A thermopneumatically actuated microvalve for liquid expansion and proportional control

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SUMMARY

The analysis, design, fabrication, and testing of a thermopneumatic expansion valve to control single-phase and two-phase flow of liquids is described. The valve is normally open, and shuts off flow with low power consumption, below 0.5 watt, reducing the power consumption of earlier thermopneumatic designs by a factor of ten. The device has been applied as an expansion valve to the problem of proportional control of refrigerants. Differential pressures of 140 psid (~1 MPa) are sustained across the valve. Flow rates up to 10 gm/sec for the refrigerant R-134a have been demonstrated.

Keywords: Micro-fluidics; thermopneumatic actuation; low-power microvalve; liquid flow control; anodic bonding

INTRODUCTION

Thermopneumatic actuation of microvalves has been utilized for some time to control fluid flow [1]. More generally, microvalves have been used to control flows of non-corrosive gases, and of water, over wide ranges of pressure drop and mass flow [2]. In this work, we describe the analysis, design, fabrication, and testing of a thermopneumatic expansion valve to control single-phase and two-phase flow of fluids. The valve is normally open, and shuts off flow with low power consumption, below 0.5 watt. This power level represents a roughly ten-fold reduction in thermopneumatic microvalve power consumption, compared to existing Si-membrane technologies.

The device has been applied as an expansion valve to the problem of proportional control of refrigerants. Differential pressures of 140 psid (~1 MPa) are sustained across the valve. Flow rates between 2 and 12 grams per second (g/sec or gm/sec in this paper) for the refrigerant R-134a have been demonstrated. These flow rates and pressures make the valve an ideal, active-mode candidate to replace passive-mode capillary tubes, commonly used in home refrigeration, automotive air conditioning, and smaller scale commercial air conditioning applications. The replacement of a passive "cap tube" with an active EXV (electronic expansion valve) can yield energy efficiency improvements of between 2 and 14 percent in these applications [3].

LOW-POWER TECHNOLOGY

An EXV for proportional control of liquids, which also enables two-phase flow, must meet several requirements. Power input to the valve must be isolated from the controlled liquid, in order to minimize heat transfer from the valve to the liquid. The valve components must be sealed hermetically, in order to confine the liquid without escape from the flow path. The valve materials must be compatible with the liquids to be controlled.

Redwood's existing normally-open valves consist of a top Pyrex layer, a middle Si membrane layer, and a bottom Si orifice layer. This configuration suits gas flow control applications well. However, control of liquids (especially refrigerants) becomes more difficult, since the heat transfer coefficient of the Si membrane surface exposed to the liquid flow can be quite high. As a consequence, we determined to isolate the power input from the Si membrane. 1D, 2D, and 3D analyses were undertaken to establish the heat transfer aspects of this low-power technology.

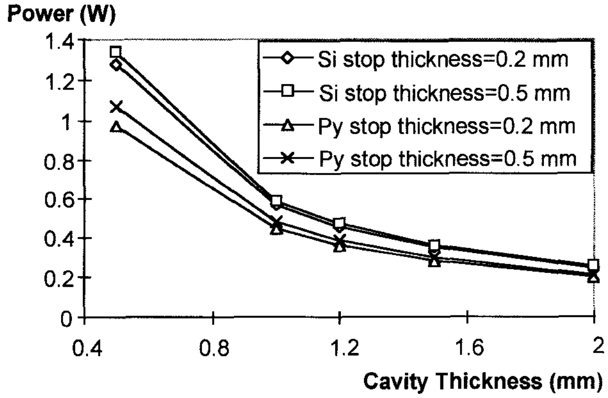

Figure 1: Simulation of valve turn-off power versus cavity (Fluorinert™) thickness. Simulations for both Si and Pyrex were performed. The thickness of the membrane stop layer was also varied.

Figure 1 shows a sample of one-dimensional, finite-difference simulations of the valve structure shown in Figure 2. "Stop thickness" refers to the thickness of the lower portion of the second Pyrex layer. We explored, in simulation and experiment, the use of either Si or Pyrex to constitute this layer. As shown in Figure 1, Pyrex provides superior thermal isolation compared to Si. "Cavity thickness" refers to the thickness (or, in 3D, the volume) of the Fluorinert™ layer. This relative analysis demonstrated the importance of these variables. It suggested the choice of Pyrex over Si for the cavity layer (confirmed in experiments), and drove the decision to maximize the cavity thickness, and minimize the stop layer thickness.

FABRICATION SEQUENCE

Figures 2 and 3 show cross-section and exploded views of the EXV, which extends the features of previous work [4]. A normally-open configuration was chosen for the power-off state, as refrigeration valves should (usually) 'fail open'. The EXV consists of four micromachined components, encapsulating a Fluorinert™ liquid for thermopneumatic actuation, which are attached to a ceramic substrate. The top layer is Pyrex, with a Pt resistor patterned on the lower surface. Holes for electrical feedthrough and Fluorinert™ insertion are made ultrasonically [5]. The second layer is a Pyrex cavity, also patterned ultrasonically. The lower portion of this layer provides a mechanical stop which protects the Si membrane under conditions of rapid cool-down.

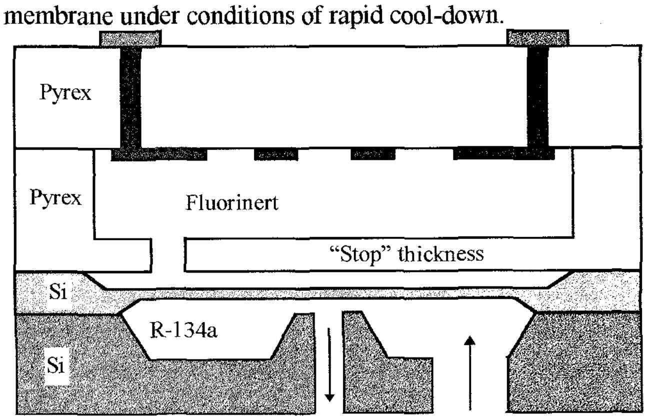

Figure 2: Schematic cross-section of the thermopneumatic expansion valve. The Pyrex layers are each ~1 mm thick. The Si membrane layer is ~300 μm thick, with a 50 μm thick membrane and 50 μm gap between the membrane and the valve seat. The orifice Si layer is ~500 μm thick.

The third layer is a Si membrane patterned using KOH and fillet etching (HF:Nitric:Acetic). The bottom orifice layer is patterned Si, which enables surface mounting to the ceramic substrate. In terms of assembly, the Si layers are first fusion bonded in a conventional manner [6]. The remaining components (two Pyrex layers, and the membrane/orifice sandwich) are bonded using anodic techniques [7].

Figure 4 shows an exploded view of a complete EXV, including the ceramic substrate and copper tubes which comprise key portions of the package. The copper tubes are ¼" in diameter, and are brazed to the ceramic substrate. The die is attached eutectically following the ceramic-copper brazing process. The final fabrication steps involve filling the die with Fluorinert™, capping the fill holes, attaching wire bonds and leads, and applying silicone atop the structure to provide mechanical support for the electrical connections.

The package design was demonstrated to withstand pressures in excess of 1800 psia, applied to the inlet and outlet simultaneously.

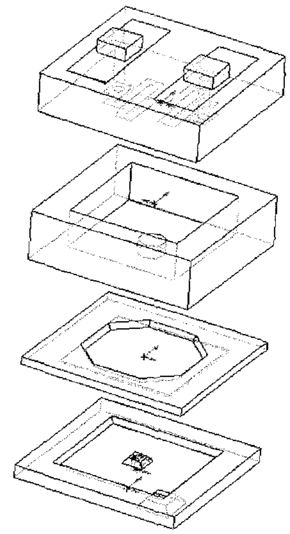

Figure 3: Exploded view of the EXV.

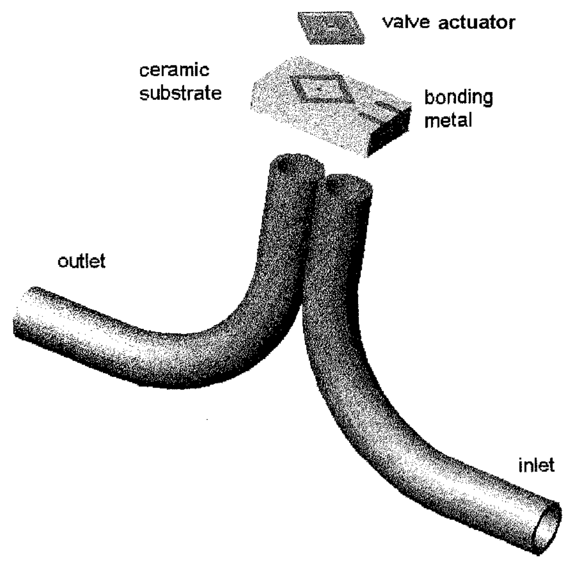

Figure 4: Exploded view of the complete refrigeration valve, including the ceramic substrate and the copper tubes for inclusion in a refrigeration system. The ceramic has defined metal landing pads to effect a eutectic bond between the valve and the ceramic.

TEST, EXPERIMENTS AND CHARACTERIZATION

A test station to measure refrigerant flow was designed, built, and characterized. A schematic of this test station is shown in Figure 5. The station was designed to measure the thermodynamic state of refrigerant, and refrigerant-oil mixtures, on either side of the device under test (DUT), in order to determine the flow behavior of the microvalve as a function of temperature, pressure drop, and absolute pressure on the valve inlet. LabView™ was used to provide computer control and measurement.

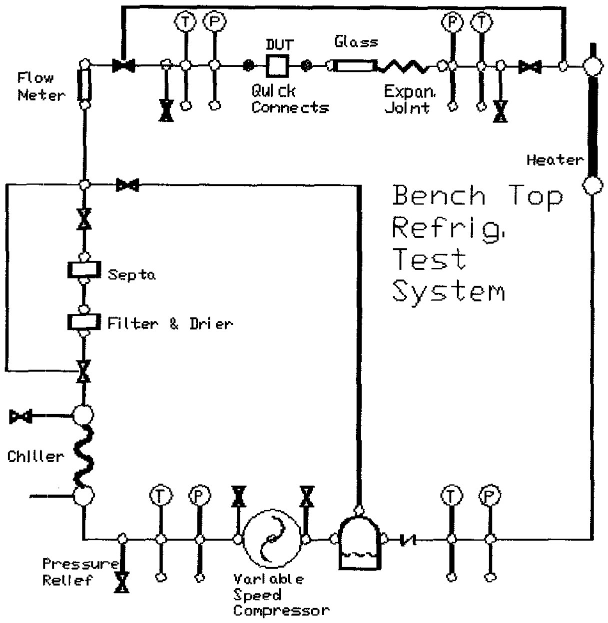

Figure 5: Schematic of test station developed for characterization of refrigerant flow devices.

Over 200 valves, with a variety of Pyrex thicknesses, Fluorinert™ properties (especially coefficient of thermal expansion, and boiling point), and outlet orifice size were fabricated and packaged. Roughly 25% of these devices have been tested to date. Generally speaking, the following parameters result in lower power consumption: lower boiling point Fluorinert™; thicker Fluorinert™ cavity; Pyrex instead of Si as the "stop" layer; suction flow (instead of impingement flow).

RESULTS

Materials Compatibility

The compatibility of the wetted materials with the liquids controlled by the microvalve is a critical issue. Table I shows some of the results of our materials compatibility experiments. As shown, none of the materials used on the microvalve suffer significant degradation when exposed to R-134a, and R-134a/ester oil mixtures.

	Polyetherimide	Neoprene	Viton	Silicone	Ablebond	Hysol	Silicon	Au, Cr, Cu, Pt	Glass Ceramic	Alumina	Pyrex	Fluorinert	Valve	Control
Weight Changes														
Refrigerant	1%	**11%**	**24%**	0%	0%	1%	1%	-2%	0%	0%	-1%	NA	0%	NA
Lubricant	2%	**22%**	**4%**	2%	1%	0%	-1%	1%	0%	0%	1%	NA	2%	NA
50/50 Ratio	1%	**19%**	**14%**	**5%**	1%	1%	-1%	1%	0%	0%	2%	NA	1%	NA
Dimensional Changes														
Refrigerant	2%	**5%**	**14%**	**-9%**	**-6%**	**-3%**	0%	+/-1%	0%	-2%	2%	NA	2%	NA
Lubricant	2%	**17%**	**3%**	**-8%**	**-4%**	-1%	0%	+/-1%	0%	0%	-1%	NA	2%	NA
50/50 Ratio	2%	**9%**	**7%**	**-4%**	**-3%**	**-3%**	0%	-2%	0%	0%	2%	NA	2%	NA

** These numbers represent the maximum change observed.

Table I: Results of materials compatibility study..

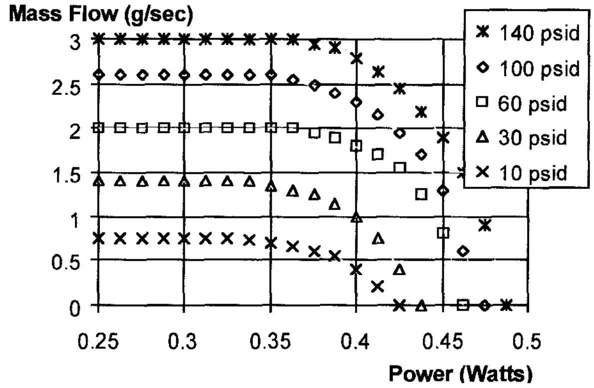

Figure 6: Flow of refrigerant R-134a vs. power input to the valve. The Pt heater resistor is approximately 50 Ω. The exit orifice is 11 mils. The Si membrane thickness is 50 μm. The membrane area is ~13.2 mm². The refrigerant inlet temperature is 24 °C, as is room temperature. The outlet pressure is 650 kPa.

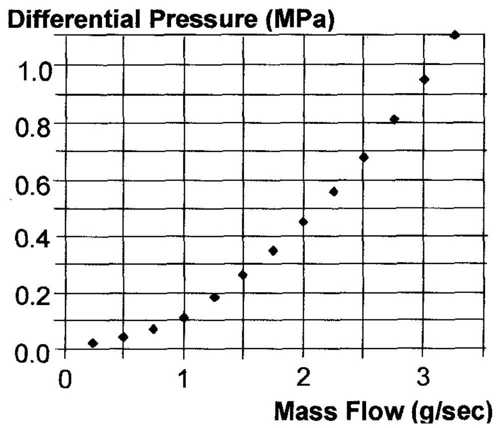

Figure 7: Differential pressure versus R-134a mass flow for an unpowered valve. The conditions and valve parameters are the same as in Figure 6.

Flow

The next figures show the control behavior of the EXV (flow vs. power, with pressure differential as a secondary variable). The curves are obtained for the application of either increasing power, or decreasing power. Little hysteresis is noted for conditions of decreasing power, when compared to the power-increasing measurement mode. Figure 6 shows the behavior of one valve which closely meets the specifications for home refrigeration applications. Figure 7 shows the unpowered behavior of this valve. Figure 8 shows a 3D spatial representation of the flow vs. pressure vs. power characteristics of a second refrigerant flow valve. Figure 9 shows the effects on water flow of this generic EXV design.

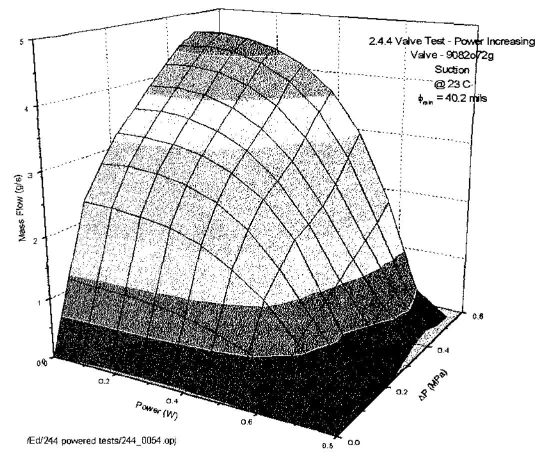

Figure 8: Pressure vs R-134a flow vs. power for a representative microvalve.

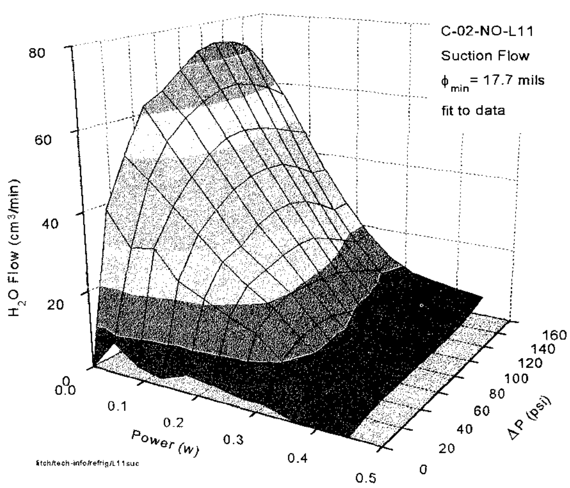

Figure 9: Pressure vs water flow vs. power for a representative microvalve.

CONCLUSIONS

We have demonstrated flow rates at the equivalent of between ~2 and ~10 gm/sec at differential pressures of 140 psid. Measurements are repeatable. Filtration is required, since the smallest cross-sectional area is on the order of 50 um. Suction flow is superior to impingement flow in terms of thermal isolation and achievement of the lowest power possible. Power consumption well below 0.5 W has been demonstrated, for both R-134a and water.

In terms of response speed, we note that on-to-off transition times are on the order of 1 sec. Such speeds are consistent with the requirements for air conditioning and refrigeration applications.

ACKNOWLEDGEMENT

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