

Vapor lubricant transport in MEMS devices

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Vapor phase lubrication is considered one of the most likely means of lubricating MEMS devices with replenishable solid films. Since gas phase diffusion is the primary means of vapor lubricant transport into the long, narrow channels of MEMS devices, it is necessary to determine that this is sufficient to replenish lubricant films worn at high rates. The diffusion of vapor phase lubricant into a long, narrow channel has been modeled in order to solve for the lubricant partial pressure distribution along such a channel in a MEMS device. This has been used to estimate the maximum channel length for which vapor phase transport can replenish adsorbed lubricant films. Using reasonable parameters for description of the channel, the vapor lubricant properties, and the diffusion constant, it can be shown that gas phase diffusion is sufficient to support the replenishment of vapor lubricant films being worn at rates as high as 1 monolayer(s) in channels with aspect ratios of 100 or higher.

KEY WORDS: vapor phase lubrication, MEMS device

1. Introduction

Microelectromechanical systems (MEMS) integrate mechanical devices and semiconductor electronics on single substrates for applications that require mechanical actuation, but only at low power. The elements of MEMS devices have length scales of <1 mm and feature widths or component spacings of <1 μm . Common examples of MEMS that are used in commercial applications include accelerometers and optical beam deflectors; however, motors, valves, and microfluidics systems have also been designed and fabricated. As with all mechanical devices, tribological issues are critical to the long term performance and reliability of MEMS [1–3]. As a result the most successful designs have been those that avoid putting surfaces into sliding contact with one another. MEMS devices such as motors which must incorporate surfaces in sliding contact all suffer from high friction and wear and will only operate for limited periods of time before failure [4]. Until viable means for lubricating such devices are developed, the practical scope of MEMS applications will be limited.

The development of successful lubrication schemes for MEMS is hampered by two issues. The first is that the materials most commonly used for MEMS fabrication are semiconductors and ceramics such as Si or SiO_2 which are hard, brittle materials that are not commonly used for mechanical devices [5]. As a consequence, there is little experience with their lubrication. The second issue is the fact that MEMS components are very small and do not develop much power or much inertia when in motion. In addition, the fact that

the surface to volume ratio of MEMS is very high, means that they are highly susceptible to the influence of surface forces such as friction. Adhesion forces between surfaces can quite easily exceed the maximum forces developed in the device and thus bind surfaces together irreversibly.

The scope of materials that might be compatible lubricants for use with MEMS is quite different from that of commonly used lubricants. Traditional liquid lubricants are incompatible with MEMS simply because their viscosity is sufficiently high that they would prevent motion of the device components. Solid lubricants have been developed for a number of applications for which liquids are inappropriate. Their use, however, is constrained by the fact that one needs to devise a means for replenishment of solid lubricant films which become worn by sliding motion. Since one cannot tear down, refinish, and then reconstruct MEMS, one must resort to vapor phase lubrication as a means of continuously replenishing solid lubricant films on MEMS surfaces [6]. Vapor lubrication has the advantage that it can allow the lubricant film to conform to all surfaces provided that the vapor can be transported into the interstices of the MEMS device. Vapor phase lubrication has traditionally been developed for use in extremely high temperature applications for which liquid lubricants cannot be found [7–9]. Vapor phase lubrication functions by use of high vapor pressure compounds which can be transported to the load bearing surfaces through the gas phase. At the surfaces they react or decompose to produce the solid lubricant film. The most highly studied example has been tricresylphosphate (TCP) which can be used to lubricate the surfaces of iron base materials at

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temperatures in excess of 500 °C. Although the solid lubricating film produced on the surface does wear with use, it can be replenished by transport of the lubricant precursor, TCP, through the gas phase. Provided that one can identify a lubricant precursor that is compatible with MEMS materials, vapor phase lubrication is ideally suited for use with MEMS devices.

Empirical evidence indicates that vapor phase lubrication can reduce friction and wear in MEMS. There are a number of reports of the effects of humidity on the operation of MEMS devices. These all indicate that their lifetimes are extended by increases in ambient humidity [10]. This must be a result of the diffusion of water vapor into the interstices of the MEMS devices where it can adsorb onto the MEMS surfaces and act as a lubricant.

A number of issues arise in considering the use of vapor phase lubrication with MEMS. One is the choice of appropriate lubricants for use with MEMS fabrication materials. A second issue is whether or not the very high aspect ratio of the spacings between MEMS components will allow sufficiently rapid diffusive transport of the vapor lubricant to surfaces within the device. In MEMS, components or elements with lengths on the order of 100 μm can be separated by spacings on the order of 1 μm [11]. This is illustrated in figure 1(a) by a pair of surfaces separated by a

narrow channel of length $2l$ and gap height h . Vapor lubricant must diffuse into and along the length of the gap while also adsorbing onto the surfaces to react and form a lubricating film. If the aspect ratio of the gap is too high or the wear rate of material from the surfaces is too fast, the transport of lubricant to the surfaces deepest in the channel will not be sufficient to replenish and lubricate the sliding surfaces.

This paper describes a model for the combined gas phase diffusion and surface reaction processes that must occur in the long narrow channels of a MEMS device in order to provide effective vapor phase lubrication. The objective is to determine the conditions under which gas phase diffusion can serve as an effective means of lubricant transport into MEMS devices. More precisely, for a given partial pressure of vapor lubricant, P_0 , and a given wear rate, r_w , what is the maximum aspect ratio, l/h , of a channel in a MEMS device which can be lubricated via the vapor phase?

2. Model for vapor lubricant transport in a MEMS device

In order to understand the problem of vapor lubricant diffusion and reaction in the interstices of MEMS devices consider the simple, one dimensional model that is depicted in figure 1(a). Two parallel surfaces of length $2l$ are separated by a narrow gap of height h . The two surfaces are in some sort of relative motion and occasional contact between the two requires lubrication to reduce friction, and minimize wear. At either end of the channel the lubricant is present in the vapor phase at a partial pressure, P_0 , which must be less than or equal to its equilibrium vapor pressure at the ambient temperature. The vapor diffuses into and along the channel with a gas phase diffusion constant, D . Within the channel the vapor lubricant adsorbs reversibly on the surfaces to form a lubricating film. Sliding contact between the two surfaces results in the loss or wear of the lubricating film at a rate, r_w . As the lubricating film is worn away it must be replaced by adsorption of additional vapor phase lubricant. In order for the vapor lubricant to serve its purpose, the steady state rate of film replenishment must equal the wear rate. If one assumes that the vapor lubricant has been chosen such that it adsorbs rapidly on the surface exposed by wear, then the limitation on the formation rate will be the rate of vapor transport. Consumption of the vapor lubricant on the surfaces results in a drop in the lubricant partial pressure along the length of the channel. The limit on the effective length of a channel is imposed by the fact that at some length the partial pressure in the middle of the channel will drop to the point that it can no longer maintain a high coverage of the adsorbed lubricating film. Hence, for a given lubricant film wear rate, r_w , we need to determine the maximum allowable length of a channel such that

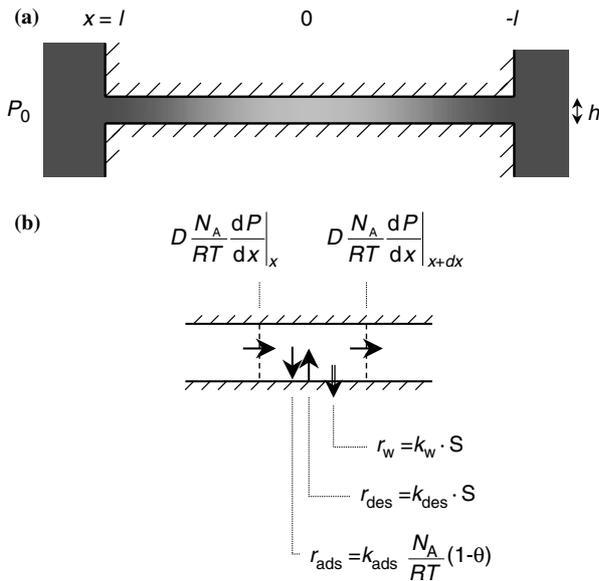


Figure 1. (a) Schematic of a channel between two moving surfaces in a MEMS device. The gap between the two surfaces is h and the length of the channel is $2l$. The partial pressure of the vapor phase lubricant is shown in shades of grey decreasing along the length of the channel as it is consumed by adsorption onto the surfaces and wear. (b) An infinitesimal volume of the MEMS channel. The mass balance in the volume is dictated by diffusive flow in and out, adsorption and desorption onto the walls and loss by wear at the surfaces.

vapor diffusion is sufficient to maintain a high coverage of the lubricant film.

Diffusion of the vapor lubricant along the channel is assumed to occur in the gas phase only. Although diffusion of adsorbed lubricant molecules along the surfaces can also occur, this is likely to be much slower than diffusion through the gas phase. In any case, the assumption of pure gas phase diffusion represents a worst case scenario and the inclusion of surface diffusion would only increase the maximum channel length amenable to vapor phase lubrication. Given the high aspect ratio, l/h , of the channel it is reasonable to assume rapid diffusional mixing across its width, h , and thus that the partial pressure of the lubricant across the width of the channel is uniform. Under these conditions the problem can be solved in one dimension to find the lubricant partial pressure distribution, $P(x)$, along the length of the channel. At steady state the partial pressure distribution along the length of the channel will be given by the solution to

$$\frac{d^2P}{dx^2} = \frac{2RT}{N_A} \cdot \frac{1}{Dh} \cdot r_w, \quad (1)$$

where R is the gas constant, T is the temperature and N_A is the Avogadro's number. This expression is developed in Appendix A. The wear rate, r_w , is in units of molecules per unit area per unit time. The solution of this equation requires the specification of two boundary conditions and an expression for the lubricant wear rate, r_w , in terms of the coverage of the adsorbed lubricant, θ .

To provide lubrication the vapor must adsorb from the gas phase onto the surfaces of the channel. Under equilibrium conditions the coverage of an adsorbate on a surface is described by an adsorption isotherm which gives the coverage as a function of temperature and pressure, $\theta(T, P)$. The simplest is the first-order Langmuir adsorption isotherm. Under conditions of vapor lubrication, true equilibrium is not established because there is consumption of lubricant on the surface as a result of wear. Nonetheless, if the lubricant consumption rate at the surfaces is proportional to its coverage, then one ends up with an expression for the steady-state lubricant coverage that is analogous to the Langmuir isotherm (Appendix B).

$$\theta = \frac{K'P}{1 + K'P}. \quad (2)$$

The quantity, K' , is the pseudo-equilibrium constant for vapor lubricant adsorption and is defined in equation (B6). Note that for a wide range of pressures, $K'P > 1$, the coverage of adsorbed lubricant approaches $\theta = 1$ and the surface is saturated with adsorbed vapor lubricant molecules. Once the partial pressure drops significantly below $1/K'$ the coverage drops below one

monolayer and the film may fail to provide adequate lubrication.

A vapor phase lubricant can function in a number of ways. For the sake of this work we consider a mechanism in which the vapor phase species adsorbed on the surface is itself the lubricating species. We assume that in order to lubricate the surface, the coverage of the vapor phase lubricant on the surface, θ , must be close to saturation or one monolayer. Wear in this case is assumed to mean loss of the adsorbed vapor phase lubricant as a result of sliding contact and it is assumed that the rate of lubricant loss from the surface is first-order in coverage.

$$r_w = \frac{d\theta}{dt} = -k_w\theta \cdot S \quad (3)$$

S is the areal/density of lubricant adsorption sites. The rate constant for wear of the lubricating film, k_w , is uniform along the length of the channel. In reality, of course, the consumption or wear of adsorbed lubricant will occur only at contact points between the two surfaces. The model assumes that these points are distributed roughly uniformly along the length of the channel. This is a conservative assumption since it assumes that lubricant is being adsorbed and consumed along the entire length of the channel, when in reality it is only likely to be consumed at a number of discrete points.

Wear of the lubricant is assumed to mean its loss from the surface by some mechanism other than simple thermally induced desorption. This could be mechanically induced desorption into the gas phase or a surface reaction that results in a chemical transformation of the adsorbed vapor lubricant. The details need not be specified, however, there are certain constraints that must be met in order for a vapor phase lubricant to function effectively. If wear of the lubricant film simply results in the creation of solid deposits or wear particles that will ultimately fill the MEMS channel, then it will not be an effective lubricant. The ideal vapor lubricant is one whose wear products are molecules that can desorb from the surface and then diffuse out of the MEMS channel.

Note that the efficacy of a particular molecule as a vapor phase lubricant must depend on the rate constants for adsorption, desorption and wear (k_{ads} , k_{des} and k_w) that are combined to define the effective pseudo-equilibrium constant for adsorption, K' , defined in App. B. The goal of this paper is to show that for realistic values of the parameters in this model, diffusive transport of the vapor phase lubricant into channels with high aspect ratios is sufficient to maintain a high coverage of the lubricating species on the surface.

3. Vapor lubricant transport in a narrow channel

The model for vapor lubricant transport into a high aspect ratio channel has vapor phase diffusion as the

transport mechanism. Along the length of the channel the vapor phase lubricant adsorbs reversibly on the channel walls. Consumption of lubricant occurs on the channel walls by degradation due to wear. Under these conditions the pressure distribution of vapor lubricant, $P(x)$, along the channel will be given by the solution to

$$\frac{d^2P}{dx^2} = \frac{2RT}{N_A} \cdot \frac{1}{Dh} \cdot k_w \theta \cdot S. \quad (4)$$

The vapor lubricant coverage as a function of pressure is given by the pseudo-adsorption isotherm of equation (2). Equation (4) cannot be solved analytically for the pressure distribution. It is the case, however, that for reasonable values of the pseudo-equilibrium constant, K' , the coverage of adsorbed vapor phase lubricant will be close to saturation ($\theta \approx 1$) for a wide range of pressures, $P_0 > P > K'^{-1}$. As a consequence equation (4) reduces to

$$\frac{d^2P}{dx^2} = \frac{2RTS}{N_A} \cdot \frac{1}{Dh} \cdot k_w \quad (5)$$

over a wide range of pressures.

The solution to equation (5) requires two boundary conditions on $P(x)$. One boundary condition is simply that the partial pressure of the vapor phase lubricant at the entrances to the channel be a constant, P_0 . This is the partial pressure of vapor phase lubricant outside the MEMS channel and for practical applications would probably be on the order of its equilibrium vapor pressure at the ambient temperature.

$$P(l) = P(-l) = P_0 \quad (6)$$

The second boundary condition is that the gradient of the pressure distribution at the center of the channel be zero.

$$\left. \frac{dP}{dx} \right|_{x=0} = 0 \quad (7)$$

This is simply dictated by the symmetry of the problem.

Given equation (5) and the appropriate boundary conditions, the lubricant partial pressure distribution within the channel is

$$P_0 - P(x) = \frac{RTS}{N_A} \cdot \frac{k_w}{Dh} (l^2 - x^2). \quad (8)$$

Thus the partial pressure distribution along the length of the channel is quadratic as illustrated in figure 2. The quadratic approximation to the solution of equation (4) is valid as long as the coverage on the surface remains high. It is important to keep in mind that

although the pressure drops along the length of the channel, the coverage of adsorbed vapor lubricant remains high while the pressure remains $K'P > 1$. As such the coverage on the surface can remain high enough to provide adequate lubrication or wear protection along the full length of the channel.

4. Allowable aspect ratio for MEMS vapor lubrication

The final question to be answered is the maximum allowable length of the channel, l , for a given width, h . As long as the partial pressure of the vapor phase lubricant at the center of the channel satisfies the condition that $K'P > 1$, equation (8) provides a good approximation to the partial pressure distribution and the coverage of the vapor lubricant on the surface will be high along the entire length of the channel. Thus the maximum allowable length of the channel is given by

$$P_0 - 1/K' = \frac{RTS}{N_A} \cdot \frac{k_w}{Dh} \cdot (l^2). \quad (9)$$

Provided that the partial pressure of the vapor lubricant at the entrances to the channel is sufficiently high, $P_0 \gg 1/K'$, the maximum allowable length of the channel is given by

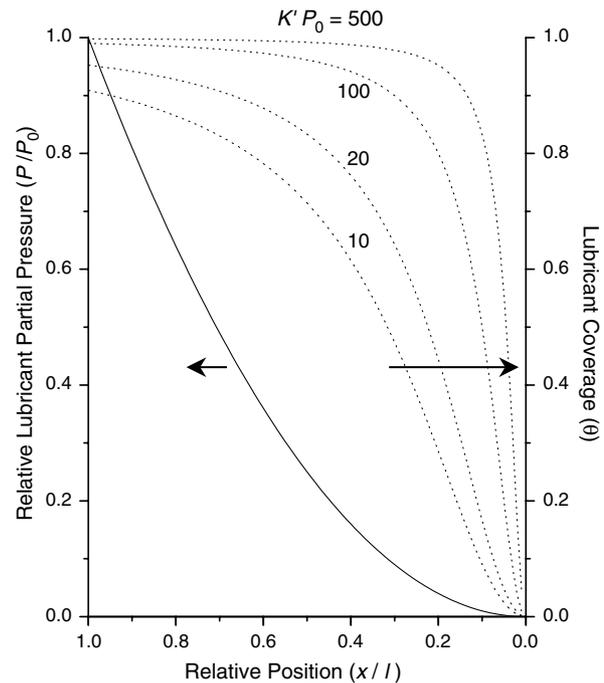


Figure 2. The relative lubricant partial pressure distribution, P/P_0 (solid line), and the adsorbed lubricant coverage, θ (dashed lines), plotted as functions of the relative position, x/l , along a channel of length l . The coverages are plotted for a range of values of $K'P_0$. As the value of $K'P_0$ increases, the lubricant coverage remains higher for greater distances in to the channel.

$$l^2 \approx \frac{N_A P_0}{RTS} \cdot \frac{Dh}{k_w}. \quad (10)$$

A number of the variables in this expression are either constants or take on a limited range of values. Gas phase diffusion constants have magnitudes on the order of $D \approx 10^{-5} \text{ m}^2/\text{s}$. The areal density of lubricant adsorption sites on any surface is approximated at $S \approx 10^{19} \text{ m}^{-2}$. Thus the maximum allowable channel length is dictated principally by the partial pressure of the vapor lubricant, P_0 , the channel height, h , and the rate constant for wear, k_w . At room temperature equation (10) can be evaluated by

$$l^2 \approx \alpha \frac{P_0}{k_w} \cdot h \quad \left(\alpha = 10^{-4} \frac{\text{m}}{\text{Pa} \cdot \text{s}} \right). \quad (11)$$

Obviously, the allowable length of the channel increases with increasing lubricant pressure, P_0 , and decreases with increasing wear rate, k_w . The condition under which this estimate of the allowable length holds true is that $K'P_0 \gg 1$ or

$$\frac{P_0}{k_{\text{des}} + k_w} \gg 10 \text{ Pa} \cdot \text{s}. \quad (12)$$

This represents the constraint on the properties of the lubricant, its interaction with the surface, and its rate of wear. The rate constant for desorption is dictated by the heat of adsorption of the lubricant. Clearly, a successful lubricant must have a high vapor pressure and must have a strong interaction with the surface such that k_{des} is low and the lubricant does not desorb readily. The rate of loss should be dictated by the rate of wear and thus $k_w \gg d_{\text{des}}$. This then defines the necessary constraints on the lubricant vapor pressure and the rate of wear,

$$\frac{P_0}{k_w} \gg 10 \text{ Pa} \cdot \text{s}. \quad (13)$$

As an example, a lubricant for which $P_0/k_w = 100 \text{ Pa} \cdot \text{s}$ will lubricate a channel of length $l = 100 \text{ } \mu\text{m}$ with a channel height of $h = 1 \text{ } \mu\text{m}$ or, in other words, a channel with an aspect ratio of $l/h = 100$. For a relatively high wear rate of 1 monolayer/s (or $r_w = 10^{19} \text{ molecules/m}^2/\text{s}$), this requires a lubricant with a pressure of at least $P_0 = 100 \text{ Pa}$. Numerous common liquids have room temperature vapor pressures of this magnitude. Water, for example has a room temperature vapor pressure of roughly 3100 Pa. Ethanol has a vapor pressure of $\sim 8000 \text{ Pa}$ and octane a vapor pressure of $\sim 2500 \text{ Pa}$. Thus there are many compounds with room temperature vapor pressures that are high enough to support vapor phase lubrication of MEMS.

5. Lubricant pressure distribution and coverage along a MEMS channel

The analysis above provides a description of the lubricant partial pressure distribution along a long, narrow channel and a description of the coverage of the lubricant on the surfaces of the channel. The partial pressure distribution is approximated by equation (8) provided that the condition $K'P_0 \gg 1$ is met and that the length of the channel is limited to the estimate given by equation 10. If the position along the channel is scaled by l to define a dimensionless position $x' = x/l$ which covers the range $x' = 0 \rightarrow 1$, then the scaled, dimensionless pressure $P' = P/P_0$ simply takes the form

$$P'(x') = x'^2. \quad (14)$$

Figure 2 plots P' and the lubricant coverage, θ , versus x' for several different values of $K'P_0$. Note that P' underestimates the true dimensionless pressure and thus the predictions of coverage are also underestimates. The point is that the lubricant coverage remains high along a large fraction of channels of length l . Although the model predicts that the partial pressure and the lubricant coverage drop to zero for channels of length l , equation (10) nonetheless provides a good estimate of the allowable channel length. Figure 2 also illustrates the fact that higher values of $K'P_0$ result in higher lubricant coverages deeper into the channel and thus longer allowable channel lengths.

6. Conclusions

Vapor phase lubrication is one of the most likely mechanisms to be able to solve the tribological problems associated with the long term operation of MEMS devices with surfaces in sliding contact. At high wear rates, however, the allowable length of a channel within a MEMS device will be limited by the ability of vapor phase lubricants to diffuse into and along the narrow channel. Analysis of the mass transport problem has shown that for reasonable lubricant properties and for wear rates as high as 1 monolayer/s, vapor phase lubrication is amenable to MEMS designs with aspect ratios as high as $l/h = 100$. For wear rates that are significantly higher or aspect ratios significantly greater than those predicted by equation 10, one would have to design MEMS with active mechanisms for vapor lubricant transport into confined regions of the device. Although the analysis presented in this paper does elucidate some of the necessary properties of a good vapor phase lubricant, it remains to find a lubricant that is amenable to the materials used for MEMS fabrication.

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Appendix A

The development of the steady state equation (equation (1)) for the pressure drop along the length of the MEMS channel assumes three processes: diffusion of lubricant vapor along the length of the channel, reversible adsorption and desorption of lubricant on the surface, and consumption of lubricant as a result of wear. These processes are illustrated in figure 1(b) which shows the flow of material in and out of an infinitesimal volume of length dx between the two surfaces of the MEMS channel. Two variables are required to define the number of molecules in the infinitesimal volume: the concentration in the gas phase and the concentration on the surface. The concentration in the gas phase is proportional to the pressure ($N_A P/RT$). The concentration on the surface is given by the product of the fraction of filled adsorption sites, θ , and the areal density of adsorption sites, S . The mass balances are given by:

$$\frac{N_A}{RT} \frac{dP}{dt} = D \frac{N_A}{RT} \frac{d^2P}{dx^2} - \frac{2}{h} k_{\text{ads}} \frac{N_A P}{RT} (1 - \theta) + \frac{2}{h} k_{\text{des}} \theta \cdot S \quad (\text{A1})$$

$$\text{and} \quad S \frac{d\theta}{dt} = k_{\text{ads}} \frac{N_A P}{RT} (1 - \theta) - k_{\text{des}} \theta \cdot S - r_w. \quad (\text{A2})$$

In the first expression the factors of two in the terms for adsorption and desorption account for the existence of two walls. Under steady-state conditions equations (A1) and (A2) reduce to

$$0 = \frac{Dh}{2} \frac{N_A}{RT} \frac{d^2P}{dx^2} - k_{\text{ads}} \frac{N_A P}{RT} (1 - \theta) + k_{\text{des}} \theta \cdot S \quad (\text{A3})$$

$$\text{and} \quad 0 = k_{\text{ads}} \frac{N_A P}{RT} (1 - \theta) - k_{\text{des}} \theta \cdot S - r_w \quad (\text{A4})$$

which combine to yield equation (1) for the pressure distribution along the length of the channel.

Appendix B

The steady-state coverage of vapor lubricant on the surfaces of the MEMS channel is dictated by a balance

between the rates of adsorption, desorption and consumption due to wear. The rate of adsorption can be given by

$$r_{\text{ads}} = k_{\text{ads}} \frac{N_A P}{RT} (1 - \theta). \quad (\text{B1})$$

The rate constant for adsorption, k_{ads} , is determined by the molecular flux to the surface and the sticking coefficient for adsorption, S_0 . Since the sticking coefficient for molecular adsorption of most large molecules to surfaces is roughly unity, the rate constant for adsorption is given by

$$k_{\text{ads}} = \left(\frac{RT}{2\pi m} \right)^{1/2} \quad (\text{B2})$$

where m is the molar mass of the adsorbing molecule. The rates of lubricant desorption from the surface and lubricant loss by wear are given by

$$r_{\text{des}} = k_{\text{des}} \theta \cdot S \quad (\text{B3})$$

$$\text{and} \quad r_w = k_w \theta \cdot S \quad (\text{B4})$$

The steady-state balance between these three

$$r_{\text{ads}} = r_{\text{des}} + r_w \quad (\text{B5})$$

$$\text{yields} \quad \theta = \frac{K' P}{1 + K' P} \quad (\text{B6})$$

$$\text{with} \quad K' = \frac{1}{k_{\text{des}} + k_w} \left(\frac{RT}{2\pi m} \right)^{1/2} \left(\frac{N_A}{RT \cdot S} \right). \quad (\text{B7})$$

The expression for coverage, θ , is analogous to the first-order Langmuir isotherm but with a pseudo-equilibrium constant K' . Under conditions in which $k_{\text{des}} \gg k_w$ the pseudo-equilibrium constant approaches the value of the thermodynamic adsorption equilibrium constant, K .

References

- [1] B. Bhushan, Proc. Inst. Mech. Eng. J- J-Eng. Tribol. 215 (2001) 1.
- [2] R. Maboudian, Surf. Sci. Rep. 30 (1998) 209.
- [3] M.P. de Boer and T.M. Mayer, Mrs Bulletin 26 (2001) 302.
- [4] M.T. Dugger, D.C. Senft and G.C. Nelson, in: *Microstructures and Tribology of Polymer Surfaces*, eds. V.V. Tsukruk, K.J. Wahk (American Chemical Society, Washington, D.C., 1999) 455.
- [5] M.N. Gardos, in: *Tribology Issues and Opportunities in MEMS*, ed. B. Bhushan (Kluwer Academic Publisher, Dodrecht, 1998) 341.

- [6] J. Krim and M. Abdelmaksoud, in: *Tribology Issues and Opportunities in MEMS*, ed. B. Bhushan (Kluwer Academic Press, Dordrecht, 1998) 273.
- [7] E.E. Graham, A. Nesarikar, N. Forster and G. Givan, *Lubr. Eng.* 49 (1993) 713.
- [8] M.J. Wagner, N.H. Forster, K.W. Van Treuren and D.T. Gerardi, *J. Eng. Gas Turb. Power-Trans. ASME* 122 (2000) 185.
- [9] N.H. Forster, *Tribol. T.* 42 (1999) 10.
- [10] S.T. Patton, W.D. Cowan, K.C. Eapen and J.S. Zabinski, *Tribol. Lett.* 9 (2000) 199.
- [11] R. Maboudian, W.R. Ashurst and C. Carraro, *Tribol. Lett.* 12 (2002) 95.
- [12] J.O. Hirschfelder, C.F. Curtiss, and R.B. Bird, in: *Molecular Theory of Gases and Liquids* (John Wiley & Sons, New York, 1954).