Acta Futura 6 (2013) 9-16
DOI: 10.2420/AF06.2013.9

Acta
Futura

A bioinspired pump for space applications

Derek Rinderknecht[*], Mory Gharib
Option of Aeronautics, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA. 91125, USA

Abstract. This paper discusses a valveless pumping mechanism, the impedance pump, inspired by the embryonic vertebrate heart in the context of fluid management aboard spacecraft. The impedance pump relies on a resonant wave mechanism to produce flow and can be highly efficient as well as robust to changes in material properties and size scale. Data is presented on the flow rate versus frequency response of the impedance pump demonstrating the basic characteristics of its output such as resonant flow peaks and flow reversals. The impedance pump is also examined for thermal management, a critical role for pumps aboard spacecraft, demonstrating its ability to provide flow in single-phase forced convection cooling loops for heat removal from electronics and thermal regulation of astronauts.

1 Introduction

Effective fluid handling is essential for long term space travel being fundamental to thermal management of electronics, supplying fuel to thrust generating systems and maintaining life support systems for manned space missions. Along with valves, and other fluidic components, pumps are critical to fluid management systems aboard spacecraft. Currently many different types of pumps have been implemented on spacecraft, the most frequently occurring types being passive pumps that operate by capillary forces such as, capillary pumped loops (CPLs) [9, 26] and heat pipes [6], or rotating vane turbo pumps to provide the high pressures required by fuel systems [13, 5]. Other pump systems, mainly being adapted from earth driven industrial based designs, have less of a history in mission based space flight. At present further development is needed as the current options for pumps do not provide a complete solution nor possess the flexibility in design to address all the needs of pumps aboard space missions.

More recently with the hope of reducing the cost and burden of long term missions, space programs have endeavored to move towards smaller spacecraft such as microsatellites and rovers, thereby prompting instruments and other components aboard the craft to proceed to smaller and smaller packages [2]. In this regard, pumps for space need to emphasize low power consumption, high efficiency and high reliability, in addition to meeting the pressure and flow requirements as well as payload and weight restrictions. Similar to consumer electronics, these constraints force more electronics into smaller areas resulting in drastically increased thermal heat fluxes. Extravehicular activity by astronauts is another circumstance requiring pumped fluid for thermal management. Current techniques employ either sublimation based systems or require the astronaut to be tethered to the craft through an umbilical cord which supplies coolant [11]. Sublimating systems require pressure to be relieved and umbilical cords are often difficult to manage creating a need for a self-contained circulating system with zero mass loss which can provide sustained

---

[*] Corresponding author. E-mail: rinderkn@caltech.edu

thermal regulation for astronauts.

Instrumentation and hardware for space applications, particularly with the drive to reduce the size and mass of spacecraft, have looked to microelectromechanical systems (MEMS) as a means to attain integrated sensing and diagnostic capabilities even micropropulsion, leveraging the low mass, low power consumption, small footprint and potential redundancy of these technologies [3]. Many of these MEMS technologies involve microfluidics. Microfluidic pumps have been tested in many different configurations to create thrusters for the next generation of microspacecraft [22]. There is also a growing need for MEMS pumps for nanosatellites or on rover missions to perform biological assays of planetary matter and to study the effects of microgravity and other environmental conditions found in space on biology. MEMS technologies also have a role in the medical well-being and performance enhancement of astronauts through their integrated drug delivery and diagnostic abilities. While there is much promise in MEMS for space technologies, the MEMS based pumps currently being utilized are for the most part miniaturizations of successful terrestrial designs, which commonly suffer due to reliability issues caused by wear on moving parts.

Although the environment of space varies quite a bit from that on the surface of the earth, engineers and scientists have benefitted greatly from understanding the methods by which nature solves problems. The idea of bioinspired design or learning from examples in nature, presents carefully crafted solutions to biochemical and physical sensing, actuation, and pumping. Organismal systems have the ability to perform multiple functions, self-sustain, adapt and evolve to maintain operation, concepts which are desirable for space based systems. To the aerospace and aeronautics community flight is an example which is close to heart. Observations of birds gave us the shape of the wing however, it was not until humans realized that a wing provides both lift and thrust that its functions were able to be separated and implemented for air travel. Nature has given us numerous mechanisms to move fluid whether for propulsion or pumping. One example is capillary action, utilized to draw water into plants, which involves similar physics to CPLs and many two-phase fluid systems currently utilized aboard spacecraft. Other examples are peristaltic action by the gut to move the contents of the stomach or valve-based positive displacement pumps who share an action similar to the heart. In this regard nature or biology has the potential to reveal many solutions applicable to long term space travel.

This paper will explore a bioinspired valveless pumping mechanism, the impedance pump, for its potential use in space applications first describing the mechanism and method of manufacturing, and then describing its potential use for space driven thermal management applications.

2 Background impedance pumps

Inspiration for the impedance pump mechanism came from a study of the developmental biology of the vertebrate heart [12]. The heart has the requirement of maintaining adequate cardiac output to supply nutrients and oxygen to the tissues and organs of the body. In its earliest stages, the vertebrate heart consists of a primitive tube that drives blood through a simple vascular network nourishing tissues and other developing organs. At this stage the embryonic heart does not possess valves and only has a simple band of active cardiomyoctes (the contractile cells in the heart), yet it demonstrates unidirectional blood flow. *In vivo* cell lineage tracking studies on the developmental biology of the primitive vertebrate embryonic heart revealed that early stage pumping relied on a wave based mechanism to produce a net mean flow. As a result of these wave based dynamics, the mechanism was named the impedance pump.

The impedance pump mechanism was first discovered in 1954 by Liebau who realized that periodic compression of a pliant tube at an asymmetric location relative to its ends could pump fluid against a pressure gradient [19]. In the late 1990s and beyond, a number of computational studies have appeared describing the pumps behavior [1, 4, 17, 21]. The first experimental parametric study of impedance pump behavior was conducted by Hickerson *et al.* while observations that the same mechanism was present in the embryonic zebrafish heart led to the first experimental investigation showing the ability of the impedance pump mechanism to function at the microscale [15, 24, 14]. Of late many papers on microimpedance pumps have appeared demonstrating the utility of the impedance pump mechanism for micro pumps [7, 18, 27].

In brief, the mechanism of pumping utilizes a mismatch in fluidic impedance to create constructive wave interactions which result in a time varying pressure gradient across the pump that generates a mean flow. The pump is simply formed requiring only a flexible medium on which wave interactions can occur, the pres-

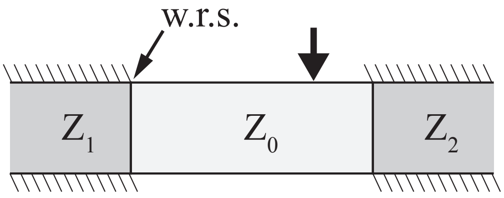

Figure 1. *A schematic of the basic arrangement of an impedance pump. The impedances of respective segments are denoted by Z_0, Z_1 and Z_2, the boundaries between these segments creates two wave reflection sites (w.r.s). The arrow designates the location of the excitation.*

ence of one or more wave reflection sites and an excitation located asymmetrically with respect to the fluidic impedance of the system. A schematic of the basic requirements for an impedance pump can be seen in Figure 1. In practice, the pump is formed by coupling a compressible material at either end with material differing in compliance or geometry in order to reflect wave energy. Figure 1 depicts these wave reflection sites through a distinct mismatch in fluid impedance represented by Z_0, Z_1 and Z_2. Commonly in its implementation Z_1 and Z_2 are of identical materials and geometries and asymmetry is imposed by an offset in the excitation location along the length of the compressible section, Z_0. Excitation in the case of meso- and micro-scale impedance pumps is commonly provided through electromagnetic or piezoelectric actuation due to their ease of implementation however, any actuation scheme that provides sufficient frequency dynamics and displaces the wall of the compressible section can be used. A more complete description of the mechanism of impedance pumping can be found in the literature [15, 24].

3 Design considerations for impedance pumps in space

The extreme environment of space presents many challenges when designing pumps. Pumps not only must meet the performance and lifetime requirements of space operation but also be able to withstand the impacts of solar radiation as well as function in the low pressures and temperatures of space. Reliable space based fluid systems must also resist biofouling and the growth of contaminating bacteria that can harm water quality and degrade performance [25]. In addition to mitigating the impacts of space operation, pumps must also provide high efficiencies and meet the cost, size, and weight requirements of the payload.

The impedance pump is a valveless pump and therefore, has no internal moving parts such as valves or rotary mechanisms which often result in failure particularly, in the harsh environment of space. The impedance pump also requires only a single actuator and can be controlled by frequency making it easy to actuate and drive. The resonant wave based mechanism by which it operates can make the pump highly efficient at converting input power to fluid work, meaning high performance can be attained with minimal power cost. While there is a wide array of needs for pumps aboard spacecraft, the impedance pump mechanism has been demonstrated to be robust to changes in size scale and material properties [24]. In this regard, given that the pump has minimal required components and most of the weight results from the components required to drive the actuator, with careful design impedance pumps can be implemented to add only minimal weight increase to space based fluid management systems. As a valveless pump the impedance pump will not pump air. The pumping mechanism however has been observed to be tolerant to two-phase flows, which are common aboard spacecraft. In designing impedance pumps for space, care would therefore need to be exercised to ensure that bubbles present in the flow do not have the tendency to stick to the interior of the pump where they might merge and create a blockage, or in general to ensure that bubbles carried by the flow are adequately small relative to the inner diameter of the pump. Additionally changes in stiffness resulting from variations in transmural pressure have been shown to shift the resonant frequency of the pump [15]. Similar behavior would likely be observed if the materials comprising the pump were not tolerant to the low temperatures of space. Consequently, materials should be chosen which exhibit stable properties over the expected range of operating temperatures. Furthermore in choosing materials to construct impedance pumps for space applications, consideration would also need to be made to minimize permeability and resist fluid loss. These are metrics by which any material would be chosen for fluid based applications in space. However with regards to the impedance pump, if temperature tolerant materials were identified, a reasonable solution is a hermetically sealed case protecting the pump from the vacuum and radiation of the space environment.

4 Results

4.1 The behavior of impedance pumps

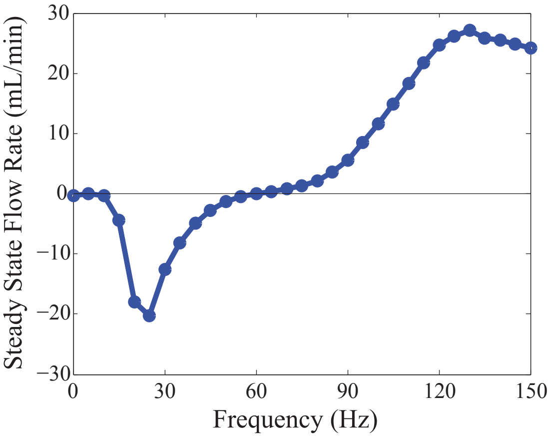

Figure 2. *A typical flow response of an impedance pump showing resonant flow peaks and bidirectional flow as seen by examining the flow response at 25 Hz and 130 Hz where the flow rate is -20 mL/min and 27 mL/min, respectively.*

Impedance pumps are commonly characterized in a flow loop that in addition to the parameters associated with pump actuation enables both the flow rate and pressure difference across the pump to be measured. Flow rates are evaluated using a Transonic flow meter model TS410 with a ME 2 PXN flow probe. Pressure is recorded using two differential pressure transducers (PX26) located on either side of the pump. The best performance is achieved when the resonant frequencies of the actuator coincide with that of the pump. In order to understand and design the required actuator response, actuator performance is decoupled from the material response during testing. This is enabled through the use of a voice coil actuator providing a fixed displacement over a wide range of frequencies. Figure 2 shows a typical frequency response of the pump and many characteristics of its flow output.

The flow response in Figure 2 was produced with an impedance pump made of a silicone tube with a length of 15 mm, with an inner diameter of 2 mm and a wall thickness of 780 μm coupled on either end to glass tubes with a 2 mm outer diameter and 1 mm inner diameter. The change in material compliance between the silicone tube and the glass creates two wave reflection sites. Given that both wave reflection sites have similar impedance, the pump is excited at a position of 12.4 mm with respect to the left-hand-side of the pump. If the impedance pump was actuated directly along the midline of the tube length zero net flow would be produced, due to a lack of asymmetry. A peak-to-peak amplitude of 400 μm was applied around the transverse axis of the pump at frequencies spanning 0 to 150 Hz. Positive flow as measured is flow from the left-hand-side to the right-hand-side of the pump. The maximum flow rate of 27 mL/min can clearly be seen at around 130 Hz as represented in the flow response curve. Another trait of impedance pump is bidirectionality, meaning the pump can output flow in both directions. In this example, the impedance pump exhibits negative flow between the frequency range of 10 Hz and 60 Hz and a positive flow above 60 Hz up to the maximum input frequency of the experimental actuator. Examining Figure 2, it can be seen that the maximum negative flow rate occurs at 25 Hz where the flow is -20mL/min and the maximum forward flow frequency occurs at 130 Hz where the flow rate is 27 mL/min. The pressure output of an impedance pump follows a similar trend as the flow response curve shown in Figure 2. In this regard, the maximum power output of the pump also occurs at resonance and therefore represents the optimal frequency at which to convert actuator work to fluid work.

4.2 Impedance pumps for thermal management

Here we will examine the potential of the bioinspired impedance pump for thermal management in space. The system consisted of a pump constructed and driven similarly to that described in the previous section and included a custom designed micromachined brass heatsink with a channel depth of 100 μm. The heatsink was attached to the backside of a 100 Ω power resistor in order to dissipate a heat flux of 10 W/cm^2. Water at room temperature was pumped from a reservoir across the heatsink depositing the heated fluid in a second reservoir. Although a closed loop with a radiator to dispose of the heat would be ideal, the aforementioned experimental scenario was similar to a situation where the fluid is jettisoned after being used for heat removal. The temperature distribution on the heatsink was monitored using a FLIR Phoenix DTS thermal camera. After 10 seconds of resistive heating, the pump was turned on at a flow rate of 6 mL/min. At 6 mL/min the pressure drop across the heatsink was measured to be 0.6 kPa. Figure 3A is a thermal image of the heatsink roughly 50

Table 1. *A summary of the performance specifications of common small-scale pump technologies.*

Pumping technology	Actuation method	P_{max} [kPa]	Q_{max} [mL/min]	Power [mW]	$\eta_{thermodynamic}$ [%]
Impedance	electromagnetic	20	10	21	4.0
Electroosmotic [8]	-	33	0.015	0.42	0.49
Electroosmotic [16]	-	160	7	2000	0.23
Electrohydrodynamic [23]	injection-type	2.5	14	420	0.034
Microgear pump [10]	magnetic motor	14	0.35	500	0.0041
Valveless diffusion [20]	piezoelectric	16	16	72	1.5

seconds into the experiment. Figure 3B is an inset plot of the temperature of two points, one located on the surface of the heatsink and the other located on the outlet tube (indicated by the two crosses in the thermal image). In Figure 3B Region of interest (ROI) 0 indicates the temperature on the surface of the heat sink whereas, ROI 1 indicates the temperature of the outlet tube.

The general objective of single-phase forced convection thermal management systems is to remove the maximum amount of heat energy for a given volume of fluid per unit time. The major power cost of such thermal management systems is the pump. The pump is required to provide the fluid work required to meet the pressure demands of the system while maintaining adequate volume flow rate. The efficiency of the pumping mechanism is therefore a key metric in determining the efficacy of forced convection single-phase thermal management systems. Table 1 examines the performance of the impedance pump versus other potential pump technologies available for thermal management. $\mathbf{P}_{max}$ is the maximum pressure output of the pump and likewise Q_{max} is the maximum flow rate. The thermodynamic efficiency, $\eta_{thermodynamic}$, is defined as the ratio of fluid work output to power input for the pump. It can be noted in Table 1 that the impedance pump delivers relatively high efficiencies in terms of the ratio of fluid work done by the pump to power input to the actuator.

5 Discussion

Impedance pumps have been made on size scales ranging from a few centimeters to tens of microns producing flow rates from liters per minute to microliters per minute, respectively, and therefore are a viable option for many pump driven applications. Due to the simplicity of the governing principle, any tube, if compressible, can be turned into a valveless pump. This presents an opportunity for redundancy in space based fluid management, eliminating system-wide failures when a pump component fails. In this regard, impedance pumps not only have the ability to drive systems in space but also can be used to supplement existing pump systems in case of performance degradation during space flight. The flow results presented in Figure 2 reveal many characteristics typical of impedance pumps such as flow reversals and frequency dependent flow peaks, making available a wide range of potential flow outputs with a single pump.

Micro impedance pumps with characteristic diameters of around 100 µm generally have outputs in the tens of microliters per minute making them widely useful in a number of biotech driven applications such as theranostic applications for astronauts providing a means for both drug delivery and aid in diagnostic efforts for astronaut health. Impedance pumps could also be implemented as standalone systems for thermal management of electronics or body temperature regulation for astronauts. As demonstrated by Figure 3, even without design optimization, the impedance pump has the potential to remove moderate heat loads for cooling electronics. The effect of convective thermal transport driven the by the impedance pump is clearly visible in the inset plot on the right in Figure 3B. During the first 10 seconds of the experiment the surface temperature of the heat sink plateaus at around 34 °C. After the pump is activated this temperature quickly drops and the temperature at the outlet tube peaks before decreasing, as stagnant fluid which remained in the heatsink for the first 10 seconds is swept out and flow is maintained. With improvements to both the heatsink and the pump, such systems would most likely possess the capability to exceed the reported power density of 10 W/cm^2 in the experiment and approach the likely 25 W/cm^2 power densities of next generation electronics and instrumentation aboard microspacecraft [3].

Efficiency and low power consumption are critical

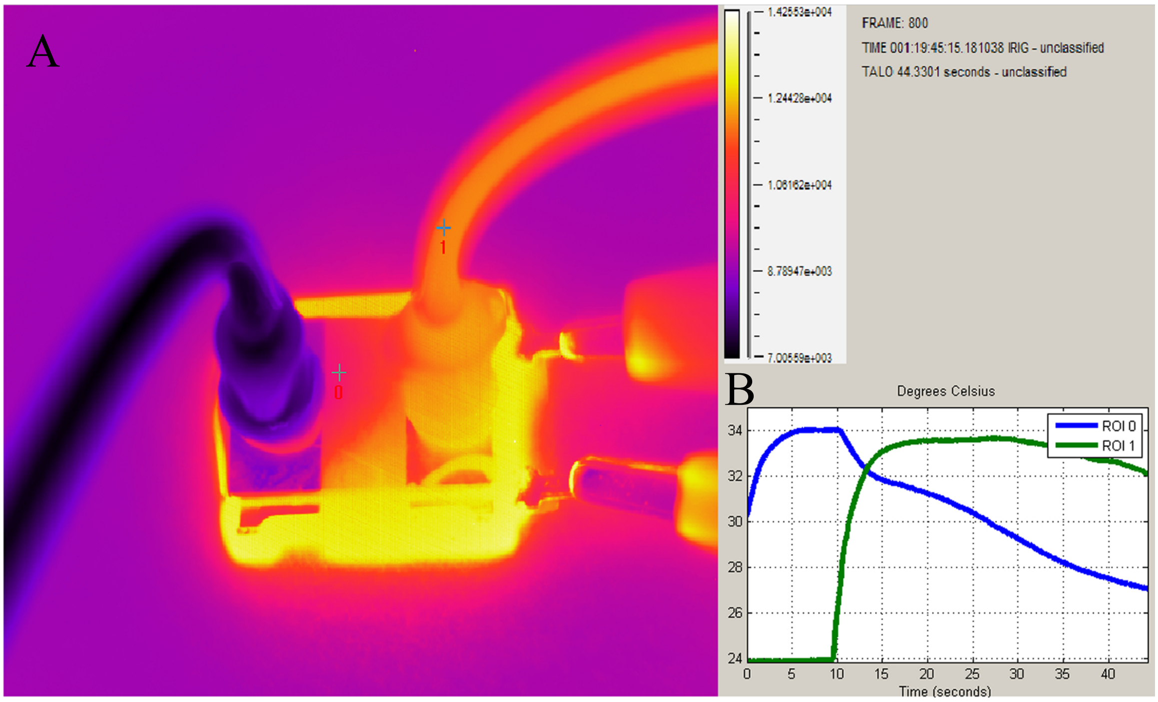

Figure 3. *(A) A thermal camera image of a heatsink attached to a resistor dissipating 10 W/cm^2 being cooled by an impedance pump with a mean output flow rate of 6 mL/min. (B) A plot showing the temperatures of two ROIs depicted by the cross-marks in the thermal camera image versus time. ROI 0 corresponds to the temperature on the surface of the heatsink whereas ROI 1 corresponds to the temperature on the surface of the outlet tube.*

aboard spacecraft where power is often only available through onboard fuel reserves or solar power generation. Due to the resonant wave based mechanism by which the impedance pump operates, properly designed pumps can be highly efficient when compared to other micropump technologies. Computational models of the impedance pump have demonstrated that as much as 75% of the mechanical work done by the actuator on the pump can be directly converted to fluid work [1]. Such analysis may lend some insight into why nature chose to utilize an impedance pump through its very early stages of development. Although no study exists where the response of the actuator has been matched to that of the pump, the impedance pump still exhibits high efficiencies when compared to other pump technologies with similar package sizes. In contrast to other mechanisms, Table 1 shows the impedance pump has the potential to significantly increase the efficiency of fluid power conversion in space missions while delivering relatively high flow rates and pressures.

6 Conclusion

As a bioinspired pump whose mechanism is modeled after the embryonic vertebrate heart the impedance pump holds great promise to provide fluid flow in a wide array of applications for pumps aboard spacecraft. In particular, the versatility in format and lack of internal moving parts make it a viable candidate for thermal management of electronics or standalone liquid cooling underneath the protective clothing used in space to mitigate the effects of fatigue on astronauts. The impedance pump mechanism has been demonstrated to be scalable and, as a result, has been designed to deliver a wide range of flow rates from microliters to liters per minute. The 2 mm tubular pump presented in this manuscript displayed many characteristics typical of impedance pumps including flow reversals and resonant flow peaks in response to changes in the excitation input frequency. A preliminary study examining the impedance pump for thermal management applications utilizing a microchannel heatsink has demonstrated the capability of impedance pumps to provide levels of heat flux removal which approach those projected for the next generation of microspacecraft [3]. With further testing and development of space based designs, impedance pumps have the potential to be a highly effective solution for fluid management in future space missions.

References

[1] I. Avrahami and M. Gharib. Computational studies of resonance wave pumping in compliant tubes. *Journal of Fluid Mechanics*, 608:139–160, 2008.

[2] S. Benner and M. Martins. Development of a heat-driven pulse pump for spacecraft applications. ii. In *Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference (IECEC-97)*, volume 2, pages 1482 – 1485, 1997.

[3] G. Birur, T. Waniewski Sur, A. Paris, P. Shakkottai, A. Green, and S. Haapanen. Micro/nano spacecraft thermal control using a mems-based pumped liquid cooling system. pages 196–206, 2001.

[4] A. Borzi and G. Propst. Numerical investigation of the liebau phenomenon. *Zeitschrift Fur Angewandte Mathematik Und Physik*, 54(6):1050–1072, 2003.

[5] R. Burian, A. Hetem, J. Miraglia, and C. Caetano. Parametric design of rocket engine turbopumps with genetic algorithms. In *MIPRO, 2011 Proceedings of the 34th International Convention*, pages 925 –929, May 2011.

[6] D. Butler, J. Ku, T. Swanson, and A. Obenschain. Loop heat pipes and capillary pumped loops: An applications perspective. Technical report, NASA, 2001.

[7] H.-T. Chang, C.-Y. Lee, and C.-Y. Wen. Design and modeling of electromagnetic actuator in mems-based valveless impedance pump. *Microsystem Technologies*, 13(11):1615–1622, 2007.

[8] C. Chen. A planar electroosmotic micropump. *Journal of microelectromechanical systems*, 11(6):672–683, 2002. 1057-7157.

[9] P.-C. Chen and W.-K. Lin. The application of capillary pumped loop for cooling of electronic components. *Applied Thermal Engineering*, 21(17):1739–1754, 2001.

[10] A. Dewa, K. Deng, D. Ritter, C. Bonham, H. Guckel, and S. Massood-Ansari. Development of liga-fabricated, self-priming, in-line gear pumps. In *International Conference on Solid State Sensors and Actuators*, volume 2, pages 757 – 760, 1997.

[11] A. Flouris and S. Cheung. Design and control optimization of microclimate liquid cooling systems underneath protective clothing. *Ann Biomed Eng*, 34(3):359–72, 2006.

[12] A. Forouhar, M. Liebling, A. Hickerson, A. Nasiraei-Moghaddam, J.-H. Tsai, J. Hove, S. Fraser, M. Dickinson, and M. Gharib. The embryonic vertebrate heart tube is a dynamic suction pump. *Science*, 312(5774):751–753, 2006.

[13] S. Gaddis, S. Hudson, and P. Johnson, editors. *Cold flow testing of the Space Shuttle Main Engine alternate turbopump development high pressure fuel turbine model*, June 1992.

[14] A. Hickerson. *An experimental analysis of the characteristic behaviors of an impedance pump*. PhD thesis, 2005.

[15] A. Hickerson, D. Rinderknecht, and M. Gharib. Experimental study of the behavior of a valveless impedance pump. *Experiments in Fluids*, 38(4):534–540, 2005.

[16] L. Jiang, J. Mikkelsen, J.-M. Koo, D. Huber, S. Yao, L. Zhang, P. Zhou, J. Maveety, R. Prasher, J. Santiago, T. Kenny, and K. Goodson. Closed-loop electroosmotic microchannel cooling system for vlsi circuits. *IEEE Transactions on Components and Packaging Technologies*, 25(3):347 – 355, 2002.

[17] E. Jung and C. Peskin. Two-dimensional simulations of valveless pumping using the immersed boundary method. *SIAM J. Sci. Comput.*, 23(1):19–45, 2001.

[18] C.-Y. Lee, H.-T. Chang, and C.-Y. Wen. A mems-based valveless impedance pump utilizing electromagnetic actuation. *Journal of Micromechanics and Microengineering*, 18(3):035044, 2008.

[19] G. Liebau. Uber ein ventilloses pumpprinzip. *Naturwissenschaften*, 41(14):327–327, 1954.

[20] A. Olsson, G. Stemme, and E. Stemme. A valveless planar fluid pump with two pump chambers. *Sensors and actuators. A, Physical*, 46-47:549–556, 1995.

[21] J. Ottesen. Valveless pumping in a fluid-filled closed elastic tube-system: one-dimensional theory with experimental validation. *Journal of Mathematical Biology*, 46(4):309–332, 2003.

[22] K. Patel, M. Bartsch, M. McCrink, J. Olsen, B. Mosier, and R. Crocker. Electrokinetic pumping of liquid propellants for small satellite microthruster applications. *Sensors and Actuators B: Chemical*, 132(2):461–470, 2008.

[23] A. Richter. A micromachined electrohydrodynamic (ehd) pump. *Sensors and actuators. A, Physical*, 29(2):159–168, 1991.

[24] D. Rinderknecht, A. Hickerson, and M. Gharib. A valveless micro impedance pump driven by electromagnetic actuation. *Journal of Micromechanics and Microengineering*, 15(4):861–866, 2005.

[25] E. Thomas, M. Weislogel, and D. Klaus. Design considerations for sustainable spacecraft water management systems. *Advances in Space Research*, 46(6):761–767, 2010.

[26] G. Wang, D. Mishkinis, and D. Nikanpour. Capillary heat loop technology: Space applications and recent canadian activities. *Applied Thermal Engineering*, 28(4):284–303, 2008.

[27] C. Wen, C. Cheng, C. Jian, T. Nguyen, C. Hsu, and Y. Su. A valveless micro impedance pump driven by pzt actuation. *Materials Science Forum*, 505-507:127–132, 2006.