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Micropump Modeling: Current Status and Challenges

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Abstract: Micropumps are one product which was commercialized from Microsystem Industries. It has many applications and many potential as well, and due to this there is a growing interest in their modeling, simulation, and performance and this is going and in hand with research on their fabrication as well. In this paper, we are reviewing the basic aspects of modeling of micropump and their challenges. Basically, the microfluid behavior and the structural behavior in these devices. Also, we are exploring the fluid structural interaction.

Key words: Micropump, MEMS, Microfluid, Fluid-structure interaction.

INTRODUCTION

Since the electronic revolution in the sixties, miniaturization has become an important goal of technology. This is quite clear in the doubling of the number of transistors per chip every two years since the sixties (Michalicek, 2000). Since the first bulk-etched silicon wafers were used as pressure sensors in the 1970*s*, a new discipline arose known as *Micro-electro-mechanical Systems* (MEMS) in the USA and *integrated systems* in Europe (Michalicek, 2000). MEMS are usually defined as highly miniaturized devices or array of devices combining electrical and mechanical components that are fabricated using integrated circuit (IC) batch-processing techniques (Michalicek, 2000). MEMS have received a great deal of attention in recent years. This is due not only to the excitement naturally associated with a new emerging technology, but also to the great promise of increased miniaturization and improved performance of these devices over conventional devices. Miniaturization means less energy input, increased reliability, reduced cost, and a room for more complicated and advanced applications.

Applications of MEMS are very wide. In automotive engineering applications, MEMS-based sensors are used as coolant pressure sensors, manifold gas pressure sensors, airbag accelerometers, and speedometers. In medical applications, MEMS sensors are used for measuring blood pressure and micropumps (MEMS pumps) are used for drug delivery. In defense applications, MEMS are used in inertial navigation, as distributed unattended sensors for security surveillance and process control, as integrated fluidic systems for propellant and combustion control, as mass data storage devices, and in active and conformal surfaces for distributed aerodynamic control of aircraft (Michalicek, 2000).

The worldwide MEMS market is growing at a very fast rate. In 1993, it was less than 1 Billion US Dollars and in 2000 it approached 14 Billion US Dollars. The lion's share in 2000 was for pressure sensors, which constituted about one quarter of the worldwide market, and for microfluidic devices, which constituted slightly less than one quarter of the worldwide market (Michalicek, 2000).

Analysis of the dynamics of microelectromechanical (MEMS) devices poses new challenges. Classical analysis in structural dynamics does not lend itself easily to the new types of forcing and nonlinearities one encounters in dealing with MEMS. New approaches have to be developed to deal with these challenges, combining the rigor of theory and the practicality of engineering design approaches.

Micropumps technology is one of the most advanced technologies in MEMS now. They are designed to handle small and precise volumes in various medical, biomedical, and chemical applications. The function of a micropump is to raise the pressure of a specific volume of gas or liquid. Usually, micropumps are integrated with other microflow devices and sensors to allow precise control and sensing of flow of the order of microliters. Several pumping principles are available in the literature. Avery comprehensive review on the different pumping principles by Laser and Santiago (Laser and Santiago, 2004)

The electrostatic load applied to the plate has an upper limit beyond which mechanical restoring force can no longer resist the opposing electrostatic force, thereby leading to the collapse of the structure. This structural instability phenomenon is known as `pull in', and the critical voltage associated with it is called the `pull in voltage'.

Usually, micropumps are integrated with other microflow devices and sensors to allow precise control and sensing of flow of the order of microliters. Several pumping principles are available in the literature and most of them mimic macroscale pumps.

Generally, micropumps are classified into two categories (Tay and Phoon, 1997): mechanical and non-mechanical. Mechanical micropumps include reciprocating and peristaltic pumps, and non-mechanical micropumps include electrohydrodynamic pumps. Reciprocating micropumps with different actuating

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techniques are widely used. Piezoelectric, pneumatic, electrostatic, and thermopneumatic actuation principles are used. Electrostatic actuation is gaining popularity because of its simplicity and high-flow output pressures (Tay and Phoon, 1997). Different shapes of electrostatic actuating elements are reported in the literature, such as rectangular, square, circular, and annular (Saif *et al.,* 1999; Tay and Phoon, 1997). They are also used in other MEMS devices, such as sensors, valves, deformable micromirrors, and micro-turbo generators. Several transduction techniques have been used for micromachined devices, in general, and micropumps and sensors, in particular. These include piezoelectric, capacitive, optics, and resonance.

Microfluidic devices are posing more challenges to modelers, the key issues that this paper will look at are: the structural modeling, fluid modeling for micro-level, and fluid/ structure interaction.

Structural Modeling:

In micropumps, the main structural element is the membrane. The literature has many controversies about it. Many people claim that the membrane theory is enough ( ) and some others claim that linear plate theory is sufficient ( ). Finally, some groups claim that nonlinear plate theory is the most accurate one for such applications (Faris *et al.,* 2002). To give a good insight into the subject we are going to review in short the main theories of thin plates that are used.

Plates are flat structures whose thickness h is small compared to the other in-plane dimensions. For a circular plate, the only in-plane dimension is the radius R.

Plate theories are classified in many ways. One way of classification is based on the thickness (Bairagi 1986); that is, thin- and thick-plate theories. We focus on thin-plate theories because most of the applications that we address in this work are thin plates. Since we are concerned with circular and annular plates, the theoretical development we present here is based on the cylindrical coordinate system $(r;\theta;z)$. Geometrically, a plate is said to be *thin* if its *thinness ratio h/R* remains less than 1/20, otherwise, the plate is said to be *thick*. In thin-plate theories, the stresses σ_z , τ_{rz} , and $\tau_{\theta z}$, which are directed towards the z-axis across the thickness, are considered to be of negligible magnitude compared to the other stresses. In thick-plate theories, the stress components σ_z , τ_{rz} and $\tau_{\theta z}$ are comparable to the other stresses and cannot be neglected. The various in-plane stresses σ_z , σ_θ , and τ_{rz} do not remain proportional to the distance z measured from the neutral plane though the variation of the stresses τ_{rz} and $\tau_{\theta z}$ across the thickness can still be assumed to be parabolic.

Thin plates can withstand external loads and moments and develop resistive loads and moments which can be classified into two distinct groups of action:

1) Membrane (in-plane) action.
2) Bending (transverse) action.

Thin-plate theories are classified according to the transverse deflection w relative to the thickness h as follows:

Plates with Small Deflection:

In this case, w is small compared to the plate thickness. In theory w must be $\leq 0.2h$ for the application of thin-plate theory with small deflections to give accurate results, but in practice this theory is used for deflections up to the order of the plate thickness with fairly good results for the static case. Because of the smallness of the deflection, the slope and any higher-order terms in the slope or deflection are neglected. Accordingly, in small-deflection theory, the bending effect is dominant whereas the membrane effect is totally disregarded. Though, there are several trials to derive theories within the small deflection framework, the most in use is the Kirchoff plate theory, which is sometimes referred to as the classical plate theory or (CPT).

Plates with Large Deflections:

When $w \leq h$, the results calculated by the small-deflection theory are usually not in good agreement with the observed results. Such cases are better treated by using theories developed on the basis of large deflection. Large deflections should be accounted for, also, in cases that do not necessarily involve deflections larger than the plate thickness. For example, as the thickness of the plate tends to be thinner and thinner, there is considerable reduction in the bending rigidity $D = \frac{Eh^3}{12(1-v^2)}$, causing the plate to be more flexible. Another example is plates subjected to the action of in-plane loads. A third example is plates operated in the elasto-plastic range. In the case of large deflection, both membrane and bending forces take part in resisting the action of the loads. The larger the deflection is, the greater is the curvature and the membrane actions and vice versa.

There are several theories for plates under large deflections, the most commonly used of them is the von Karman plate theory which is sometimes referred to as the Kirchoff-Foppel plate theory, and we use this theory in this thesis. Berger in 1955 (Chia, 1980) proposed an alternate formulation for the nonlinear static isotropic theory of plates, in which he disregarded the elastic energy due to the second invariant of the membrane strain compared to the square of the first invariant. This hypothesis came to be known in the literature as Berger's approximation or hypothesis and the resulting plate equations are known as Berger's plate equations or model. Nowinski and Ohnabe (1972) showed that the Berger approximation may lead to grave inaccuracies and even become meaningless if the edge of the plate is free to move in the in-plane directions.

Plates with Excessive Large Deformations:

Plates having very thin sections offer practically no bending resistance to deformation. Also, plates subjected to excessive loads particularly towards the stage of collapse, are susceptible excessive deflections. In such cases, a plate will behave as a perfectly flexible structure known as *membrane*.

Due to the scarcity of experimental work on this level the controversy will continue until a solid body of evidences is available.

Fluid Modeling:

The science of the flow of liquids and gases in channels and ducts with length scales less than a millimeter and greater than 1 μm is termed as microfluidics. The scale of the flow makes them distinct from the macroscale flows, where conventional fluid mechanics is applicable. Various surface effects which are neglected in macrofluid mechanics can no longer be ignored. Body forces which may not be neglected in macrofluid mechanics play an insignificant role in microfluidics. Closer attention needs to be paid to boundary conditions.

The essential physics is governed by a set of dimensionless numbers which relate competing phenomena in such fluid systems. The Reynolds number Re, is a ratio of inertial forces to viscous forces; the Peclet number, Pe, relates convection to diffusion; the Grashof number Gr, and the Ralyleigh number Ra, which act like the Reynolds number and Peclet number respectively for buoyancy driven flows. The ratio of viscous forces to surface tension is expressed by the capillary number Ca; For polymeric fluids we have the Deborah number De, and the Weissenberg number Wi, expressing elastic effects; the Knudsen number Kn, which relates the microscopic and macroscopic length scales; and the elastic number El, a ratio of elastic to inertial effects. The various dimensionless numbers involved are listed in Table 1 below: (Squires and Quake, 2005)

Table 1 : Dimensionless number in microfluidics.

Re	Reynolds	Inertial/viscous
Pe	Péclet	Convection/diffusion
Gr	Grashof	Re for buoyancy driven flows
Ra	Rayleigh	Pe for buoyancy driven flows
Ca	Capillary	Viscous/interfacial
De	Deborah	Polymer relaxation time/flow time
Wi	Weissenberg	Polymer relaxation time/shear rate time
Kn	Knudsen	Slip length/macroscopic length
El	Elasticity	Elastic effects/inertial effects

Fluid flow in microdevices are different than those in macromachines. The behaviour of MEMS devices using microfluidics cannot *always* be predicted from conventional flow models like Navier-Stokes equations with no-slip boundary conditions as routinely done for large devices. Many experimental results from microdevices could not be explained with conventional continuum flow model, Gad-el-Hak(2005).

For fluid flow through microdevices, questions that arise are, which mathematical model to choose, and what are the proper boundary conditions? With a million fold increase in surface area relative to the mass of a device, surface effects are dominant in microdevices.

Modeling of Gases and Liquids:

A fluid whether a gas or liquid may be modeled as (1) a collection of molecules or (2) as a continuum. For modeling at the molecular level, molecular dynamics simulations are not feasible to be applied for flows with a realistic extent, time or number of molecules, hence continuum models (widely used for macro scale problems), if applicable, may be used. (Gad-el-Hak, 2005)

The flow must satisfy two conditions for the continuum model to be valid:

1. Local flow properties such as density, velocity can be defined as averages over elements which are large compared to the microscopic structure of the fluid but small enough in comparison to the scale of the macroscopic phenomena so that differential calculus can be used to describe them. (Usually satisfied).
2. The flow must not be too far from thermodynamic equilibrium. (Likely cause for inapplicability of the continuum model).

The second condition needs to be satisfied because the shear stress and heat flux terms are expressed (linearly) in terms of velocity and temperature gradients, are only valid when the flow is in thermodynamic equilibrium.

Gas Flows

For gases the continuum model is valid when the mean free path λ is much smaller than a characteristic flow dimension. The flow is then in thermodynamic equilibrium. The Knudsen number defined as the ratio between the mean free path λ and a characteristic length scale of the flow L, determines the degree of rarefaction of the gas flow. The continuum approach is valid as long as (with modified boundary conditions if required) $Kn<0.1$. As Kn increases beyond this threshold value rarefaction effects become more and more important.

The governing equations for the flow field in the various Knudsen number ranges are:

1.	$Kn \rightarrow 0$	Euler equations with boundary condition on the normal velocity.
2.	$Kn < 10^{-3}$	Navier-Stokes equations with no-slip boundary conditions.
3.	$10^{-3} \leq Kn < 10^{-1}$	Navier-Stokes equations with slip boundary conditions.
4.	$10^{-1} \leq Kn < 10$	Transition regime.
5.	$Kn \geq 10$	Free-molecule flow.

Compressibility:

The flow is usually treated as incompressible i.e. a constant density flow, when the Mach no. of the flow is less than 0.3. However the density can vary significantly, at much lower Mach numbers, as in buoyancy driven flows in heat transfer problems, and in flows in microdevices where the pressure may change considerably due to viscous effects. It follows that the well known $M > 0.3$ criterion for compressibility (variable density) is just a necessary condition and not a sufficient one. (Gad-el-Hak, 2005).

Results of several experiments confirm the variable density flow in low speed microchannels. These results among others are from Prud'homme *et al.,* (1986), Pfahler *et al.,* (1991), van den Berg *et al.,* (1993), Liu *et al.,* (18993; 1995), Pong *et al.,* (1994), Harley *et al.,* (1995), Piekos and Breuer (1996), Arkilic (1997), and Arkilic *et al.,* (1995; 1997a; 1997b).

Boundary Conditions:

In the case of inviscid flows, a single boundary condition on velocity is required as the spatial velocity derivatives are of the first order. In this case the condition of zero normal relative velocity at the boundary suffices. For the case of viscous flows, where the spatial velocity derivatives are of second order, the relative velocity vector is required to be zero at a solid-fluid boundary, which is the well known no-slip boundary condition. The no-slip boundary condition implies that there cannot be any finite discontinuities in velocity or temperature at the fluid–solid interface.

The zero fluid velocity relative to a solid boundary is only possible if the flow near a solid boundary is under thermodynamic equilibrium, which requires an infinitely high frequency of collisions between the fluid and the solid at the interface. This situation is possible, for gases, as long as $Kn < 10^{-3}$. A certain degree of slip must be allowed in the velocity and temperature at an interface boundary as thermodynamic equilibrium is not possible for $Kn > 10^{-3}$.(Gad-el-Hak, 2005).

For liquids and gases the standard linear boundary condition for velocity slip at the wall is

$$\Delta u\Big|_{w} = u_{fluid} - u_{wall} = L_s \left.\frac{\partial u}{\partial y}\right|_{w}$$

Where L_s is the constant slip length, and is the strain rate at the solid boundary. The slip length, in most situations, is very small and thus the no-slip boundary condition is usually valid. For gas flows in microfluidic devices this no-slip condition may not always be valid.

For isothermal gas flows the slip boundary condition has been derived by Maxwell Gad-el-Hak (2005), based on the kinetic theory of dilute monoatomic gases where gas molecules are modeled as perfect rigid spheres which continuously strike each other and the solid surface. For a solid boundary modeled as a perfectly smooth surface at the molecular scale, the molecules reflect off the surface like a ray of light on a mirror obeying Snell's law; the incident angle being equal to the reflected angle (specular reflection). In this case the molecules exert no shear at the wall because the tangential momentum is conserved and results in perfect slip at the boundary. For a perfectly rough surface the molecules reflect at random angles resulting in a perfectly diffused reflection and zero tangential momentum for the reflected molecules which is balanced by a finite slip velocity to account for the shear stress transmitted to the boundary. The slip velocity may be obtained from the relation, Gad-el-Hak (2005).

$$u_{gas} - u_{wall} = L\left.\frac{\partial u}{\partial y}\right|_w$$

Which is the result of a force balance near the wall. Here *L* is the mean free path. The above equation states that significant amount of slip occurs only if the gradient of the mean velocity (of the molecules) is large enough, or the strain rate is large enough at the boundary. This does happen in the case of flow in microdevices or vacuum applications where thermodynamic equilibrium cannot be established due to the relatively smaller number of molecules. Additional terms from the Taylor's series expansion are required as the Knudsen number increases.

In the case of real walls both specular and random diffusion occur, part of the momentum of the incident molecules is lost to the wall and a (usually) smaller portion is retained by the reflected molecules. The tangential-momentum-accomodation coefficient σ_v is defined as the fraction of molecules reflected diffusively. The experimental value of the coefficient is between 0.2 and 0.8 and depends on the fluid, solid and the surface finish. (Thomas and Lord (1974), Seidl and Steiheil (1974), Porodnov et.al. (1974), Arkilik et. al. (1997) and Arkilik (1997). The smaller value for exponentially smooth surface and the larger value for most practical surfaces. Maxwell obtained the following expression for an isothermal boundary as, (Gad-el-Hak (2005))

$$u_{gas} - u_{wall} = \frac{2-\sigma_v}{\sigma_v} L\left.\frac{\partial u}{\partial y}\right|_w$$

It is important to note that very small values of σ_v and σ_T lead to substantial velocity slip and temperature jump even for low Knudsen number flows (macrofluidic model). The first term on the RHS of the Equation is first order term in Knundsen number while the thermal creep term is of second order. At large values of Kn(vacuum/ less molecules/lower density) the thermal creep phenomenon can become dominant. The temperature jump equation is of first order in the Knudsen number.

The continuum Navier-Stokes equations with no-slip and, or, no temperature jump boundary conditions are valid as long as $Kn \leq 0.001$. First order slip and or temperature jump boundary conditions should be applied to the N-S equations for Knudsen numbers in the range $0.001 < Kn < 0.1$. For the transition range of Knudsen numbers $01. < Kn < 10$, the second order or higher order slip and or temperature jump boundary conditions are applicable. It should be noted that the Navier-Stokes equations are not valid in the transition range of Knudsen numbers. For $Kn > 0.1$ higher order continuum equations like the Burnett equations should be used as the continuum approach is no longer valid. (Gad-el-Hak 2005).

There is sufficient experimental data available to confirm that slip boundary conditions must be applied for flows with large Knudsen numbers. Experiments in low pressure ducts conducted by Pfahler *et al.,* (1991), Tison(1993), Liu *et al.,*(1993, 1995), Pong *et al.,* (1994), Arkilic *et al.,* (1995), Harley *et al.,* (1995), and Shih *et al.,*(1995, 1996) and numerical simulations carried out by Beskok (1994, 1996), Beskok and Karniadakis (1994, 1999) and Beskok *et al.,*(1996) provide ample evidence as well.

Molecular-Based Models:

In continuum based models the macrospcopic flow properties; velocity, pressure, temperature, and the fluid properties density, viscosity, etc; are functions of the independent variables: the three space coordinates and time. In the molecular based approach the fluid is composed of discrete particles; the molecules, atoms, ions and electrons. The aim of the molecular-based model is to compute the position, velocity and state of all particles at all times. This approach can be either deterministic or probabilistic. The modern molecular dynamics computer simulations have been pioneered by Alder and Wainwright (1957, 1958, and 1970).

Using the deterministic approach for molecular based models the current state of the art computers and modeling techniques can simulate the flow for a time interval of about 0.001 μs and linear dimensions of 0.02μm. To completely simulate the molecular behavior for a physical time interval of just 1 second using the current state of the art supercomputers and parallel machines would require a CPU time of several hundred years, a wholly unrealistic adventure. (Gad-el-Hak, 2005)

An alternative to the deterministic molecular dynamics is the statistical approach where the goal is to compute the probability of finding a molecule at a particular position and state. This technique is well discussed in text books such as Bird (1994), Cercignani(1988, 2000), Chapman and Cowling(1970), Kogan(1969), Vincenti and Kruger(1965). The reader is referred to the above texts for a complete treatment of the statistical approach. For the transitional regime where $0.1 < Kn < 10$, the direct simulation Monte Carlo method discussed well in Bird (1994), is best suited.

Flows in Liquids:

Liquids and gases, from the continuum point of view, obey the same set of equations of motion. For incompressible flows, Reynolds number is the dimensionless parameter which governs the flow behavior, regardless of the fluid type, liquid or gas. In flows through microfluidic systems, the possibility of nonequilibrium flows exists, where the Navier-Stokes equations and the no-slip boundary conditions may not be valid. Such flows may be best analyzed by the molecular approach.

The mechanisms of transport phenomena in liquids are very different than that for gases. In dilute gases, random molecular motions cause the various transport processes to occur. In liquids the molecules are so closely packed (but not fixed in one position) that they are always in a state of collision. Thus most of the momentum transfer takes place due to intermolecular forces and not due to the random motion of molecules. Some molecules are separated from their original neighbors due to the straining and come into contact with new molecules. The sum of all intermolecular forces across the plane of shear stress, must, on the average, balance the applied shear force. It is well known that liquids at rest transmit normal forces only, and when a velocity gradient occurs, the net intermolecular force would have a tangential component.

The incompressible Navier-Stokes equations with the regular no-slip boundary conditions describe liquid flows for most macro and microfluidic flows. However it is not known from first principles, when and under what conditions are the no-slip boundary conditions incorrect. It is also not known when does the stress – strain rate relation, or the heat flux-temperature gradient relation fail to be linear. This may be because there is no kinetic theory of ‘fluids’, like a kinetic theory of gases, there is no Knudsen number for liquids and the conditions under which a liquid flow ceases to be in a quasi-equilibrium state is not known. There are some cases when the linear relationships between stress and strain rate (Newton’s law of viscosity) or the temperature gradient and heat flux (Fourier’s law), break down. For high molecular-weight polymers it has been observed that they show non-Newtonian behavior at fairly moderate shear rates. For water the non-Newtonian behavior is predicted to occur at unrealistically high shear rates. (Gad-el-Hak, 2005)

For the moving contact line problem in the spread of liquids over a solid surface, the Navier-Stokes equations must be solved with slip boundary conditions to avoid singular or unrealistic solutions as shown by Dussan and Davis (1974), Dussan (1976, 1979), Thompson and Robbins (1989). Flows occurring in corners and polymer extrusion are other examples where slip boundary conditions must be used to obtain physically realistic flows, Moffatt (1964), Koplik and Banavar (1995), Pearson and Petrie (1968), Richardson (1973) and Den (1990).

Experimental results in microfluidic devices are contradictory. The experimental data has been summarized in Pfahler *et al.,* (1990, 1991), Pfahler (1992), and Bau (1994). Sharp (2001) and Sharp (2002) claim that liquid flows in microchannels can be predicted by the macroscale continuum theory. However there are instances in microfluidic flows when this theory fails to work properly. Experimental works though difficult, are still required for liquid flows.

In the absence of a molecular based theory for liquids, molecular dynamics simulations offer a unique approach to scrutinize the assumptions made in the continuum model, even though these simulations are valid over a very tiny extent in time and space. Thompson and Troian (1997) performed molecular dynamics simulations to quantify the slip-flow boundary condition dependence on the shear rate. Based on their results they suggest a universal boundary condition at a solid-liquid interface.

The nonlinear behavior of the variation of the slip length with the shear rates implies that the boundary condition can significantly affect the flow behavior at macroscopic distances form the wall. Experiments confirm this observation, Atwood and Schowalter (1989). Thompson and Troian (1997) conclude that the no-slip boundary condition is the lower-shear-rate limit of the general nonlinear relationship which is also divergent. The general relationship provides a mechanism for relieving the stress singularity in contact line flows as well as flows in corners, as it naturally allows varying degrees of slip in regions of high strain rate.

Surface Effects:

From a macroscopic (continuum) approach, all forces at a solid-fluid interface are due to normal (pressure) and shear (viscous) stresses acting on an area parallel to the interface, displaced into the fluid, under the limit of the displacement distance tending to zero. From the molecular point of view, all surface forces (macroscopic or microscopic) are due to intermolecular forces, Israelachvili (1991). From the molecular viewpoint there are four fundamental forces that occur in nature; (1) the strong and the (2) weak forces which describe the interactions between neutrons, protons, electrons, etc; (3) the electromagnetic forces between atoms and molecules; and (4) the gravitational forces between masses. The range of action of the first two forces is about 10^{-5}nm, too small for micro applications, the electromagnetic forces are effective over a distance of 0.1 to 0.2 nm. Effects over a longer distance arise due to short range intermolecular forces. Gravitational forces decay with distance squared, whereas intermolecular forces decay with distance to the power of seven. Cohesive forces are therefore negligible if the distance between molecules exceeds a few molecular diameters, whereas massive bodies like stars and planets interact through astronomical distances through gravity.

Intermolecular interactions and cohesive forces which hold atoms and molecules together in liquids and solids are due to electromagnetic forces. These forces can be subdivided into (1) purely electrostatic forces, (2) polarization forces, and (3) quantum mechanical forces. Electrostatic forces arise due to the Coulomb force between charges, interaction between charges, permanent dipoles, quadrupoles, etc; Polarization forces arise from the dipole moments induced in atoms and molecules by the electric field of nearby charges and permanent dipoles. Quantum mechanical forces give rise to covalent or chemical bonding and to repulsive steric or exchange interactions.

The surface to volume ratio of a typical machine operating in the macro domain with a characteristic length of 1m is 1m^{-1}. A typical dimension of a micro device is 1µm, leading to a surface to volume ratio of 10^6 m^{-1}, a million fold increase! The mass being proportional to the volume, the relative increase in the surface area with respect to the mass of micro devices is also 10^6. Naturally, surface effects are dominant in micro systems.

In MEMS devices, both convective and radiative heat transfer increase due to the extremely large surface-to-volume ratio. A similar argument can be made for the case of mass transfer in micro systems.

Body forces are of equal importance as surface forces in many macro scale systems. However as the size of the devices gets smaller, the effects of surface forces dominate at the expense of body forces. In a biological study Went (1968) points out that the length scale below which surface forces become dominant is around 1mm. Above this size body forces dominate over surface forces. Stiction is a major problem in micro devices. As a simple demonstration: a 10 mm piece of paper when placed gently over a smooth vertical wall will fall due gravity, while a 0.1 mm piece will stick to the surface.

Dry friction, in macro systems is proportional to the normal force which is usually a component of the weight of the moving body. The friction force is independent of the contact surface area because the surface cohesive forces (van der Waals) are negligible when compared to the weight of the body. In micro devices the van der Waals forces are significant giving rise to stiction which is independent of the weight but is proportional to the surface area. In the case of the first micromotor, the rotor did not move until its contact area was reduced through dimples, to reduce stiction. Gad-el-Hak (2005)

Another important surface effect is due to the adsorbed layer in gaseous wall-bounded flows. Gas molecules flowing over a surface are attracted to it through van der Waals and other cohesive forces. When the gas molecules reach the surface their potential energy drops. These molecules can only escape the attraction of the solid surface when their energy exceeds the potential energy minimum, even though the molecules partake the thermal vibrations of the solid. In equilibrium a one-molecule thick layer of adsorbed molecules covers the solid surface. The layer may be two or more molecules thick depending on the molecular species with significant partial pressure, relative to their vapour pressure. (Gad-el-Hak (2005))

Fluid/Structure Interaction:

This is one of the major challenges at the microlevel. It is as well a challenge at the macrolevel, and though there are considerable work on the macrolevel in this area, little work has been done at the microlevel, Squires and Quake (2005). As far as we know Jiang et al (Jiang et al, 2000) modeled a fluid/ structure case for micropumps but they did not detail their model to be properly judged. Fluid structure interactions in the context of biofluid dynamics have been studied by Grotberg and Jensen (2004).

Conclusion:

In this paper, we reviewed the main significant works related to modeling of microfluidic/micropumps. The challenges in modeling were divided into three main areas: structural, fluidic, and fluid/structure interaction. It is noticeable that some issues related to all the above areas still in controversy and the main reason is lack of enough reliable experimental evidences that can lay down the last statement in these issue.

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