

Micropump Technology and Applications

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ABSTRACT

This paper describes reversed engineered biological peristaltics through the insightful evolution of MEMS technology. While the emphasis on pump applications is in the miniaturization of spacecraft bus and payload, terrestrial applications are evident. For spacecraft propulsion, the use of the peristaltic pump as a low leakage valve, a pressure regulator and a flow meter are discussed. Spacecraft stabilization is addressed through a fluidic reaction wheel while thermal management of spacecraft, flight instruments and lander is addressed through heat pumps and Joule-Thompson compressors.

Keywords: Peristaltics, micropump, valves, flow metering, eutectic bonding, thrusters, fluidic reaction wheel, heat exchanger, Joule-Thompson cooler, spectrometer.

INTRODUCTION

The Jet Propulsion Laboratory (JPL) is a NASA Federally Funded Research and Development Center (FFRDC). It is endowed with NASA equipment that is managed and staffed by California Institute of Technology with a highly educated and world-class community of 6,000 engineers and scientists. JPL's principal NASA responsibility is to design, build, test and operate robotic spacecraft for the exploration of the solar system, and to observe our universe across the whole EMR spectrum - essentially, to go where no one has gone before and, in doing so, determine the origins of our solar system and the universe.

The days of large, multi-instrumented, billion-dollar robotic spacecraft are over. The emphasis is now on miniaturizing instruments and spacecraft and reducing the costs of fabrication, test, launch and operation. The ramifications of miniaturization are global, encompassing every element of a spacecraft, instrument, lander or penetrator. Micro pumps, valves and flow meters were conceived to address the variety of fluid flow control elements, thermal management and a gas analyzer. This paper discusses the evolution of this technology from other MEMS programs and presents a variety of 'space' applications.

1. DERIVATIVE MEMS TECHNOLOGIES

The derivative MEMS technologies came from a NASA advanced technology development contract with JPL and Northeastern University for the fabrication of nano-g accelerometers (range 10^{-2} - 10^{-8} g over 0.0001 - 25 Hertz bandwidth) to measure tri-axial orbital drag on the Shuttle and Space Station.^{1,2,3}

The specific innovations that led to realization of a robust micro pump where zero thickness wafer bonding and encapsulation techniques enabled the intimate joining of two wafer surfaces: intra- and wafer-to-wafer inter-electrical contacting or electrical isolation^{4,5,6}; and high force electrostatic 'caging'⁷.

In the nano-g accelerometer zero thickness referenced bonds were essential to attain tight spatial tolerancing. A eutectic bonding procedure was developed where etched channels were created in the bond regions (Figure 1) on which a spreading layer of metal was deposited and patterned in the channels. Finally, the bond metal was deposited and patterned on top of the spreading layers in such a way that it protruded above the wafer surface and was narrower than the spreading layer so its volume was less than the volume of the channel. When two dice prepared in this way are brought in contact and heated, the bond metal melts and spreads by wicking and capillary forces, reducing the spacing between the wafer surfaces to zero. Where contact metals are, or are beneath, the spreading layers, this bonding procedure provides electrical inter-connection between wafers in addition to hermetic sealing.

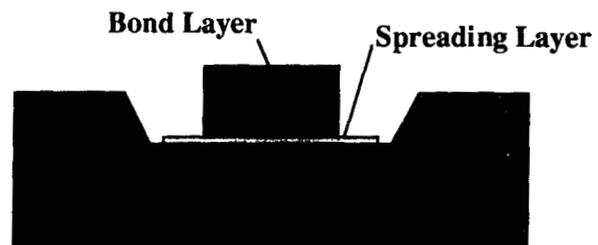


Figure 1 Zero Thickness Eutectic Bonding

The nano-g accelerometer contained a flimsy proof-mass suspension system and a fragile tunneling tip, both of which required protective, re-deployable electrostatic 'caging' during quiescent handling and high acceleration or shock loading. Figure 2 presents such an innovative 'caging' mechanism. This is the top view of the force plate die where the metal platen is covered with an oxide layer (0.5 μm) to prevent an electrical contact between the proof mass and the force plate when the proof mass is being electrostatically clamped.

The electrostatic force relationship is

$$F_c = \frac{\epsilon_{ox} \cdot A \cdot V^2}{2d_{ox}^2}$$

where ϵ_{ox} is the dielectric constant of oxide
 ($4 \times 8.85 \times 10^{-12}$ Newton/Volt²)
 A is area of conductive strip
 V is applied voltage
 and d_{ox} is the thickness of the LTO (0.5 μm).

Where the distance (d_{ox}) is small, at fractions of a μm , it is clear that small voltages generate large electric fields of Mvolts/m, which in turn produce significant attractive forces. For larger voltages, the attractive forces increase with the squared function of the applied voltage. The breakdown electric field strength of the insulation layer sets the limit for attainable 'caging' forces.

2. PERISTALTICS

Peristaltics is a form of fluid transport that occurs when a progressive wave of area contraction or expansion propagates along the length of a dispensable tube containing a liquid. Physiologically, peristaltic action is an inherent neuromuscular property of any tubular smooth muscular structure. This characteristic is put to use by the body to propel or to mix the contents of a tube, as in the urethra, gastrointestinal tract and the bile duct.

The following description outlines the mechanisms of a reverse engineered micro peristaltic - type pump⁷. Envision a substrate in which a smooth contoured concave channel has been etched, the whole surface coated with a thin metal layer and, over this metal, a thin coating of insulation material. When an electrically conductive membrane is clamped in intimate contact with the thin insulation layer of two shells (as illustrated in Figure 3) and a voltage is applied to the lower metal layer and the membrane, an electrostatic attractive force pulls the membrane down into the channel. The membrane rolls down the surface of the insulation because the greatest attractive forces are generated where the distance from the conductive strip are smallest (i.e. insulation thickness). Conversely, when a voltage is applied across the upper metal layer and the membrane, the

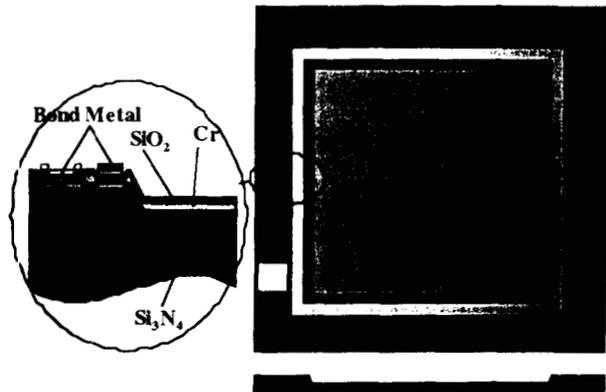


Figure 2 Top View of Force Plate

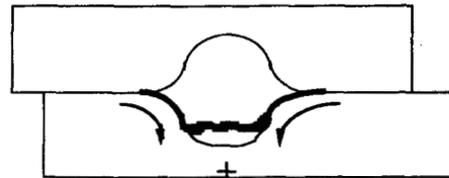


Figure 3. Electrostatic Actuator - Lower Shell

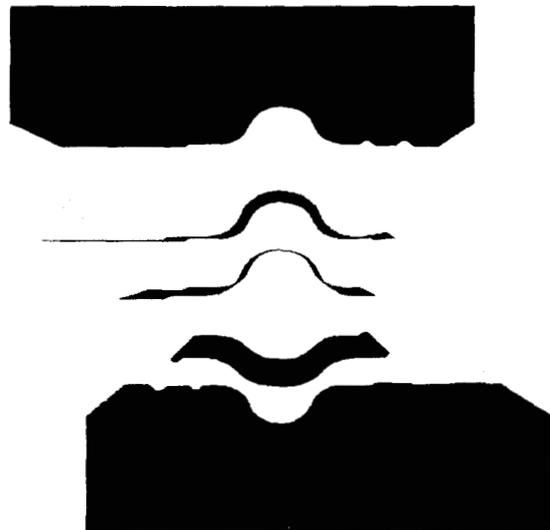


Figure 4. Exploded View of Micro Peristaltic Pump



Figure 5. Assembled Micro Peristaltic Pump

membrane rolls up the surface of the insulation of the upper channel.

As demonstrated in the 'caging' application small insulation thickness, fractions of a μm , lead to significant electrostatic forces. Flexible membranes are largely unaffected by the surface flatness and the LTO particles' separation of rigid platens and thus peristaltic pumping forces are greater than for solid platens. Essentially the breakdown electric field strength of the insulation layer sets the limits on pump pressure and pumping rate for an electrostatic peristaltic pump.

Figure 4 presents an exploded diagram of two complementary smooth concave channel pump shells, patterned series of electrically conductive strips, insulation layer, and the flexible electrically conductive membrane. Figure 5 illustrates the assembled micro peristaltic pump where the two substrates sandwich a single membrane between them. A hermetic seal is created by the compression of the membrane and the outer eutectic bond wall. Earlier the effects of applying voltages to the lower and upper conductive surfaces were discussed. When a suitable voltage between the membrane and each of the conductive strips is applied in succession, the membrane is pulled into the channel and successively along the length of the channel. And, when the actuator elements are connected to the outputs of dual interlaced and interlocked shift registers, the membrane initially flows along the upper channel surface before the membrane is released for several periods (zero), drawn down into the lower channel and along the lower channel surface.

This actuation progression of a membrane "wall" across the composite channel provides a miniature peristaltic pump. Alternate inversions of the bit streams sequences creates multiple membrane "bubbles" that move down the channel (Figure 6), pushing the entrapped fluid in front of and pulling the fluid behind each membrane "wall." The electrostatic actuator has no resistive loss so pump power is only consumed by the membrane, in the compression work function and in circulating the fluids through micro channels.

This miniature digital peristaltic pump architecture represents a true two-dimensional analog of the three-dimensional peristaltic mechanisms that are endemic in living organisms. It is valueless and impervious to gas bubble entrapment that has plagued other attempts at miniature pumps. Also it does not require priming and can tolerate the adherence of small foreign particles (gracefully degraded) on channel or membrane surfaces. The pump is self-purging, tending to push everything before the membrane in its intimate rolling motion across the channel surface. This basically digital pump can transport fluids or vapors over an extended range of flow rates, is impervious to

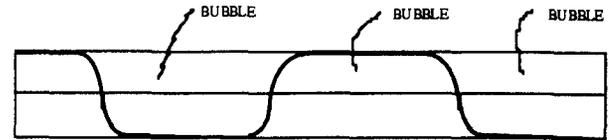


Figure 6. Multiple "Bubble" Peristaltics

high mechanical shock or vibration, is a positive displacement flow meter, and can function in a static mode as a valve.

3. SPACEFLIGHT APPLICATIONS

Spaceflight hardware is made up of two broad categories: the spacecraft, penetrator or lander, and the payload of instruments. The spacecraft engineering functions that are pump or valve related are propulsion, orientation, thermal management and propellant management. Elevation control is relevant for aerobots and thermal management is required for aerobots, penetrators and landers.

3.1 Valves

Propulsion management requires pressure regulation and isolation of both propellant and oxidant. Valve modulation can be used for pressure regulation and fluid isolation can be achieved with low leakage valves. A variant of the peristaltic pump can, if the electrostatic force exceeds supply pressure, provide a fast valving regulator function. And impervious membraned valves can provide fluid isolation. The electrostatic flexible membrane valve (see Figure 7) is a normally open device and can only regulate and seal when powered. As the electrical insulation in these valves is very high, current flow and thus power requirements are minute. Hence if power is perpetual, as is the case on spacecraft, electrostatic valving is viable.

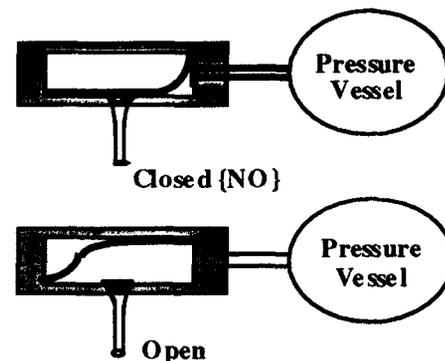


Figure 7 Electrostatic Valve

3.2 Ion Propulsion

In ion propulsion systems small high energy plasmas ionize small volumes of low pressure gas and high electric fields accelerate these ions to high exit velocities. Figure 8 is a

cartoon of a honeycomb ion thruster where each cell is a separate ion engine. A miniature peristaltic pump is dedicated to each cell to seal off or provide metered gas flow.

By controlling which engines in the array are operating the honeycomb thruster can provide gimbal-less 'steering'. If some of the peripheral cells are offset from the perpendicular then spin control is possible. Finally, the massive redundancy of the array increases the thruster's reliability.

3.3 Fluidic Reaction Wheel

Inertial wheels are another technique utilized to maintain the orientation of spacecraft. Figure 9 presents a cartoon of a fluidic reaction wheel that consists of a closed toroidal pump. The angular velocity of the fluid in the peristaltic toroid is increased or decreased to provide the requisite change in angular momentum. In miniature spacecraft multiple concentric 'wheels' could be located at the periphery of silicon disks running in the same or opposite directions, depending on required reaction.

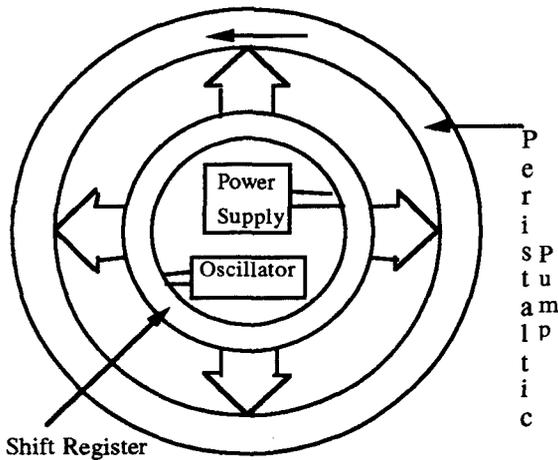


Figure 9 Fluidic Reaction Wheel

3.4 Heat Exchanger

Effective thermal conductivity of fluid cooling loops is markedly superior to that of the best passive thermal conductive materials. A micro pump may be used to circulate a fluid between a thermal source and sink, effectively transferring heat both within the circulating medium by thermal mass transfer and between the medium

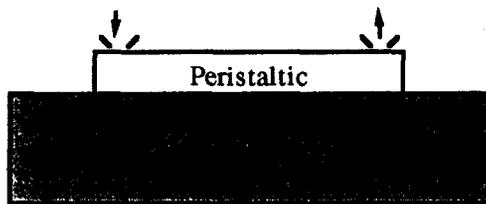


Figure 10 Forced Convective Transfer Heat Exchanger



Figure 8 Honey Comb Thruster

and the source and sink by improved convective transfer. Micro channels have large surface area to cross-section ratios, which ensures intimate thermal coupling with forced flow gasses and micro channels.

Shuttle systems and many of the flight experiments utilize forced convective cooling. The mechanical nature of these cooling systems (fans) makes them the least reliable element in a thermal catastrophic failure scenario. This, and the crew fatigue through exposure to sustained high noise levels, was the impetus for the conception of a MEMS cooler.

Microstructured peristaltic pump-channel implementations, complete with substrate imbedded drive electronics, provide high thermal transfer coefficient 'breathing skin'. In a nonvacuum environment such pumps draw from still air at the surface and expel away from the surface. The heat pump is not dependent on density gradients and gravity fields, as are convective heat sinks, and is thus space deployable. A small pump-channel cell may be bonded to the surface of integrated circuit chips (see 'hot body' Figure 10) to dissipate their heat directly: no forced ventilation, no orientation constraints, no noise, and no moving parts. With many pump-channel cells per square centimeter large area slabs may be bonded to the surface of power packs or system chassis to remove heat.

3.5 Joule-Thompson Cooler

The absorption or dissipation of latent heat generated from gas/liquid or liquid/gas phase transitions further enhances thermal transfer capacity. These phase transitions can be orchestrated by pumping where compression liquefies and expansion vaporizes. The Rankine vapor compression cycle defines such a heat engine. In a micro-machined version of a closed loop vapor compression cycle as shown in Figure 11⁸, the whole refrigerator, or a serial cascade of refrigerators, may be fabricated from two fused wafers.

A miniature peristaltic pump draws refrigerant vapor and compresses it. The gas is then cooled and condensed, the liquid is then cooled by convective transfer into the surrounding substrate micro channel and onto a highly

thermally conductive heat exchanger created in the substrate. Another micro channel conducts the cooled liquid refrigerant to an expansion nozzle (valve) in a thermally isolated cold pad where the refrigerant expands into its vapor phase, drawing the latent heat of vaporization from the cold pad. This cold vapor is conveyed in yet another micro channel to the inlet port of the miniature peristaltic pump. The peristaltic pump exhibits very low vibration, as it has no reciprocating parts, but instead has a very low mass membrane that rolls across the surfaces of the channels. The high thermal transfer capacity of fluid cooling (or heating) loops, and particularly phase change loops, are of significant interest in the thermal management of spacecraft and planetary rovers. In communication satellites, thermal management of individual high energy transmission amplifiers and fast computers are preferred to general electronic 'hot box' management. Another interesting thermal management application is the heating, rather than the more general cooling, of a Martian rover. During daylight, the heat absorbed in solar panels is collected in liquid forced through micro channels in rear of panels. This heat is transferred to, and stored in, thermal capacitors within the rover. In the evening, the heat bank warms the rover's quiescent electronics.

3.6 IR Detector Cooler

A sophisticated application of a phase interchange heat pump is the cooling of optical instrument's IR imaging objectives, specifically the space based focal plane cooling of a Quantum Well Infrared Photon (QWIP) detector. The QWIP focal plane temperature needs be maintained at 70 K for a heat load of 50-270 mW and a radiator temperature of 200 K. The most efficient cooling cycles are cascaded systems and the most expeditious means of implementing these cycles is the pseudo cascading of mixed gasses in a single expansion process. JPL^{9,10} have extended the Russian¹¹ work on increasing the Joule-Thompson (J-T) cooling power with a variety of gas mixtures.

Figure 12 presents a plot of the temperature-entropy (T-H) diagram for the analysis of a five gas mixture with the high pressure (25 PSI) enthalpy data represented by 'squares' and the dotted best-fit curve and the low pressure (5 PSI) enthalpy data represented by the 'circles' and dashed best fit curve.

A preferred embodiment of a focal plane cooler would incorporate the whole system on two bonded (4" dia.) silicon wafers. The radiators would occupy the outer rim (0.75" both sides), the pump (pumps) and interchanger (interchangers) would be inboard and the 2 x 2 cm cold pad would be in the center. Using silicon as the substrate for the cooler has several advantages: the pump electronics can be incorporated directly into the substrate, silicon exhibits high thermal conductivity (particularly at low temperatures) and

its micro machining chemistries and characteristics are mature. For space applications it may be prudent to have redundant pumps as a reliability measure, should a micro channel become blocked or a particular pump fail. Miniature pressure and temperature sensors could also be incorporated around the various micro channels to provide health monitoring and efficiency optimization capabilities.

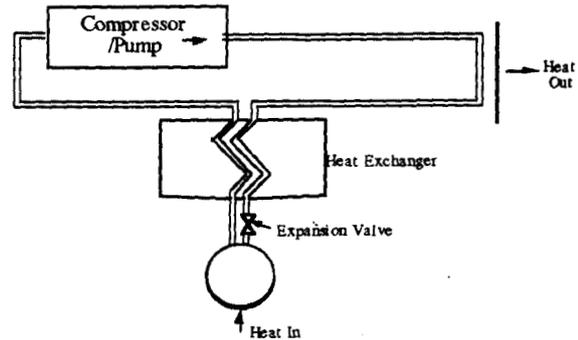


Figure 11. Compressor For Phase Interchange Heat Pump

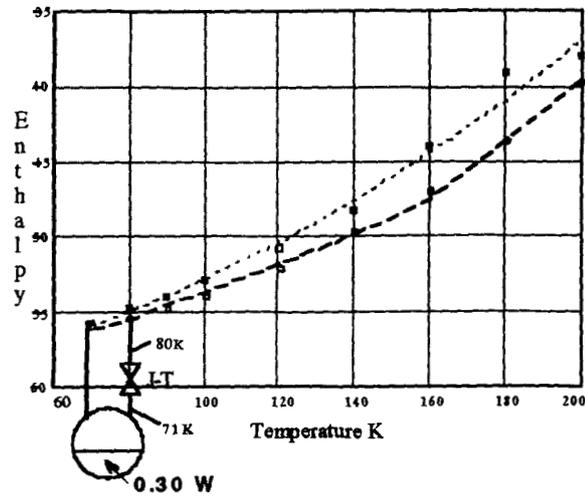


Figure 12 T-H Diagram for Selected Gas Mix

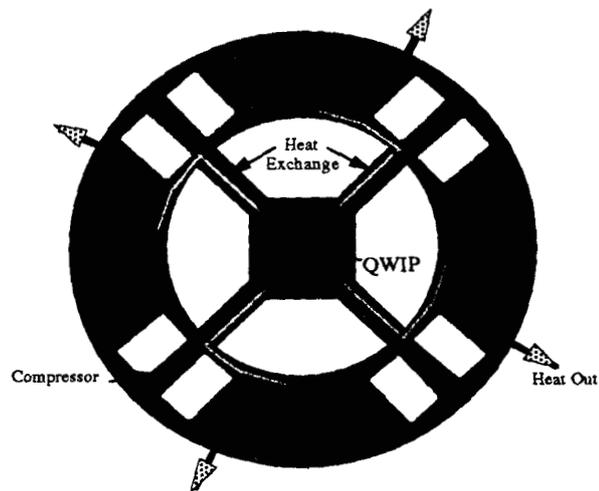


Figure 13 Wafer Cryo Cooler and Detector Mount

Convective coupling between forced flow gasses and micro channel surfaces are high and channel surface area, relative to cross section, increases as dimensions decrease. The thermal conductive loss across thin silicon partitions between neighboring channels are also small particularly when these channels are contained within insulated silicon bridges. Such thermally isolated micro channel structures are very efficient heat exchangers.

The peristaltic pump is also a micro channel that can exchange compression heat with a neighboring channel to approach the efficiency of an isothermal compression cycle. The compression profile of a peristaltic pump is determined by the diminishing thickness profile of the actuator strips. For an ideal pump the step volume profile would be matched to the effective ratio of specific heats (γ) of the gas mixture and thermal gradient down the pump. Once this profile was determined, the photo lithographic masters can be computer generated with the required actuator spacings.

Were the complete cryo cooler fabricated out of two 4" diameter silicon wafers (see Figure 13), the total mass would be 35 grams, and with etched out bridges and non-utilized areas this mass would be less than 25 grams. A single peristaltic pump would weigh less than a gram. The J-T expansion valves would be just inboard of the focal-plane thermal insulation bridges where the parasitic heat loads would be balanced and the low pressure return conduit would pass back along the same bridge to cool the high pressure gas feed.

3.7 Micro Gas Analyzer

The reason for sending rovers, aerobots and penetrators to planets is to gain ground truth for the remote measurements of orbiters and telescopes. Atmospheric gas species and abundance are one such measurement class requiring a miniaturized gas analyzer or mass spectrometer. Figure 14 presents a cartoon of a miniaturized gas analyzer that

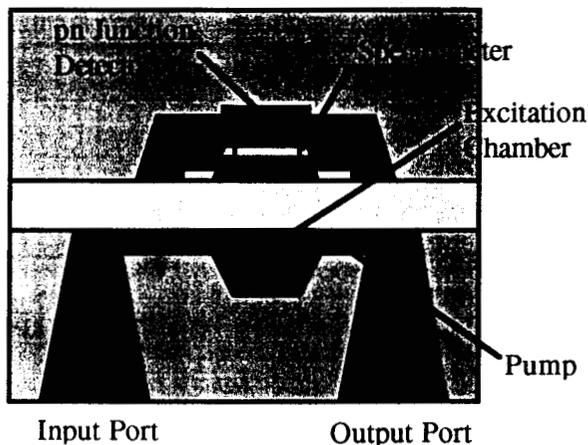


Figure 14 Schematic Representation of micro gas analyzer

incorporates all the components and operates under the same principles as conventional bench top equipment. The instrument contains a miniature peristaltic pump, a wavelength resolving spectrometer^{12,13} and a gas excitation chamber¹⁴. The pump continually draws and regulates the pressure of gas into the excitation chamber where it is ionized by a unique miniature plasma generator. Light emitted by the ionized gas is directed toward the miniature Fabry-Perot interference spectrometer and detector.

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