Position Paper: Planar Thermal Sensors and Actuators

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Most of today's MEMS (Micro-Electro-Mechanical Systems) are fabricated by means of surface- or bulk- micro machining techniques, which involve photolithography, physical or chemical vapor deposition, and etching. These processes are highly compatible with the processing of semiconductor devices, making it easy to fabricate hybrid electronic/mechanical systems monolithically. The use of photolithography also allows batch fabrication of micro mechanical and chemical systems on wafers. These features considerably simplify MEMS fabrication and packaging, but on the other hand limit MEMS configurations to be planar (or semi-planar if multiple-layer techniques are employed). The restriction of a planar structure often requires innovative designs of micro sensors and actuators with geometries and boundary conditions quite different from those of the conventional ones. New databases and modeling tools are needed for MEMS applications in sensors and actuators. The focus of this position letter is on micro-thermal sensors and actuators having a planar (2D) or semi-planar (2 & 1/2 D) configuration.

Thermal Sensors Thermal sensors are physical sensors. They measure the changes in thermodynamic properties or energy transport rates of a heated or cooled sensing element or substance. Without chemical reactions involved, physical sensors are often reusable, have a longer shelf life, and require much less calibration effort than their chemical counterparts. Planar thermal sensors which have been widely used in industries and research labs include mass flow meters, heat flux gauges, thermal conductivity detectors, etc. Other micro sensors of planar configuration, such as hot-film anemometers, are currently being developed and tested. The design of most planar thermal sensors involves heating and sensing elements deposited on the floor or suspended in the middle of a flow channel. The mass flow meter measures the flight time of a thermal pulse between an upstream heating element and a downstream sensing element, or measures the cooling rate of a heating element to determine the flow rate in the channel. The thermal conductivity detector measures the change in heat conduction rate in the thermally fully developed region of a heated flow channel when a small amount of gas sample is introduced into the stream of a carrier gas.

Models developed for macro-scale thermal phenomena such as Fourier’s law of conduction and the Navier-Stokes equation for viscous flow have been successfully applied to the design and analysis of many micro- thermal sensors. It is anticipated the macro-scale models and databases are applicable to most micron- or even sub micron-sized sensors. Only little modification is needed if the deviations from local thermodynamic equilibrium (LTE) in the sensing process are small. These deviations include slip-velocity and temperature-jump at the solid-fluid interface for flows at moderate Knudsen numbers, thermal conductivities which are anisotropic and dependent on geometry and boundary conditions, temperatures of different energy modes and energy carriers are not equal, and so on. Some software companies are developing computer codes with these modifications taken into account, and the software will soon become commercially available for MEMS design and diagnosis. The processes for which macro-scale models require major modifications or should be totally abandoned are:

(1) Fluid dynamics and energy transport in the transition flow region in which the continuum model fails, but the flow cannot be classified as free molecular flow yet. This type of flow in MEMS often occurs at low pressures, high speeds, or in extremely small flow passageways.

(2) Processes involving high energy densities which will lead to large property gradients within or at the surfaces of the sensor. The large property change across a thin layer makes it inappropriate to invoke the LTE assumption. Models developed and experimental data measured based on the LTE assumption cannot be used in this case.

Simplified Boltzmann equations and other approaches have been employed to predict energy and momentum transfer in micro sensors. At present there is a critical need to develop measuring devices and probing techniques to verify the theoretical results. Nonequilibrium models for sensing processes not in LTE are also needed to facilitate new sensor design and analysis.

Thermal Actuators A variety of actuators utilizing thermal expansion or thermal pneumatic effects have been fabricated by MEMS techniques. Their applications range from delivering drugs or extracting fluid samples in biomedical MEMS, controlling micro mirror arrays to be used in high-definition displays, to altering the surface roughness for improved aircraft maneuverability. Some of these thermal actuators have the potential of being evolved into more sophisticated heat engines or heat pumps. Among the various micro thermal actuators, the membrane-type micro pump is probably the most successful one. The venturi effect has also been utilized to develop micro pumps without moving parts. However this design is less attractive due to the significant friction loss associated with high-speed flow through a planar micro nozzle.

The advantage of thermal actuators is their high-energy capacity. As a result thermal actuators often can produce higher power output in comparison with actuators utilizing other effects. The shortcoming of a micro thermal actuator is its high surface- to- volume ratio, which makes heat loss a major concern. The potential candidates that can alleviate the heat loss problem are actuators that can reach very high mass flow rates, or devices using a working fluid that will undergo phase changes. The former does not have sufficient time for significant heat loss during power producing, but the friction loss of a high-speed flow may result in considerable pressure drops. Use of a phase- change working fluid therefore seems to be a better solution to the heat loss problem. Phase- change processes for flows in the micron range are not well understood at present. Theories and experimental data of this phenomenon are very rare.

The impact of high heat dissipation rate on the performance of micro thermal sensors is not all negative though. Since the heated part of a small actuator can be cooled much faster than that of a large actuator during the cooling phase, small thermal pneumatic pumps can operate at high frequencies., resulting in high mass flow rates.

In this author’s opinion, research priorities in the area of thermal actuators should be placed on the following topics:

(1) High-speed reacting flow in MEMS. Large amounts of energy can be released in this type of flows to produce high torques or powers. However the planar structure and large surface-to-volume ratio make it challenging to ignite and maintain a combustion process in micron-sized devices. The height of MEMS is generally much less than the dimensions in other directions. Thus the flows involved are different from those in porous media.

(2) Better understanding of the phase-change processes in micro channels or planar evaporators and condensers. These processes are essential to the development of efficient micro energy converters and power producing devices. Few research results are available for the formation of vapor bubbles and liquid droplets in micro systems.

(3) Gas dynamics of micro nozzles and rotary machinery of planar configuration. Previous studies of these devices were based primarily on the assumption of axisymmetrical and inviscid flow. Transonic and supersonic flows with strong viscous effects and having a rectangular or trapezoidal flow cross-section have not been investigated in detail. This type of compressible flows is important to thermal pneumatic actuators of high mass flow rate.

The research topics mentioned above address the fundamentals of micro-scale thermal phenomena. They are the modeling tools essential to the development of thermal sensors and actuators of better accuracy and performance. These topics have attracted the attention of academic and industrial researchers in recent years as the shortcomings of macro-scale models and experimental data were discovered. With more universities becoming interested in MEMS research and since industries today are willing to invest heavily on new MEMS products, NSF is in a good position to encourage idea exchanging between researchers in different areas and of different expertises, and to coordinate collaborations of multi-disciplinary programs. It is NSF’s responsibility to highlight and advertise the modeling tools and probing techniques critical to MEMS design and manufacturing, and outline the roadmap for future development of MEMS research.