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DEVELOPMENT OF AN ELECTROMAGNETICALLY ACTUATED MERCURY MICROVALVE*

Douglas R. Adkins and C. Chungnin Wong

Sandia National Laboratories, P. O. Box 5800, Albuquerque, NM 87185-1425

ABSTRACT

The development of microscale fluid handling components has been recognized as a crucial element in the design of microscale chemical detection systems. Recently, work has been undertaken at Sandia National Laboratories to construct a valve that uses a small mercury droplet to control the flow of gas through capillary passages. Electromagnetic forces that are provided by small permanent magnets and a current supply are used to drive the mercury into position. Driving the mercury droplet into a tapered passage halts gas flow through a capillary, while surface tension forces prevent the mercury from passing through the passage. Models have been developed to describe the movement of the mercury droplet and the sealing of the gas passage, and millimeter-scale units have been tested to explore design options. Predictions from the model show that a valve with 10 micron sized features can seal against pressures up to 1.5 atmospheres. Experiments have highlighted the promise of mercury valves and demonstrated problems that can arise from contamination of the mercury.

INTRODUCTION

Today there is a drive to miniaturize chemical detection equipment to make the systems more portable and better able to handle small samples. With this drive towards miniaturization, there is a need to develop fluid handling equipment, such as valves and pumps, in the millimeter to sub-millimeter size range. Most of the millimeter-scale valves that are currently available control flow by forcing a diaphragm to contact a port through which the fluid is passing. Motion is introduced in the diaphragm by electrostatic forces (Lee, 1996) or thermal expansion. Zdeblick et al. (1994) pre-

sented work on a commercially available valve that vaporizes liquid to drive a diaphragm and control gas flow at differential pressures of 689 kPa (100 psi). Jerman (1994) described a microvalve that thermally actuates a bimetallic diaphragm to control flows at differential pressures up to 207 kPa. Power consumption in thermally actuated valves is typically on the order of 100-300 mW because of heat loss to the surroundings and the gas flowing through the valve. This power consumption would be considered high for battery powered systems. There are also practical limitations on the scaling of diaphragm systems since the pressure required to deflect the diaphragm scales as $1/D^4$, where D is the diameter of the diaphragm. If the size of the diaphragm is halved, the pressure must be increased by a factor of 16 to achieve the same deflection.

As an alternative to a diaphragm valve, devices have been built that use surface tension force to form a barrier to flow. Man et al. (1998) demonstrated that capillary forces could block the flow of water against pressures up to 6 kPa; flow was released in these microdevices by pulsing the pressure in the liquid with a rapidly expanding oxygen bubble created by electrolysis. Hosokawa et al. (1996) showed that surface tension would allow a mercury droplet to act as both a piston and a valve in MEMS devices. In Hosokawa's device, mercury droplets were driven around an annular groove by electromagnetic forces. Motion of the droplets compressed air in the annulus, and drove air in and out of ports in the side of the annulus. Surface tension prevented mercury from passing through the ports.

The concept of using a mercury droplet as a valve has several attractive features. The mercury droplet readily conforms to the shape of an irregular port and prevents the flow of liquids or gases. As scales are reduced, the mercury valve can seal against higher pressures because the surface tension forces scale inversely with the diameter of the port. Finally, motion in the mercury can be induced by electromagnetic forces or by electrowetting where surface tension characteristics are modified by an applied voltage (Lee and Kim, 1998).

A proposed mercury pump and valve system is shown in Fig. 1. The system is basically a double-acting pump where mercury

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Figure 1. Proposed doubling acting pump using mercury piston and valves. Shown is the power stroke of the device.

droplets are used as both valves and a piston. Fluid is drawn in on the low-pressure side and simultaneously compressed on the high-pressure side. A mercury valve on the high-pressure side releases the compressed fluid, and the low-pressure mercury valve moves to the opposite position to begin the reverse stroke of the pump. Magnets on each side of the device create a magnetic flux through the mercury droplet. Motion is induced in the droplets by driving a current through the droplets, perpendicular to the magnetic flux. Pressure forces are roughly balanced across the valve, so high electromagnetic forces are not required to actuate the valve. Sandia National Laboratories is exploring the design of such a pump for micro-chemical detection systems, and some of these design studies are discussed in the following sections.

DESIGN PARAMETERS

Valve Sealing

A schematic of the mercury valve is shown in Fig. 2. Driving a mercury droplet between the two orifices blocks the flow of gas. The mercury is driven towards the downstream orifice by both pressure and electromagnetic forces. Surface tension forces between the mercury and the orifice counter these forces. The maximum valve holding pressure is equal to the capillary pressure, which is given by the expression,

$$\Delta P = \frac{4\sigma \cos \theta}{d}, \quad (1)$$

where ΔP is the difference between the upstream and downstream pressure, d is the diameter of the orifice, σ is the surface tension at the mercury/fluid interface, and θ is the wetting angle of the mercury. Surface tension for mercury in contact with water at room temperature is 0.375 N/m, and, for mercury in contact with air the surface tension is 0.484 N/m (Fox and McDonald, 1978). The wetting angle is about 140° for both water and air contact, but this angle can be affected by surface contamination.

Figure 2. Schematic of mercury valve system.

A plot of the holding pressure for a mercury valve as a function of orifice diameter is given in Fig. 3. For a 100-micron orifice, the valve will only be effective at holding back flow for differential pressures up to 15 kPa (2.2 psi). A 2-micron orifice should be capable of withstanding pressures up to 740 kPa (109 psi). Shrinking the orifice will allow the valve to operate at higher pressures, but the pressure drop across the valve will increase as the orifice size decreases. Flow through the orifice can be estimated with the expression,

$$Q = K \frac{\pi d^2}{4} \sqrt{2\Delta P_o / \rho_f}, \quad (2)$$

where Q is the flowrate through the orifice, ρ_f is the fluid density, and ΔP_o is the pressure drop across the orifice. The orifice coefficient, K , ranges from 0.6 for a sharp edged orifice to 1.2 for a smooth, rounded transition nozzle (Streeter and Wylie, 1975).

An estimate of the maximum flow that can pass through a valve

Figure 3. Maximum holding pressure for a mercury valve and maximum flow rate for air through the valve as a function of orifice diameter. $\sigma=0.484$ N/m. $\theta=140^\circ$ and $\rho_f=1.18$ kg/m³.

can be obtained by equating the orifice pressure drop with the

maximum holding pressure for the mercury valve. Combining Equations (1) and (2) yields

$$Q_{\max} = \pi K \left(\frac{\sigma \cos \theta}{2\rho_f} \right)^{1/2} d^{3/2}, \quad (3)$$

The estimated maximum flow of air through the mercury valve is shown in Fig. 3. For a 2-micron diameter orifice, a maximum flow of about 300 $\mu\text{liters/min}$ can pass through the valve. At higher flowrates, the pressure drop will be too great to be sealed by the mercury droplet. Of course, it is possible to use multiple orifices or permeable materials to accommodate higher flows with lower pressure drops.

Valve Actuation

Figure 4 provides a simplified description of the electromagnetic forces on the mercury droplet. Magnets above and below the mercury drop induce a magnetic flux, B . When a current, I , passes through the drop, the Lorentz (or electromagnetic) force acting on the droplet is

$$F = IsB. \quad (4)$$

The pressure increase from the Lorentz force is therefore,

$$\Delta P_{EM} = \frac{F}{sd} = \frac{IB}{d}. \quad (5)$$

From this expression, it is clear that reducing the thickness, d , of the mercury droplet between the electrodes will increase the electromagnetic pumping pressure. Reducing the thickness, however, will increase flow resistance and power consumption. If the width of the mercury droplet is much larger than its thickness ($s \gg d$), the frictional pressure drop through the pump can be

Figure 4. Lorentz force on a mercury droplet.

estimated with the expression for laminar flow between parallel plates,

$$\Delta P_f = 12 \frac{\mu_{Hg} L}{d^3 s} Q_{Hg}, \quad (6)$$

where L is the length of the actuation channel, μ_{Hg} is the mercury viscosity, and Q_{Hg} is the volumetric flowrate of the mercury droplet. This frictional pressure drop reduces the total pressure rise across the electromagnetic actuator. Reducing d will lower the volumetric flow rate that the pump can deliver, and therefore increase the valve actuation time.

When the mercury is driven to a stationary position, power is consumed as a result of resistance heating only. This power is

$$P = I^2 (R_{Hg} + R_{electrodes} + R_{contact}), \quad (7)$$

where R_{Hg} , $R_{electrodes}$, and $R_{contact}$ are respectively the mercury, electrode, and contact resistances. The mercury resistance is estimated as,

$$R_{Hg} = r_{Hg} \left(\frac{s}{wd} \right). \quad (8)$$

The specific resistivity for mercury, r_{Hg} , at 50°C is $0.984 \Omega \text{ m}$, (Weast and Astle, 1981). A similar expression can be developed for the electrode resistance. The contact resistance is a function of the film thickness between the electrode and the mercury droplet. The effective resistance over the contact area can range from $10^{-8} \Omega \text{ cm}^2$ for a 5-angstrom thick film to $10^{-2} \Omega \text{ cm}^2$ for a 100-angstrom thick film (Holm, 1967). Since the film thickness is unknown, the contact resistance will be determined from experimental results.

EXPERIMENTAL RESULTS

A series of sub-component tests were performed to validate the models and to discover other potential design issues. To test valve sealing, two devices similar to the one in Fig. 2 were made of acrylic in Sandia National Laboratories' miniature machine shop. The main channel was 1-mm wide and 1-mm deep, and it was connected to circular ports at the ends and in the middle by smaller connecting channels. The small connecting channels served as an orifice to block the mercury droplet when it interrupted the flow of air. On one test unit, the connecting channel was $500 \mu\text{m}$ wide by $500 \mu\text{m}$ deep, and, on a second unit, the channel was $250 \mu\text{m}$ by $250 \mu\text{m}$.

High pressure was applied to both ends of the mercury droplet, so the electromagnetic actuation force was not required to drive the mercury droplet against the full system pressure. For the tested valves, the electromagnetic forces could provide only about 2,000 Pa of actuation pressure with a current of 5 A, but this was sufficient to move the mercury droplet in and out of the gas flow passage. Photographs in Fig. 5 show the mercury valve in both an open and closed condition. The valve with the $500\text{-}\mu\text{m}$ passage was able to block the flow of air against pressures up to 1300 Pa (0.19 psi). This is only about one-third of the holding pressure that is predicted for a

Figure 5. Operation of the mercury valve. Mercury forms a leak-tight seal in the downstream flow passage (bottom).

500- μ m circular orifice using Eq. (1). For the valve with a 250- μ m passage, the maximum holding pressure was 4000 Pa (0.58 psi) compared to a predicted holding pressure of 5930 Pa for a 250- μ m circular orifice.

Some of the difference between the measured and predicted valve-holding pressure could be attributed to geometry differences. Capillary pressures in circular and square orifices of the same size are comparable (Brennan and Kroliczek, 1979), but the mercury did not always conform well to corners. It was observed that gas would

Figure 6. Electromagnetic pump built to test actuation for mercury valve.

flow past the mercury droplet from the pressure test port to the low-pressure port shown in Fig. 2. It is also likely that wetting at the mercury-wall-air interface was altered by contaminants during the tests. After several minutes of operation, a black residue would form on the surface of the mercury, and then transfer to the wall. (The likely composition of this residue will be discussed later.)

The device that is shown in Fig. 6 was built to further test the actuation mechanism for the mercury valve. The electromagnetic pump was located between two capillary tubes, and mercury could be pumped up either capillary against gravity to measure the pump pressure. In the pump, the mercury flowed through a passage between two copper electrodes where current was injected. The electrodes were 3.2-mm wide and 0.13 mm thick, and the distance between the electrodes was 3.2 mm. Between the electrodes, the mercury droplet was approximately 0.22-mm thick.

Neodymium-iron-boron magnets were located on each side of the mercury passage at the electrodes. The magnets were 6.3-mm long, 5.6 mm in diameter, and 1.46-mm apart. The magnetic flux density was determined by measuring the weight levitation induced by Lorenz forces when a current-carrying wire was positioned in the gap between the two magnets. At a 1.46-mm gap, the magnetic flux density was 0.551 N/A m.

A plot of the actuating pressure as function of current is given in Fig. 7. Measured pressures were found to correlate well with the predictions of Eq. (6). At 3.84 A, the pump provided 10.7 kPa of static pressure and it consumed about 119 mW of power. The electrical resistance was approximately 0.008 Ω and it did not vary with current during the tests. Based on Eq. (8), the theoretical resistance of the mercury was about 0.005 Ω , and similarly, the resistivity of the copper electrode was about 0.001 Ω . If the remaining 0.002 Ω resulted from contact resistance over the 3.2 mm x 0.13 mm electrode/mercury interface, it would indicate that the film thickness was on the order of 50 angstroms.

As in the valve tests, a black residue formed on the surface of the mercury, and collected on the walls of the glass capillary tubes. When the mercury was driven to oscillate in the column at about 2

Figure 7. Pressure as a function of current for the electromagnetic pump shown in Fig. 6.

Hz, the residue formed in about 2 minutes and then began to impede the flow of mercury. Originally it was suspected that this residue was an oxide of mercury, but in practice, mercury will not readily combine with oxygen at room temperature. Mercury will, however, form an amalgam with most metals with platinum and iron as notable exceptions (Metcalf, et al., 1970). It is most likely that the black residue was an oxide from the copper electrode that had formed an amalgam with the mercury. The copper amalgam was probably migrating to the air interface and combining with oxygen as mercury moved in the column. Bubbling air through mercury to form copper oxides is one of the traditional methods used to purify mercury (Strong, 1986). Residues did not form in mercury pumps that used nickel electrodes, but the overall electrode resistance did increase by a factor of 10. Some of the resistance increase could be attributed to the lower conductivity of the nickel, but a higher contact resistance between the nickel and the mercury could also have been a factor.

SUMMARY AND CONCLUSIONS

Sandia National Laboratories is in the process of developing micropumps and microvalves for miniature chemical detection systems. One of the valves being investigated uses a mercury droplet to impede the flow of gas, and electromagnetic actuation to control the position of the mercury droplet in the valve. A parameter study was performed to determine the capabilities of the mercury valve, and tests were performed on valve components.

Theoretically, the mercury valve should be able to withstand several atmospheres of differential pressure across the valve, but this capability has not yet been demonstrated in tests. Experiments on a millimeter-scale device showed that a mercury droplet could control gas flow up to 4000 Pa (0.58 psi) differential pressure. This is roughly one-third lower than the predicted pressure limit, but the discrepancy could be a result of contamination and the square shape of the orifice. In future devices, it may be beneficial to bore holes for valve ports rather than milled grooves.

Electromagnetic actuation of the mercury droplet was demonstrated in a valve and separately in a small test fixture. The tests showed that about 10.7 kPa of pressure could be developed with 119 mW of power consumption. Results of the tests correlated well with a presented model. Based on the model, significantly higher pressures can be developed by reducing the thickness of the mercury droplet between the current injection electrodes. Contamination of the mercury was found to be a problem, but it is likely that the copper electrodes caused the contamination in the test system. Platinum or nickel electrode materials will be used for electrodes in future systems.

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REFERENCES

- Brennan, P. J., and Krolczek, E. J., 1979, "Heat Pipe Design Handbook: Vol. 1," NTIS Pub. No. N81-70112, pp. 118.
- Fox, R. W., and McDonald, A. T., 1978, *Introduction to Fluid Mechanics*, 2nd ed., John Wiley and Sons, NY, pp. 583.
- Holm, Rangar, 1967, *Electric Contacts: Theory and Application*, Springer-Verlag, NY.
- Hosokawa, K., Shimoyama, I., and Miura, H., 1993, "Study of MHD (Magnetohydrodynamic) Micropump," *Nihon Kikaigakkai Ronbunshuu (C gumi)* 59 maki, 557 go (1993-1), Japan.
- Jerman, H., 1994, "Electrically-activated normally-closed diaphragm valves," *J. Micromach. Microeng.*, Vol.4, pp. 210-216.
- Lee, A., Hamilton, J., and Trevino, J., 1996, "A Low Power, Tight Seal, Polyimide Electrostatic Microvalve," *Micromechanical Systems (MEMS) Proceedings at the 1996 International Mech. Eng. Congress and Exposition, DSC-Vol. 59*, pp. 345-348, Atlanta, GA, Nov. 17-22.
- Lee, J., and Kim, C. J., 1998, "Liquid Micromotor Driven by Continuous Electrowetting," *Proceedings of IEEE MEMS 98*, pp. 538-543, Heidelberg, Germany.
- Man, P. F., Mastrangelo, C. H., Burns, M. A., and Burke, D. T., 1998, "Microfabricated Capillarity-Driven Stop Valve and Sample Injector," *Proceedings of IEEE MEMS 98*, pp. 45-50, Heidelberg, Germany.
- Metcalf, H. C., William, J. E., and Castka, J. F., 1970, *Modern Chemistry*, Holt, Rinehart & Winston, Inc., NY, pp. 540.
- Streeter, V. L., and Wiley, E. B., 1975, *Fluid Mechanics*, 6th Ed., pp. 469-473, McGraw-Hill Book Co., NY.
- Strong, J., 1986, *Procedures in Experimental Physics*, Lindsay Publications, Inc., Bradlet, IL, pp. 540.
- Weast, R. C., and Astle, M. J., 1981, "CRC Handbook of Chemistry and Physics," CRC Press Inc., Boca Raton. FL., pp. F-135.
- Zdeblick, M. J., Anderson, R., Jankowski, J., Kline, Schroder, B., Cristel, Lee, Miles, R., Weber, W., 1994, "Thermopneumatically actuated microvalves and integrated electro-fluidic circuits," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 251-255, Hilton Head Island, SC, June 13-16.