics flow through a long capillary tube with longitudinal pressure and temperature gradients. If the pressure and temperature gradients are small, linear theory can be applied to solve for a mass flow rate, $\dot{M}$. By introducing a dimensionless reduced mass flow rate as:

$$Q = \frac{1}{\pi a^2 P} \cdot \left(\frac{2kT}{m}\right)^{\frac{1}{2}} \cdot \dot{M} \quad \text{Eq. (4)}$$

and also by imposing a superposition,

$$Q = -(Q_P \cdot V) + (Q_T \cdot \tau) \quad \text{Eq. (5)}$$

$$\text{with } V = \frac{a d P}{P dx} \quad \text{and} \quad \tau = \frac{a d T}{T dx} ,$$

where a is the radius of the capillary channel and x is the longitudinal coordinate. The coefficients Q_P and Q_T are determined only by the local Knudsen number and do not depend on the gradient. Past research has been focused on obtaining these two coefficients by working with the Bhatnagar-Gross-Krook (BGK) model of the Boltzmann equation or by applying the variational method to solve the s-model of the Boltzmann equation. Sharipov¹⁸ gave a good survey of existing analytical solutions and also briefly assessed their usefulness and comparison with experimental data. We will compare our DSMC results with his analytical model.

Under an equilibrium condition, when the net flow in the channel is zero, one can relate pressure and temperature at both ends as follows:

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^\gamma \quad \text{Eq. (6)}$$

with

$$\gamma = Q_T/Q_P \quad \text{Eq. (7)}$$

Hence the exponent, γ , is influenced mostly by the Knudsen number, $Kn = \lambda/L$, where L is the characteristic length and λ is the molecular mean free path. The mean-free-path can be expressed as follows:

$$\lambda = \frac{\sqrt{\pi} \mu}{2P} \cdot \left(\frac{2kT}{m}\right)^{\frac{1}{2}} \quad \text{Eq. (8)}$$

However γ also depends on other factors as length-to-radius ratio of the micro-channel, type of gas, and the nature of gas-surface interaction. At the high pressure limit (continuum flow regime), γ is zero. At the low pressure limit (free molecular flow regime), γ is about 0.5, depending on the geometry of the channel, gas type, and characteristics of gas-surface interaction.

Most of these analyses discussed above are derived for simple geometries and boundary conditions. For a complex system as in the development of a micro gas pump, it becomes attractive to apply a numerical technique such as the Direct Simulation Monte Carlo (DSMC) to study this thermal transpiration phenomenon.

Another important point is that when studying microscale transport problems, DSMC technique is applied instead of the Navier-Stokes solver because the continuum model begins to break down as the characteristic length of the micro-channel is comparable to the mean free path of gas molecules. Under certain circumstances, continuum model with a slip velocity and temperature jump boundary condition may still be useful¹⁹. However for transition and free-molecular flows, the existing correlations for the slip velocity and temperature jump condition at the boundary may be questionable.

DIRECT SIMULATION MONTE CARLO TECHNIQUE

Direct Simulation Monte Carlo (DSMC)²⁰ is a technique originally developed to simulate rarefied gas dynamics of high-altitude reentry flow problems. Recently it has been applied to study chemical vapor deposition in microelectronics processing²¹ and micro-channel flow in MEMS^{22,23,24}. This technique assumes that

the media is a dilute gas and binary collisions dominate the molecular interactions. Overall, the DSMC procedure is to treat the Boltzmann equation numerically and stochastically simulate the time evolution of a random particle system. The governing Boltzmann equation is:

$$\frac{\partial}{\partial t} f(t, x, v) + (v, \nabla_x) f(t, x, v) = J(f)(t, x, v) \quad \text{Eq. (9)}$$

with the right-hand side representing the collision term where q is the collision kernel.

$$J(f)(t, x, v) = \int dw \int de \{ q(v, w, e) \cdot [f(t, x, v') f(t, x, w') - f(t, x, v) f(t, x, w)] \} \quad \text{Eq. (10)}$$

Furthermore, v' and w' are the post-collision velocities related to the pre-collision velocities v and w , and the collision parameter e can be calculated as follows:

$$v' = v + e(e, w - v) \quad \text{Eq. (11)}$$

$$w' = w + e(e, v - w) \quad \text{Eq. (12)}$$

These expressions are derived from the conservation of momentum and energy.

Unlike other numerical schemes to solve the Boltzmann equation, DSMC technique treats the time evolution of the system from the state of the system at some time t_k , given as $(x_i(t_k), v_i(t_k))$, to the next state of the system at time t_{k+1} , $(x_i(t_{k+1}), v_i(t_{k+1}))$ differently. It decouples the simulation of the free flow of particles and simulation of their collisions within this time interval. First, the free flow is simulated disregarding the possible collision. Then, the collisions are simulated neglecting the free flow (i.e. their exact positions within each computational cells is not used in the collision calculations and the collision pairs are determined in a probabilistic manner).

DEFINING THE PROBLEM

Our approach to investigate the potential of thermal transpiration for gas pumping in micro-systems is to perform a numerical study to characterize the gas transport in a proposed design configuration. Then, evaluate and improve the design to optimize the pump performance before proceeding further on to the fabrication process to build a micro pump. Any design is substantially influenced by the limitation of current fabrication capability.

Figure 1 shows the current design being considered. It consists of a narrow micro-channel with converging and diverging nozzles at both ends connecting two plenums at different temperatures (hot and cold). This flow channel is relatively small, 0.1 micron wide and 1 micron long. This design reflects the device configuration generated from these fabrication steps: (1) front and back etch a silicon wafer by bulk micro-machining to create the converging and diverging nozzle, (2) heavily dope the neck region of silicon between the two nozzles, (3) wet etch the doped silicon to form porous silicon that has a pore size of about 0.1 μm or smaller, depending on the doping level. A small resistive heater will be built to provide the required

heating of the gas. The proposed temperature difference of 30 K between the two plenums is relatively small.

Two simulations have been performed to analyze gas transport in this micro-channel due to thermal transpiration, one at the atmospheric pressure of about 100 kPa and the other at a lower

pressure of about 1 kPa (Table 1). The lower pressure case will have a longer mean free path and a larger Knudsen number. Our interest is to study how the characteristics of flow in the micro-channel will change with a larger Knudsen number.

Table 1: Boundary Conditions Used in the Simulations

<i>Configuration</i>	<i>d (μm)</i>	<i>l (μm)</i>	<i>Number Density (#/m³)</i>	<i>Kn</i>	<i>T₁(K)</i>	<i>T₂(K)</i>	<i>Surface Reflection</i>
<i>x-y</i>	<i>0.1</i>	<i>1</i>	<i>2.38e25</i>	<i>0.67</i>	<i>293</i>	<i>323</i>	<i>diffusive</i>
<i>x-y</i>	<i>0.1</i>	<i>1</i>	<i>2.38e23</i>	<i>67</i>	<i>293</i>	<i>323</i>	<i>diffusive</i>

SIMULATION RESULTS

These simulations were performed by running the ICARUS code²¹, a Sandia developed, massively parallel particle transport code based on the DSMC technique on the nCube computer. Two ICARUS simulations, one with the atmospheric pressure and the other with a lower pressure, will be presented here.

Case I: Gas Transport in the Transition Flow Regime

In this simulation, the Knudsen number is 0.67; the gas flow in this micro-channel is in the transition flow regime. Gas-surface interaction becomes significant. In the present study, the wall is modeled as a diffusive surface which is a reasonable approximation for the micro-machined silicon surfaces. We ran the ICARUS code from the initial condition until it reached the steady state condition. Thus this ICARUS result can be considered as a quasi-steady analysis. By taking a few snap-shots of the simulation in the early stage and the intermediate stage, the evolution of the gas flow through the micro-channel can be divided into 3 phases. The early phase has a temperature gradient existed longitudinally, but without any significant pressure gradient along the channel. The ICARUS code predicts a flow velocity that varies between 0.2 to 0.5 m/s, and gas moving from the cold end to the hot end of the channel. However at this early phase of the simulation, one needs to be cautious that the uncertainty of this prediction is very high. It is difficult to obtain a good statistical collection of data to generate reliable information. On the other hand, if we apply Sharipov analysis for the nonlinear thermal creep flow problem, this analytical model will predict a flow velocity of 0.37 m/s with gas traveling from the cold end to the hot end for the present conditions.

The second phase occurs when both temperature and pressure gradients exist longitudinally along the channel. If the pressure gradient term exceeds the temperature gradient term, reverse flow is observed such that the gas moves from the hot end to the cold end. Flow reversal appears because as gas moves from the cold region to the hot region in the early phase, it builds up pressure at the hot plenum. Eventually when a substantial pressure gradient is developed, it causes a reverse flow. ICARUS predicts the magnitude

of the reverse flow velocity of about 4.5 m/s, which is comparable with the analytical model of 4.25 m/s based on Sharipov's analysis.

The third phase is the final state at equilibrium condition. When the steady state condition is reached, the developed thermo-pressure effect will compensate with the temperature effect which is imposed as the boundary condition. Hence the net flow across the channel will be zero. ICARUS predicts an average velocity of -0.14 m/s with gas flowing slowly from the hot end to the cold end. For comparison, the analytical model will predict a velocity of -0.08 m/s.

Figure 2 shows a well behaved cell average integrated temperature distribution established from the cold plenum to hot plenum. The corresponding pressure and number density distributions are plotted in Figure 3 and Figure 4, respectively. Pressure is higher and number density is lower at the hot end than at the cold end of the channel. The number density is lower at the hot end because this is needed to satisfy the mass and energy conservation principles. The higher temperature at the hot end implies a higher statistical average thermal velocity. In order to satisfy the mass conservation such that the mass flux coming in from opposite directions are equal, this requires a reduced number density at the hot end of the channel. More comparison of the simulation results with other analyses will be presented in the following section.

Case II: Gas Transport in the Free-Molecular Flow Regime

This is a sensitivity study; our interest is to characterize the gas transport by thermal transpiration at a lower pressure in the same configuration. As the pressure decreases, the mean free path will increase. This gives a higher Knudsen number, thus the flow is in the free-molecular flow regime. This simulation will provide some insight to determine the flow characteristics of gas transport in a smaller channel.

Figure 5 and Figure 6 show the predicted temperature and pressure distributions in the channel. Unlike the previous case, the pressure distribution for the present case has more statistical variation throughout the length of the tube. This variation is due to the variation of number density. Usually this happens when modeling gas flow in the free-molecular flow regime. More

simulated particles per computational cell may help to build up a better statistical base for pressure evaluation and to reduce the variation. At the steady state, unlike the high pressure case, ICARUS predicts an average velocity of about 0.16 m/s, indicating a net flow of gas moving slowly from the cold end to the hot end. (*However, the uncertainty of this prediction is very large in this case because the thermal velocity fluctuation is large.) By applying Sharipov's analysis, the analytical model predicts a velocity of 0.40 m/s with gas moving from the cold end to the hot end.

DISCUSSIONS

We have applied the ICARUS code, which is based on the DSMC technique to simulate particle dynamics, to investigate a thermal transpiration problem. To assess our findings, these ICARUS results will be compared with other analyses. Specifically, these results will be checked against the empirical correlation developed from experiments¹⁶ and also Sharipov's analysis of

solving the s-model of the Boltzmann transport equation¹⁸. Additional code assessment can be found in Reference 25.

Table 2 summarizes the comparison of flow velocity between simulations and analytical predictions. Table 3 presents the comparison of pressure ratio between simulations, analytical predictions, and empirical correlation. This comparison of pressure ratio shows that for Case I, at atmospheric pressure, the ICARUS result is consistent with both the analytical model (Eq. 7) and the empirical correlation (Eq. 2). It is known that the empirical correlation slightly overpredicts the pressure ratio in the transition flow regime¹⁶. For Case II, at a lower pressure, the ICARUS simulation slightly underpredicts the pressure ratio when comparing with the analytical model and empirical correlation. The popular relationship, which has a square-root dependence on the temperature ratio and is used in many references and textbooks¹⁰, may be questionable under certain circumstances, especially when the gas flow is far from the free-molecular flow regime.

Table 2: Comparison of Flow Rate between Analytical Model and Simulation

	δ	Q_p	Q_T	Q_{net}	γ	v (m/s) Sharipov	v (m/s) ICARUS
Case I	1.228	1.521	0.369	-0.00048	0.243	-0.081	-0.14
Case II	0.0078	1.485	0.730	0.00201	0.492	0.408	-0.16*

Table 3: Comparison of Pressure Ratio between Correlation, Model, and Simulation

	T_2/T_1 ICARUS	$(T_2/T_1)^{0.5}$ Eq. (1)	P_2/P_1 correlation Eq. (2)	P_2/P_1 Sharipov Eq. (7)	P_2/P_1 ICARUS
Case I	1.091	1.044	1.031	1.021	1.028
Case II	1.092	1.045	1.044	1.044	1.035

SUMMARY

We have investigated gas transport in micro-channels by thermal transpiration using the ICARUS code based on the DSMC methodology. With a small temperature gradient across the micro-channel separating the cold and hot plenum, flow can be established. However reverse flow will occur if the opposite thermo-pressure effect becomes dominant. Comparison with other analyses demonstrate that our simulation results are consistent with the analytical model derived by Sharipov and also with the empirical correlation for predicting the pressure ratio.

In conclusion, the ICARUS simulations show that gas transport through a micro-channel by thermal transpiration is a complex phenomenon. Without any longitudinal pressure gradient, it can

move gas from the cold plenum to the hot plenum. It is important to overcome any pressure build-up that can lead to a reverse flow. ICARUS, based on DSMC technique, can address this thermal transpiration problem with complex geometries. More work is underway to study how different scales and various conditions will affect the flow characteristics in the micro-channels.

REFERENCES

- 1S. Shoji and M. Esashi, "Microflow Devices and Systems," *J. of Micromechanics and Microengineering*, Vol. 4, p. 157-171, 1994.

- ²A. Olsson, P. Enoksson, G. Stemme, and E. Stemme, "A Valve-less Planar Pump Isotropically Etched in Silicon," *J. of Micromechanics and Microengineering*, Vol. 6, p. 87-91, 1996.
- ³M. Sen, D. Wajerski, and M. Gad-el-Hak, "A Novel Pump for MEMS Applications," *Transaction of ASME, Journal of Fluid Engineering*, Vol. 118, p. 624-627, 1996.
- ⁴E. Arkilic, K. S. Breuer, "Gaseous Flow in Small Channels," *AIAA 93-3270, AIAA Shear Flow Conference*, Orlando, FL, July 6-9, 1993.
- ⁵J. C. Shih, C. M. Ho, J. Liu, Y. C. Tai, "Monatomic and Polyatomic Gas Flow Through Uniform Microchannel," *ASME DSC-Vol. 59, MicroElectroMechanical Systems*, 1996 International Mech. Eng. Congr. and Exposition, Atlanta, GA, Nov. 17-22, 1996.
- ⁶A. Manz, C. S. Effenhauser, N. Burggraf, D. J. Harrison, K. Seiler, and K. Fluri, "Electro-osmotic Pumping and Electrophoretic Separations for Miniaturized Chemical Analysis Systems," *J. of Micromechanics and Microengineering*, Vol. 4, p. 257-265, 1994.
- ⁷O. Reynolds, *Philos. Tran. Royal Society, London*, Ser. B, 170, p. 727, 1879.
- ⁸J. C. Maxwell, "On Stress in Rarefied Gases Arising from Inequalities of Temperature," *Philos. Tran. Royal Society*, Part I, No. 2, p. 255, 1879.
- ⁹M. Knudsen, "Eine Revision der Gleichgewichtsbedingung der Gase. Thermische Molekularströmung," *Ann. Physik*. 31, 205, p. 633, 1910; *Ann. Physik*. 33, p. 1435, 1910.
- ¹⁰M. H. Hablanian, *High-Vacuum Technology*, Marcel Dekker Publications Inc., New York, p. 53, 1997.
- ¹¹K. F. Poulter, M-J Rodgers, P. J. Nash, T. J. Thompson, and M. P. Perkin, "Thermal Transpiration Correction in Capacitance Manometers," *Vacuum*, Volume 33, No. 6, p. 311-316, 1983.
- ¹²L. B. Loeb, *The Kinetic Theory of Gases*, 3rd edition, Dover Publications Inc., New York, Chapter VII, 1961.
- ¹³S. E. Vargo and E. P. Muntz, "A Simple Micromechanical Compressor and Vacuum Pump for Flow Control and Other Distributed Applications," *AIAA-96-0310, 34th Aerospace Sciences Meeting and Exhibit*, Reno, NV, January 15-18, 1996.
- ¹⁴Y. Sone, Y. Waniguchi, and K. Aoki, "One-way Flow of a Rarefied Gas Induced in a Channel with a Periodic Temperature Distribution," *Physics of Fluids*, Vol. 8, No. 8, p. 2227, August, 1996.
- ¹⁵T. Edmonds and J. P. Hobson, "A Study of Thermal Transpiration Using Ultra-High Vacuum Techniques," *J. of Vacuum Science and Technology*, Vol. 2, p. 182-197, 1965.
- ¹⁶W. Jitschin and P. Rohl, "Quantitative Study of the Thermal Transpiration Effect in Vacuum Gauges," *J. of Vacuum Science and Technology A*, Vol. 5, No. 3, p. 372-375, May/June 1987.
- ¹⁷T. Ohwada, Y. Sone, and K. Aoki, "Numerical Analysis of the Poiseuille and Thermal Transpiration Flows Between Two Parallel Plates on the Basis of the Boltzmann Equation for Hard Sphere Molecules," *Physics of Fluids A*, Vol. 1, No. 12, p. 2042-2046, December 1989.
- ¹⁸F. Sharipov, "Rarefied Gas Flow Through a Long Tube at any Temperature Ratio," *Journal of Vacuum Science and Technology*, A 14 (4), p. 2627-2635, July/August 1996.
- ¹⁹A. Beskok, G.E. Karniadakis, "Simulation of Heat and Momentum Transfer Complex Microgeometries," *Journal of Thermophysics and Heat Transfer*, Vol. 8, No. 4, p. 647-655, 1994.
- ²⁰G. A. Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flows*, Clarendon Press, Oxford, UK, 1994.
- ²¹T. Bartel, S. Plimpton, J. Johannes, and J. Payne, *Icarus: a 2D Direct Simulation Monte Carlo (DSMC) Code for Parallel Computers, User's Manual - V.3.0, SAND96-0591*, Sandia National Laboratories, Albuquerque, New Mexico, October 1996.
- ²²C. C. Wong, M. L. Hudson, T. J. Bartel, and J. L. Payne, "Simulation of Rarefied Flows in MEMS Devices," *43rd American Vacuum Society National Symposium*, Philadelphia, PA, p. 28, November 1996.
- ²³E. S. Piekos, K. S. Breuer, "DSMC Modeling of Micromechanical Devices," *AIAA 95-2089, 30th AIAA Thermophysics Conference*, San Diego, CA, June 19-22, 1995.
- ²⁴C. K. Oh, E. S. Oran, B. Z. Cybyk, "Microchannel Flow Computing with DSMC-MLG," *AIAA 95-2090, 30th AIAA Thermophysics Conference*, San Diego, CA, June 19-22, 1995.
- ²⁵M. L. Hudson and T. J. Bartel, "DSMC Simulation of Thermal Transpiration and Accommodation Pumps," to be presented at *21st International Symposium on Rarefied Gas Dynamics*, Marseille, France, July 1998.

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Figure 1 Schematic Diagram and Computational Grid System of the Pump Design Configuration being Studied.

Figure 2 Temperature Distribution along the Micro-Channel Predicted by the ICARUS code for Case I: Transition Flow Regime.

Figure 3 Pressure Distribution along the Micro-Channel Predicted by the ICARUS code for Case I: Transition Flow Regime.

Figure 4 Number Density Distribution along the Micro-Channel Predicted by the ICARUS code for Case I: Transition Flow Regime.

Figure 5 Temperature Distribution along the Micro-Channel Predicted by the ICARUS code for Case II: Free-Molecular Flow Regime.

Figure 6 Pressure Distribution along the Micro-Channel Predicted by the ICARUS code for Case II: Free-Molecular Flow Regime.