Macroscopic Actuation for Deployable Microvalves: Coupling Mechanically While Isolating Thermally

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Abstract. This paper presents the design and initial experimental validation of a system that couples macroscale actuations to a micro flow control system via a hydraulic coupler that isolates the actuator from the valve both spatially and thermally. The hydraulic coupling architecture is designed to enable flow control valves at MEMS length scales to employ macroscale actuation for effective valve sealing while still keeping the size of the valve itself much smaller than the size of the actuator. Lumped-element modelling shows that separating the sealing unit from its actuator can significantly increase the thermal isolation of the valve’s sealing unit from the ambient environment. This approach can enable the valve to be heated to minimize internal condensation with a minimum amount of required power. The manufacture of the hydraulic coupler is described, and its output actuation is measured as a function of input actuation. Finally, gas flow is successfully modulated via actuations that are delivered through the hydraulic coupler.

1. Introduction
Deployable systems are limited in their size and power consumption. In some cases, microdevices’ small size and typically low power consumption can help the system meet its constraints. For example, the size and power consumption of MEMS sensors can make them attractive for space or remote sensing applications. However, the challenge is greater for actuated systems, such as for flow control via valves or pumping. For actuated systems, the limits of MEMS actuator technology [1], the principles of actuator scaling [2], and the fundamental energy densities of actuating materials dictate that decreasing an actuator’s size will also limit the force and/or displacement it can apply. When performance (force and/or displacement) is paramount, macroscale actuators (e.g. pneumatics or macroscale piezoceramic stack actuators) are typically used in place of MEMS actuators.

However, there remain applications that require both the high forces of macroscale actuators and the small size of microactuators. One example is flow control in portable or deployable chemical analysis systems. Samples must be able to enter the system for sensing, but parasitic flow must be prevented when the system is idle. Given actuators’ characteristic scaling [2], macroscale actuation is expected to be required to apply sufficient valve closing forces to ensure that the leakage remains sufficiently low. This expectation is supported by the observation of higher leakage in MEMS-actuated valves (for example [3]) and ultra-low leakage in MEMS valves with macroscale actuation [4]. However, macroscale actuation inevitably increases the system’s size, introducing its own complications. For example, macroscale valves may not fit in the available space. Alternatively,
heating them with their relatively large surface areas to avoid sample condensation may require power that exceeds the power budget for a deployable system or increase the temperature of the actuator beyond its limits (e.g. beyond its Curie temperature).

Partially isolating a microvalve sealing unit from its macroscale actuating mechanism can potentially address this dilemma. For example, if size constraints in a given space require that the microvalve be small, its actuator may be placed at some distance away from that space, as long as the actuation can still be transferred to the microvalve. At the macroscale, a related challenge arises in actuating robotic mechanisms (e.g. robotics hands) that must be small and have light weight. One approach demonstrated to address this challenge in the literature is to use hydraulic connectors to transfer forces from remote actuators to space-constrained robotic mechanisms [5]. This solution uses hydraulics to spatially isolate a larger actuator from a smaller actuated system.

When a microvalve forms part of a heated flow-control system with a limited power budget as described above, spatial isolation is not the critical requirement. Instead, the microvalve must be thermally isolated from its larger actuator. This isolation ensures that the valved flow path itself can be heated without also having to heat the larger actuator.

In this work, the use of a hydraulic connector to provide mechanical coupling and thermal isolation between a MEMS valve or flow path and its external, macroscale actuator is described. The thermal performance of a hydraulically-isolated system is described through a lumped-element model. Suitable materials are proposed for its implementation, and the corresponding hydraulic interface is implemented. The hydraulic interface is preliminarily demonstrated to transfer force and displacement from a spatially and thermally isolated external macroscale actuator to a microfluidic device, thereby modulating the flow through its flow channel. The flow modulation is similar to the function of the integrated microvalves in [6], and the hydraulic coupling for spatial and thermal isolation between the MEMS device and its larger actuator represents the innovation in the current system.

2. Design Concepts and Modeling
When a microvalve is heated to a given temperature, the required power is determined by the thermal resistance between the microvalve and the ambient. Heat conduction to the environment may be reduced by the appropriate choice of materials and structure, but heat flow via convection is unavoidable for a system in an atmospheric pressure environment. Therefore, for the present analyses only the natural convection contributions to heat transfer are considered as a lower bound on heat losses. The convective thermal resistance between these valves and the environment is calculated as the inverse of the product of the heat transfer coefficient (assumed to be 10 W/m²/K) and the surface area of the valve. The resulting models are used to characterize the advantages of the spatially and thermally isolated actuation approach as compared with the use of integrated macroscale actuators.

Figure 1a shows the equivalent thermal circuit for a conventional valve in which the valve’s actuator and its sealing unit are integrated into a single valve unit. The power input that heats the valve to a temperature $T_v$ is represented as a thermal current $I_{Q}$, and the valve’s convective resistance to the ambient is given by $R_{v,\text{conv}}$. The smallest macroscale gas flow control valves with this type of integrated architecture typically have at least few-cm dimensions; fundamentally, these minimum dimensions are driven by the valve’s actuation requirements. Dividing the desired temperature rise of the valve by its net thermal resistance to the ambient yields the required power input. For a valve with a 13 cm² surface area, this would correspond to a thermal resistance of about 70 K/W. Considered in the context of the energy density of batteries, this power requirement is better suited to benchtop systems than it is to portable or deployable systems.

Figure 1b illustrates an alternative concept in which a microvalve is spatially and thermally isolated from its actuator by a hydraulic connector comprising chambers of low thermal conductivity hydraulic
fluid on the actuating and sealing sides that are connected by a low thermal conductivity tube (e.g. glass or ceramic). The actuation input to the hydraulic coupler is provided via a membrane. When the membrane is deflected by an input actuation (e.g. an external force applied at the center of the membrane or an external bending actuation), the hydraulic fluid inside the coupler moves toward the coupler’s output. The coupler’s output is a second membrane that deflects under the influence of the hydraulic fluid. This membrane will typically be fabricated as a monolithic part of the microvalve’s sealing unit as shown in figure 1b, with the interface between the coupler and the sealing unit being created by a packaging connection. Alternatively, the second membrane may be integrated with the coupler itself, as in the present preliminary demonstrations. In this variation, the deflection of the coupler’s output membrane deflects the input membrane of the microvalve’s sealing unit.

Figure 1c shows the equivalent thermal model of a valve in which the micro sealing unit is thermally isolated from the actuator unit. In this modified architecture, the (smaller) sealing unit has a larger convective resistance $R_{s\_conv}$ to the ambient, and the (larger) actuator has a smaller convective resistance $R_{a\_conv}$ to the ambient. The hydraulic connector adds a conductive thermal resistance $R_{cond}$ between the valve’s heated sealing unit and its lower-temperature actuating unit. Adding $R_{cond}$ in series with $R_{s\_conv}$ creates a thermal divider, minimizing actuator temperature and required heating power.

The impact of this architecture on the valve’s heating requirements may be estimated. Consider a 1 cm square, 2 mm high nominal valve sealing unit, corresponding to a convective resistance to ambient of about 360 K/W. If the actuation were to be provided by a piezoceramic (PZT) bending disk, the smallest size for the actuator would be approximated at 12.7 mm. For an actuator unit with an overall diameter of 15 mm and a height of 2.5 mm, the actuator’s convective resistance would be approximately 210 K/W. If the actuator and sealing unit were coupled by a nominal 1 in long, ¼ in OD zirconia tube filled with low thermal conductivity methyl silicone oil, a conductive thermal resistance of about 840 K/W would be added between the actuator and the sealing unit. The hydraulic connector also contributes to convective heat losses from the heated region. The net thermal resistance from these elements to the ambient would then be about 160 K/W, corresponding to a 2.3X reduction in required heating power as compared with a valve that integrates the actuator with the sealing unit.

Figure 1. a) Equivalent thermal circuit for a conventional valve in which the sealing unit is integrated with the actuator, b) conceptual cross-sectional cutaway of a sealing unit that is hydraulically coupled to a separate piezoceramic actuating unit, and c) equivalent thermal circuit for a valve in which the sealing unit is thermally decoupled from the actuator by a hydraulic connector.
3. Experimental
A prototype hydraulic coupler was fabricated (figure 2), and its function was demonstrated by modulating the flow through a microchannel. The input is provided via deflection of a 25 μm thick, 14.4 mm diameter stainless steel membrane connected to a tapered hydraulic chamber printed from PLA. The actuation is transferred through a 25 mm long borosilicate glass hydraulic connecting tube filled with methyl silicone oil (Aldrich) and is output by a 70 μm thick PDMS membrane at the bottom of the tube. The oil is filled through one of two filling tubes, while the other tube permits the system to vent any bubbles. The fill tubes are then sealed with epoxy.

The actuation is provided by a micropositioner. The point at which the micropositioner first contacts the input membrane is identified by measuring electrical continuity through a circuit that is closed when the positioner’s metal tip touches the steel membrane. The input deflection is then controlled manually via the micropositioner. The deflection of the output membrane is first measured as a function of input deflection by imaging the output membrane’s motion under a stereo microscope, counting the pixels in the images, and converting the pixel count to distance according to the calibration made with a stage micrometer.

![Figure 2](image)

**Figure 2.** a) Cross-sectional diagram and b) photograph of hydraulic coupler with steel input membrane and PDMS output membrane.

The hydraulic coupler is then positioned so that its output just contacts a PDMS microchannel connected to a source of pressurized air. Actuations are applied to the steel input membrane, and the resulting flow rates are measured. Figure 3 shows the experimental set up for the flow control demonstrations.

![Figure 3](image)

**Figure 3.** PDMS flow channel under actuation by the hydraulic coupler
The flow channel was fabricated by bonding a PDMS membrane to a layer of thick PDMS with channel recesses imprinted from a die. Pressurized air at a pressure of approximately 60 psi is flowed through the channel and then through a floating ball flow meter. The micro positioner then produces the actuation to the input membrane. The resulting deflection of the output membrane compresses the flow channel, restricting the flow to the flow meter. The difference in the flow before and after actuating the input membrane is then measured.

4. Results and Discussion

Figure 4 shows the measured output deflection vs. the input deflection for the hydraulic coupler with a PDMS output membrane as described above. An output deflection of 240 μm was measured for an input deflection of 100 μm. The large deflection, low force performance of this hydraulic coupling system is enabled by its use of a PDMS output membrane. A second hydraulic coupler made with a steel output membrane provides a stiffer mechanism that demonstrates significantly smaller deflections of 10 μm. In flow testing with the first hydraulic coupler, the flow was reduced by more than 40%, from an initial flow rate of approximately 0.35 to 0.4 standard cubic feet per hour (SCFH) to a final flow rate that was typically between 0.15 and 0.2 SCFH. The hydraulic coupler technology is shown to be an effective means of transferring macroscale actuations to MEMS-scale devices to meet system-level requirements for compactness and thermal performance.

![Figure 4. Measured output deflection vs. input deflection for the hydraulic coupler with a PDMS output membrane](image)

Acknowledgements

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