A JOULE-THOMSON COOLING SYSTEM WITH A SI/GLASS HEAT EXCHANGER FOR 0.1-1 W HEAT LOADS

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ABSTRACT

This paper reports a Joule-Thomson cooling system that provides 0.1-1 W cooling power using a micromachined Si/glass perforated plate heat exchanger. The gas expansion is performed through a micromachined valve that is piezoelectrically actuated, or alternatively through a commercial jewel orifice. The modulated J-T system using the microvalve can achieve 254.5 K at a pressure difference of 430 kPa and 5-8 K temperature modulation at a given pressure. With a jewel orifice, the temperature at the expansion orifice drops 76.1 K from the inlet temperature for an inlet pressure of 1 MPa (145 psia) when the ethane mass flow rate is 0.269 g/s. The system can reach a lower temperature at 200.3 K in a transient state. The cooling power of the system is 200 mW at 228K and 1 W at 239 K, in addition to a parasitic heat load of 300-500 mW.

KEYWORDS

Joule-Thomson Cooler, Heat Exchanger, Cryogenic Microsystem, Flow Modulation

INTRODUCTION

Various micromachined Joule-Thomson (J-T) [1] cooling systems have been developed in the past three decades. Design, fabrication and cooling performance of these systems vary, depending on the intended applications. The performance is largely determined by the recuperative heat exchanger (HX) [2]. High-pressure (HP) fluid at room temperature passes through one side of the HX and is pre-cooled by the cold low-pressure (LP) fluid on the other side (Fig. 1). The cooled HP fluid leaving the HX expands through an orifice or valve and further cools down due to the J-T effect. The cold, LP fluid is then warmed by the refrigeration load and fed back into the heat exchanger. In the past, the micromachined HX structures have used glass grooved channels [3], concentric commercial glass tubes [4], micro glass pillars [5] and glass fibers [6]. However, these coolers, typically provide low cooling power (<250 mW) due to limited mass flow rate allowed by the system.

A micromachined J-T system that provides higher cooling power is highly desired in many refrigeration applications including cryosurgery [7-8] and cooling infrared detectors in space applications [9]. This paper reports a J-T system with high cooling power (up to 1 W) constructed with a micromachined Si/glass perforated plate HX [10-11] designed for superior effectiveness and robustness. Details regarding the design and fabrication of the system and its micromachined components, experimental facility and test results are described.

In addition, a modulated J-T system using a micromachined piezoelectrically-actuated microvalve for gas expansion and flow modulation is reported. The microvalve used in this system has been developed and reported to provide a large flow modulation in cryogenic temperatures down to 80 K [12]. By adjusting the opening of the microvalve, flow rate of the work fluid is modulated. Consequently, the temperature and cooling power of the J-T system can be precisely controlled.

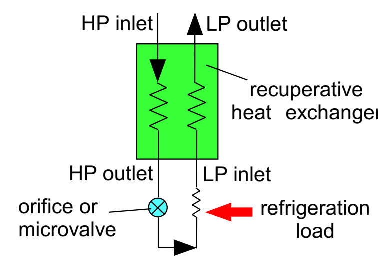
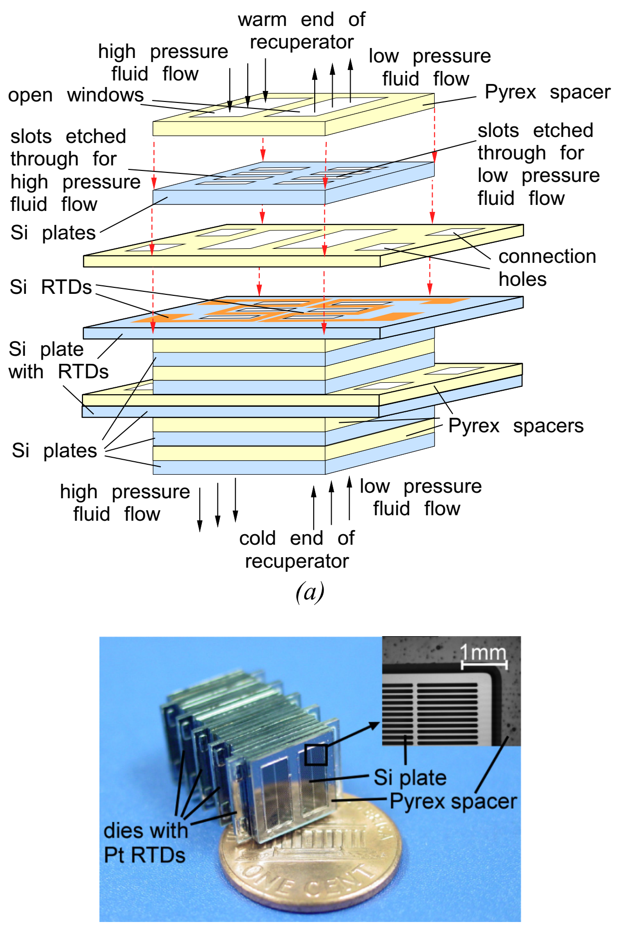


Fig. 1: Schematic diagram of the Joule-Thomson cooling system

DESIGN & FABRICATION

The basic J-T microsystem is primarily constructed with a micromachined counter-flow perforated plate HX (Fig. 2a) and a commercial jewel orifice. The HX uses numerous high-conductivity silicon perforated plates stacked alternately with low-conductivity glass spacers. Four columns of perforated slot patterns – two for the HP fluid, and the other two for the LP fluid – are located on each Si plate. Heat transfers within each Si plate while the glass spacers are used to thermally insulate the Si plates and prevent axial conduction. As a result, a large temperature gradient forms across the heat exchanger. Dies integrated with platinum resistance temperature detectors (Pt RTDs) are interleaved into the stack to facilitate real-time temperature measurements. The detailed fabrication process of this HX, which involves several fabrications steps, including KOH wet etching on (110) wafers, HF:HNO_3 glass etching, and Si-glass anodic bonding, was reported in [10-11]. A fabricated HX with 10×10 mm^2 is shown in Fig. 2b. Designed for high mass flow rates [13], this HX has shown effectiveness up to 0.91, and high robustness at inlet pressures up to 1 MPa.

In the modulated J-T system, the jewel orifice is replaced by a micromachined Si/glass piezoelectric valve (Fig. 3). In this valve, a PZT actuator drives the silicon valve seat against a glass plate, thereby varying the flow rate by adjusting the opening between the valve seat and glass plate. The valve seat is fabricated from a silicon-on-oxide wafer by deep reactive ion etching. Detailed fabrication process of this valve and its flow modulation results at both room temperature and cryogenic temperatures were reported in [12]. The overall size of the valve is $1 \times 1 \times 1$ cm^3. Experiments show that the microvalve is able to modulate the flow at cryogenic temperatures down to 80 K, although the modulation range decreases because of the reduced piezoelectric coefficient at cryogenic temperatures.



(b)

Fig. 2: (a) Perforated plate heat exchanger design. Platinum resistance temperature detectors (Pt RTDs) can be integrated on selected silicon plates. (b) The die size of the perforated plate heat exchanger is 10×10 mm^2. The total length is 20 mm with 25 dies. Thickness of Si plate is 500 µm. Thickness of Pyrex spacer is 300 µm. Two columns of opening slots are on both high-pressure and low-pressure sides of each Si plate. The slot is 50 µm wide and 1400 µm long; there is 50 µm gap between each slot.

EXPERIMENTAL SETUP

A closed-loop test apparatus is used to evaluate the cryocooler (Fig. 4). Ethane gas from an external compressor passes through the HX and expands through the jewel orifice (or microvalve) to provide the cooling. The parasitic load is minimized by inserting the device under test into a vacuum insulated dewar with multi-layer insulation covering the components. A resistive heater located down-stream of the orifice provides calibrated heat load. A vacuum pump is used to purge the residual air and ethane from the flow lines before the experiment.

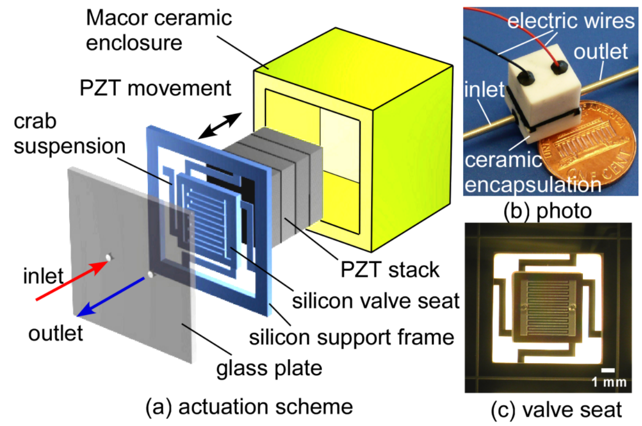


Fig. 3: Micromachined piezoelectric valve. (a) actuation scheme of the microvalve; (b) photograph of the fabricated valve encapsulated with a Macor^{TM} ceramic enclosure; (c) photograph of the fabricated Si valve seat.

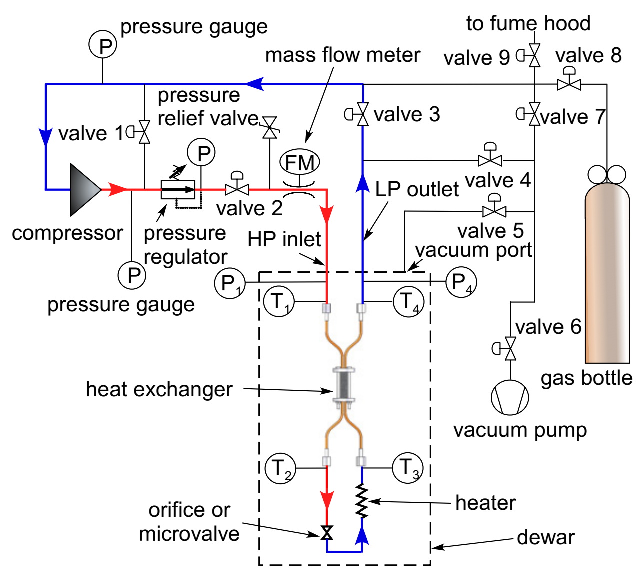


Fig. 4: Flow schematics of the test facility.

Ethane mass flow rate, temperatures and pressures are measured at locations indicated in Fig. 4. The mass flow rate is recorded by a Bronkhorst F-132M mass flow meter. Temperatures at the HP inlet (of heat exchanger), HP outlet, LP inlet and LP outlet are measured by type-E thermocouples (respectively denoted in Fig. 4 by subscripts 1, 2, 3, and 4). Pressures at the HP inlet and LP outlet are measured by digital pressure gauges. Readings from the mass flow meter, thermocouples, digital pressure gauges are simultaneously recorded using an Agilent 34970A multiplexer.

In the experiments for basic J-T system that use jewel orifices for gas expansion, the HP inlet pressure was varied while the LP outlet pressure was set at about 5 psi above the atmospheric pressure. The temperatures were recorded when the J-T cycle reached the steady state. J-T cooling tests without and with an external heat load (provided by the heater) were performed. In the experiments for the modulated J-T system, the orifice was replaced by the piezoelectric microvalve. While the HP inlet pressure was set at different pressures, the actuated voltage of the microvalve was varied. The temperatures were recorded when the system reached the steady state.

EXPERIMENTAL RESULTS

Although several heat exchangers with different length have been fabricated and tested, all the experimental results discussed in this paper are representative of heat exchangers stacked with 43 dies, i.e. with 43 pieces each of Si and glass plates.

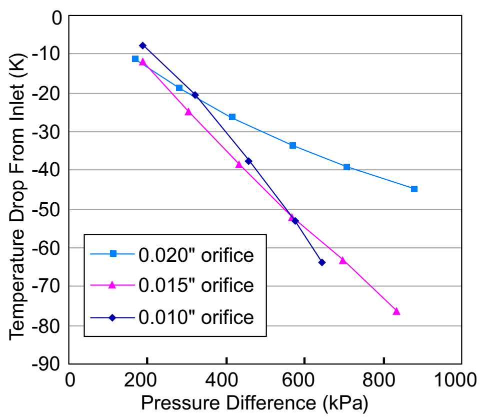


Fig. 5: Temperature drop (T_3-T_1) as a function of the pressure difference (P_1-P_4) in the J-T test. T_1 remains at 294-296 K.

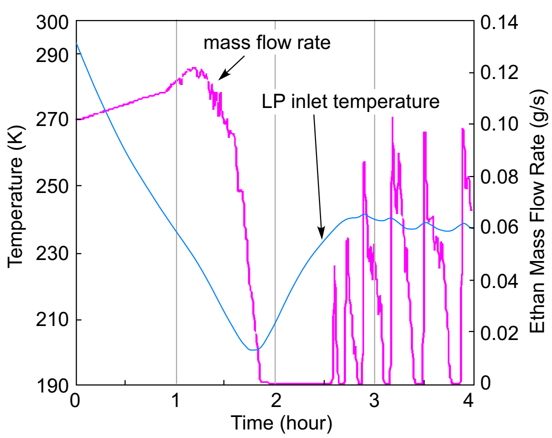


Fig. 6: Transient temperature profile of the heat exchanger in J-T test with 0.010 in. orifice. LP inlet temperature bounced back due to impurities freezing.

In the experiments of the basic J-T system, three orifices with different diameters (0.010 in., 0.015 in. and 0.020 in.) are used. The corresponding opening areas of these three orifices are 0.0507 mm^2, 0.1140 mm^2 and 0.2027 mm^2, respectively. Figure 5 shows the temperature drop from the inlet (T_3-T_1) in the J-T test, when different pressure differences (P_1-P_4) are applied to the system. The heater is off in these tests. The maximum temperature dropped is 76.1 K from inlet temperature (corresponding to an actual temperature of 218.7 K) at a 0.269 g/s ethane mass flow rate. The applied pressure difference is 835.8kPa (121.5 psid) and the HP inlet pressure (P_1) is 1MPa (145 psia). Figure 6 shows the transient temperature profile of the LP inlet when the 0.010 in. orifice is used. The ethane mass flow rate is also included in the same plot. The heater is off and the HP inlet pressure is about 1 MPa. Initially, the system is at room temperature, but settles at 230-240 K eventually. The LP inlet temperature can drop to an even lower temperature of 200.3 K but bounces back to higher temperatures. This is possibly due to impurity freezing inside the heat exchanger or around the orifice and therefore, cutting off the flow. As shown in Fig. 6, when the mass flow rate approaches zero, the temperature starts to rise. Once the temperature increases to a certain level, the mass flow rate starts to jump back, which indicates the impurities are melt.

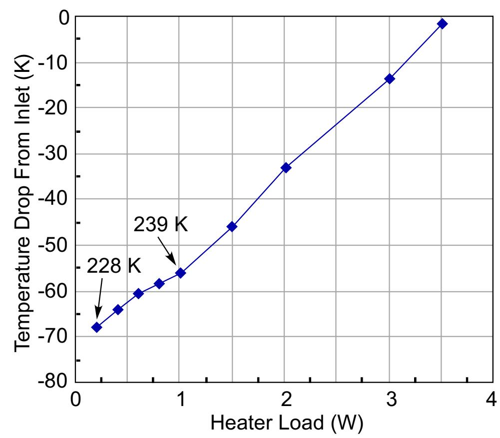


Fig. 7: Temperature drop (T_3-T_1) as a function of heat load in J-T test with 0.015 in. orifice. Estimated parasitic heat load is at least 300-500 mW. T_1 is at 294-296 K.

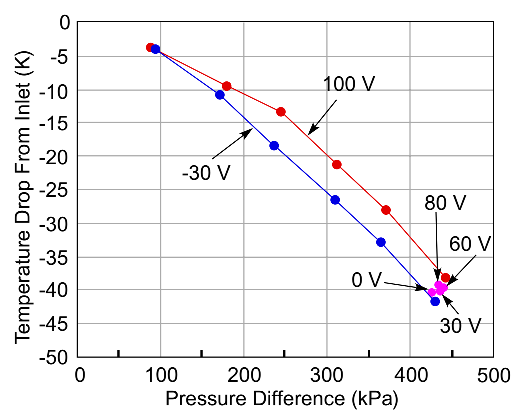


Fig. 8: Temperature drop (T_3-T_1) as a function of pressure difference (P_1-P_4) in J-T tests with both orifices and microvalve. The input voltage of the microvalve is varied from -30 V to 100V

Figure 7 shows the temperature drop (T_3-T_1) as the heat load is varied. In this test, 0.015 in. orifice is used and the HP inlet pressure is at around 1 MPa. The system provides a cooling power of 200 mW at 228 K and 1 W at 239 K in addition to a parasitic heat load of 300-500 mW due to the measurement set-up. The parasitic heat load primarily results from a) radiation from the vacuum insulated vessel wall; b) thermal conduction through the pipe lines and the Pt RTD feed-throughs, and c) ohmic dissipation from the integrated Pt RTDs.

In the modulated J-T system, the jewel orifice is replaced by the piezoelectric microvalve. Figure 8 shows the cooling results of the modulated J-T system with the microvalve actuation. The input voltage of the microvalve is varied from -30 V to 100 V, with respect to the opening from the maximum to minimum. At -30 V, the lowest steady-state temperature is 254.5 K at a pressure difference of 430 kPa. The temperature modulation is 5-8 K at a given pressure.

SUMMARY

This effort has resulted in the successful demonstration of a high cooling power J-T system that is composed of a micromachined Si/glass perforated plate heat exchanger and a micromachined piezoelectric valve for gas expansion. Both the heat exchanger and the microvalve demonstrated high robustness, and can sustain inlet gas pressure up to 1MPa.

The basic J-T system using a 0.015 in. orifice can achieve 76.1 K drop below inlet temperature at a 0.269 g/s ethane mass flow rate, when the applied pressure difference is 835.8 kPa and the HP inlet pressure is 1 MPa. During the experiment, the system is cooled to a lower temperature of 200.3 K in a transient state. However, the temperature increases due to impurity freezing inside the system. A cold trap can be installed to the inlet of the J-T system in order to eliminate this problem in the future. The system can provide a high cooling power up to 1 W at 239 K, in addition to a parasitic heat load of 300-500 mW.

The modulated J-T system using the micromachined piezoelectric valve can achieve 254.5 K at a pressure difference of 430 kPa. The temperature modulation of this system is limited to 5-8 K at a given pressure primarily due to the large leakage across the microvalve at high input gas pressures, when the input voltage of the valve is 100 V. Further improvement of the microvalve at high pressures and low temperatures will permit this modulation system to effectively control the temperature over a wider range. However, these experiments of the modulated J-T system indicate that the steady-state temperature at the cold end is very stable and demonstrate the feasibility of using a cryogenic microvalve to control temperature in a J-T system. In the long term, the microvalve and the heat exchanger can be integrated together; a fully micromachined Si/glass flow-modulated J-T cooler will serve a wide range of biomedical or space applications that demand miniature cryocoolers with high cooling power.

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