Effect of thermal variations on the Knudsen forces in the transitional regime

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When objects are maintained at different temperatures and separated by distances of the order of the mean free path of the surrounding host gas molecules, gas kinetic forces called Knudsen forces may be involved. The understanding of this effect may result in some improvements in microelectromechanical devices and measurement systems. We present the thermal dependence of these forces in the transitional regime for different gases. In this mode, the Knudsen effect can be significant and, therefore, become a problem in microscale devices. For this study, a silicon microcantilever, mounted close to a substrate, is used and changes in temperature are observed by measuring bending of the microcantilever. © *2004 American Institute of Physics.*
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A wide range of microelectromechanical devices, based on microcantilevers, are now used for sensing or imaging at the microscale. These devices, which are very sensitive to their environment, can operate in different media. However, under certain conditions, unexpected effects, which may not be observable at the macroscale, can occur in those devices that involve small distances. An example of these unusual effects is Knudsen forces. Generally, two conditions are required to generate these forces, a temperature gradient and a mean free path of the gas molecules comparable to a characteristic length of the studied devices.[1] These conditions may give rise to pressure gradients and result in mechanical force. Microcantilevers are commonly used in important fields such as chemical, physical, and biological sensors[2] or atomic force microscopy (AFM).[3] In these concepts, an AFM cantilever is used and is usually brought close to a sample substrate and its bending and/or its changes in resonance frequency are monitored. On the microscale, the temperature inhomogeneity is usually prevailing,[1,4,5] a requirement for obtaining Knudsen forces. But, frequently, the cantilever–substrate distances involved in those devices are much greater than the mean free path of the host gas molecules, so these forces are insignificant.

However, depending on the working pressure range, different modes of collisions exist, the continuum regime (high pressure), the slip flow regime, the transitional regime, and the free molecular regime (low pressure).[6] In fact, by decreasing the pressure, molecule–molecule interactions become negligible compared to molecule–surface interactions because of rarefaction of the gas. Gas rarefaction can result in a mean free path of the gas molecules on the order of the specific length of the device or even larger. Thus, Knudsen forces are no longer negligible in microelectromechanical systems (MEMS) at low pressure.[5] Furthermore, this effect can also occur at atmospheric pressure in devices with a porous medium with pore diameters comparable to the mean free path of the host gas.[7,8] Again, since the two necessary conditions are met, Knudsen forces are involved.

Apart from the geometrical and molecular dependences, these forces depend on two main physical quantities, pressure and temperature. A study of the pressure dependence was carried out[5,6] that showed all the different collisional regimes in a pressure range from below 0.1 mm Hg to atmospheric. In fact, in that work, the linear response of cantilever deflection in the free molecular regime is illustrated as well as the effect of thermal transpiration in the transitional regime. The latter effect is evident in that study by the observation of a peak, $P=P_p$, in the transitional region, depending on the molecular composition of the surrounding host gas. The peak pressure is observed at around 128 and 49 mm Hg for monatomic gases He and Ar, respectively. Moreover, similar peaks are observed for polyatomic gases such as air, O_2, and N_2 at 37 mm Hg, and at 26 mm Hg for CO_2. In this letter, we report the experimental thermal dependence of Knudsen forces in the transitional regime. Our goal here is to show how the Knudsen effect varies with the temperature and thus the absolute temperature measurement of the microcantilever itself is less vital, but will be the subject of a forthcoming article.

Our experimental setup for measurement of the temperature dependence of Knudsen forces in the transitional regime is illustrated in Fig. 1. A U-shaped doped polysilicon cantilever is controlled by an electronic chip and this device is introduced into a vacuum system. A mechanical pump allows the system to operate at low pressure ($P<0.1$ mm Hg) while a 500 sccm mass flow meter is used to regulate the host gas input flow. The working pressure is thus set to the peak pressure P_p inside the vacuum system. A resistor-thermal detector (RTD) monitors the temperature at the cantilever level and a thermocouple is used to monitor the temperature inside the vacuum system. A focused argon ion laser (529 nm line) is used to heat the cantilever. An optical density filter allows us to vary the laser power and thus the temperature to be controlled. A chopper is used to modulate the laser output at an imposed frequency and is associated

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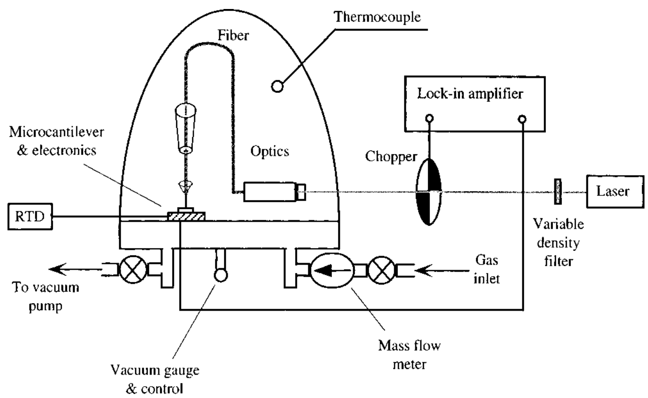

FIG. 1. Experimental setup. An Ar ion laser beam is focused onto a microcantilever inside a vacuum system. A mechanical pump decreases the pressure by evacuating the surrounding gas molecules when the mass flow meter controls the host gas flow input. Thus the system is operated at the peak pressure. The temperature inside the bell jar is monitored by a thermocouple whereas the temperature of the vicinity of the substrate of the cantilever is monitored by a resistor-thermal detector. Thermal variations, at the cantilever level, are made by varying the laser beam power via changes in the angular position of the density filter. Bending of the cantilever, induced by capacitance changes in the cantilever–substrate system, is measured by a lock-in amplifier.

with a lock-in amplifier to measure the cantilever bending. This response displays capacitance variations of the cantilever–substrate system (nominal gap size $d_0 = 2\ \mu$m) when the distance between these two is modified via cantilever deflection $W(x)$ at point x along the cantilever. Then the output signal can be shown to be given by an integration of $S(x) = \epsilon_0 U A(x)/\{c_f[d_0 + W(x)]\}$, where ϵ_0 is the permittivity of free space, U is the amplitude of the driving voltage, $A(x)$ is the differential area at x, and c_f is the reference capacitance. Static bending $W(x)$ of the cantilever with length L satisfies $W_x^{(4)}(x) = F\Theta(L-x)$, where F is the imposed molecular force scaled with the material properties of the cantilever, and Θ is the Heaviside function.[1] We carried out the same experiment for different gases.

The vacuum system was maintained at a temperature of $T = 25\,°C$ while data were obtained at peak pressure P_p. Under these conditions, the Knudsen number, denoted Kn, can be defined by the ratio of the molecular mean free path λ with a specific length of the studied system d, and can also be expressed[1] by $\mathrm{Kn} = \lambda/d = \eta(\pi RT/2M_m)^{1/2}/Pd$, where η and M_m are, respectively, the viscosity and the molecular mass of the surrounding medium, and R is the universal gas constant.[9]

Table I shows the different experimental parameters for each rest gas environment and gives a Knudsen number calculation under these conditions. The viscosity is given at peak pressure P_p for $T = 25\,°C$.[10] The working pressures are

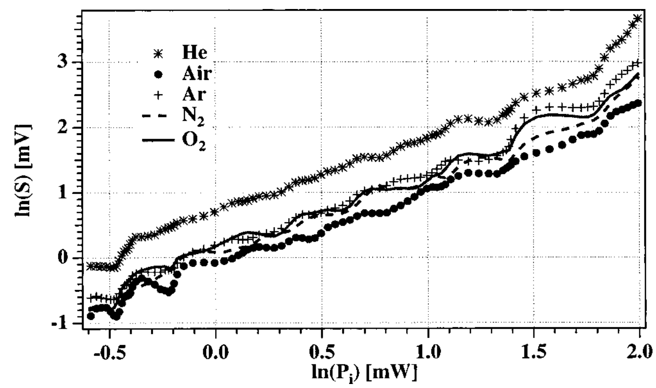

FIG. 2. Initial data showing the thermal dependence of the Knudsen effect in the transitional regime for helium, argon, air, nitrogen, and oxygen. This graph shows the signal from the lock-in amplifier (capacitance variations in the cantilever–substrate assembly) for the five gases studied. The nearly linear dependence of the Knudsen effect in the transitional regime with changes in temperature can be seen.

chosen in relation to the work described above.[6] In our case, for the gases used, Kn is between 0.1 and 10, which proves that our experiment is conducted in the transitional regime.[6]

Figure 2 displays measurement of the thermal dependence of the Knudsen effect in He, Ar, air, O_2, and N_2. The signal S is the output of the lock-in amplifier at a 1 Hz sample rate and represents the capacitance variation corresponding to cantilever bending. We note here that, since the response of the density filter is nonlinear with respect to angular variations, the data in Fig. 2 are displayed as a function of the natural logarithm of the incident power density P_i. Measurement of the laser power at the cantilever level, inside the vacuum system, was carried out when rotating the density filter, and it showed its expected exponential response. Furthermore, since the cantilever response, S, behaves nonlinearly with respect to the incident power density in the pressure regime studied, we have presented the natural logarithm of the signal in Fig. 2. Our analysis of the measured data shows that the measured signals vary almost linearly with the incident power. The deviation from linearity appears to be of approximately the same magnitude for all the gases examined. This complicated dependence of the magnitude of Knudsen forces on the magnitude of the temperature gradient can change, depending on the pressure regime. Such studies must be taken into account for proper interpretation of the behavior of many MEMS-based devices. Furthermore, the method presented can help in minimizing or eliminating the magnitude of the effect of Knudsen forces.

In this letter, we have shown that Knudsen forces have a nearly linear dependence on the relative changes in temperature at the cantilever level when the experiment is conducted

TABLE I. Experimental parameters and a Kn calculation under relevant conditions. The viscosity values are given at the working pressure and $T = 25\,°C$. In our case, the specific length d is equal to $2\ \mu$m.

Gas	Working pressure, P (mm Hg)	Viscosity at 25 °C and P_p, η (10^{-7} PI)	Molecular mass, M_m (g mol^{-1})	Kn
Air	47.9	186.2	28.950	0.77
Argon	50.2	225.3	39.948	0.75
Helium	120.8	198.4	4.003	0.87
Nitrogen	47.6	177.9	28.013	0.75
Oxygen	47.2	204.3	31.999	0.81

in the transitional regime. In this mode, Knudsen forces can be significant and, therefore, can become a problem in different devices based on microcantilevers. Good understanding of this effect could allow improvement in force measurements in MEMS,[1] and could also induce improvements of devices under development, such as rf-MEM switches based on thermal transpiration phenomena in microchannels[10] or thermal transpiration gas micropumps as an application of the Knudsen compressor.[11]

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