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Sensitivity of micromachined Joule-Thomson cooler to clogging due to moisture

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Abstract

A major issue in long-term operation of micromachined Joule-Thomson coolers is the clogging of the microchannels and/or the restriction due to the deposition of water molecules present in the working fluid. In this study, we present the performance of a microcooler operated with nitrogen gas with different moisture levels. Relatively low-purity nitrogen gas (5.0) is supplied from a gas bottle and led through a filter to control the moisture level. The filter consists of a tube-in-tube counter flow heat exchanger (CFHX) and a heat exchanger that is stabilized at a certain temperature by using a Stirling cooler. The set-point temperature determines the moisture level at the exit of the heat exchanger. It is found that the moisture level has influence on the mass-flow rate during the cool down. Once the microcooler reaches the set cold-end temperature, the main deposition area shifts into the CFHX and the moisture level at the restriction is almost independent on the inlet moisture level of the microcooler. The moisture level at the restriction increases with the increasing cold-end temperature when the cold-end temperature is lower than the saturation temperature of the water in the nitrogen gas. Higher cold-end temperature results in higher clogging rate.

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Keywords: Joule–Thomson cooler; Microcooler; Clogging

1. Introduction

Micromachined Joule-Thomson (JT) coolers have received increasing interest in applications which benefit from cryogenic temperatures, but only require the cooling power in the levels ranging from a few milliwatts to hundreds of milliwatts (Radebaugh, 2009). Such applications include detectors in space missions (Derking, 2012), low-noise

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amplifiers (Cao, 2013a) and high-temperature superconducting devices (Cao, 2013b). The long-term performance of JT microcoolers is limited by the clogging caused by the deposition of impurities in the working fluid (Little, 1984; Lerou, 2007; Zhu, 2010). In a previous study, the mechanism of clogging is investigated through experimental observation and theoretical analysis by using a microcooler operating with nitrogen gas (Cao, 2013c). It is found that the position and the rate of the deposition of water molecules in the microcooler mainly depend on the inlet partial pressure of water and the temperature profile along the microcooler. By using a getter filter (Saes, 2011), most impurities (especially water) from nitrogen gas are removed to a minimum value of about 1.0 parts per billion (ppb). In this study, the getter filter is replaced with a cryo-filter, which can control the moisture of the nitrogen gas at different levels by regulating the temperature of the cryo-filter. The effect of different moisture levels on the performance of a microcooler operating between 110 and 130 K is discussed.

2. Measurement setup

The schematic of the experimental setup for characterizing the microcooler is shown in Fig. 1. Nitrogen gas (purity level 5.0) is supplied from a pressurized gas bottle. The gas flows through a pressure controller that regulates the high pressure. After that, the nitrogen gas flows to a cryo-filter. The nitrogen gas in the cryo-filter passes through a tube-in-tube counter flow heat exchanger (CFHX) and a heat exchanger (HX). Tubes of the CFHX are made of stainless steel with a length of 0.5 m and inner/outer diameters of 0.88/1.59 mm and 1.78/3.20 mm. The HX, a stainless steel tube with a length of 1.0 m and the same inner/outer diameters as the inner tube of the CFHX, is twisted around a copper block that is cooled by a Stirling cooler. The temperature of this block is set by controlling the input power to the Stirling cooler. A fine adjustment of the temperature is established by a heater on the block. The cold gas returns to the CFHX, warms up to room temperature and then enters the microcooler. The microcooler is mounted in a glass vacuum chamber. At the low-pressure side, the pressure of the gas is measured with a pressure meter, and the outflow is measured with a mass-flow meter. A pressure relief valve is used at the outlet to maintain constant outlet pressure and also to prevent air from flowing into the system. The dashed lines in Fig. 1 indicate tubes that are used to pump and flush the system.

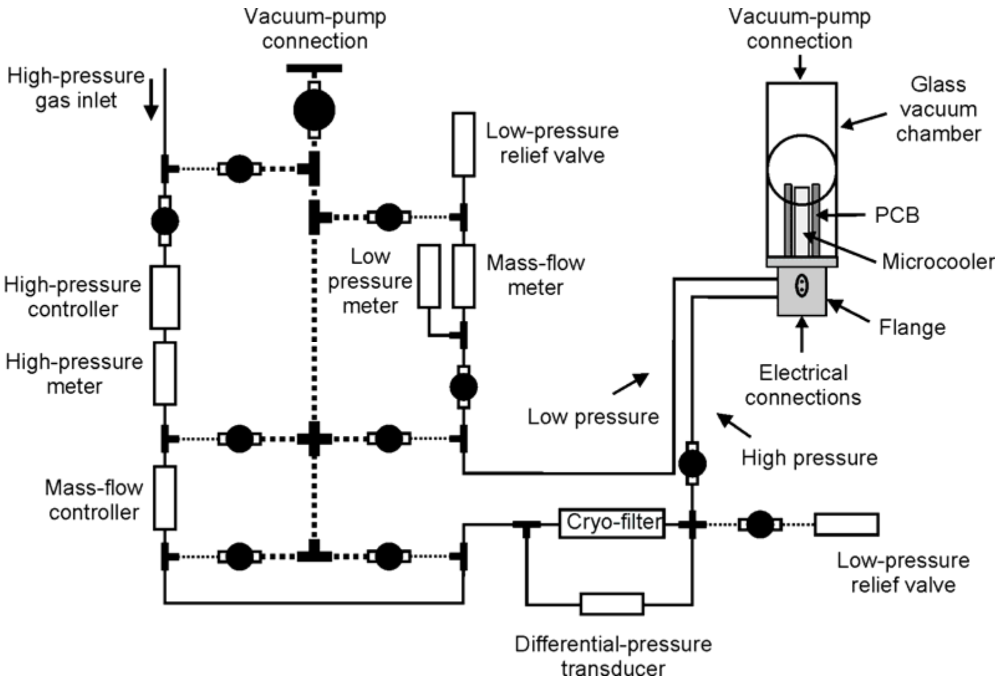

Fig. 1. Schematic of the clogging measurement set-up.

The microcooler used in the measurements and its cross section are shown in Fig. 2. The cold stage has outer dimensions of 60.0 × 10.0 × 0.7 mm^3. The height of the gas channels in the CFHX is 40 µm. The restriction of the microcooler consists of 7 parallel rectangular slits with a length of 2.8 mm, a width 0.14 mm and height 1.1 µm. A small piece of silicon is glued to on the cold end of the microcooler, covering the whole restriction area to provide a uniform temperature along the restriction. The temperature at the cold end is measured by a Pt 1000 sensor. A surface mounted device resistor used as a heater for supplying heat to the microcooler in order to measure the cooling power. The temperature sensor and heater are glued on the silicon piece with conducting silver paint and connected to the PCB using bond wires made of 99% aluminum and 1% silicon with a diameter of 25 µm.

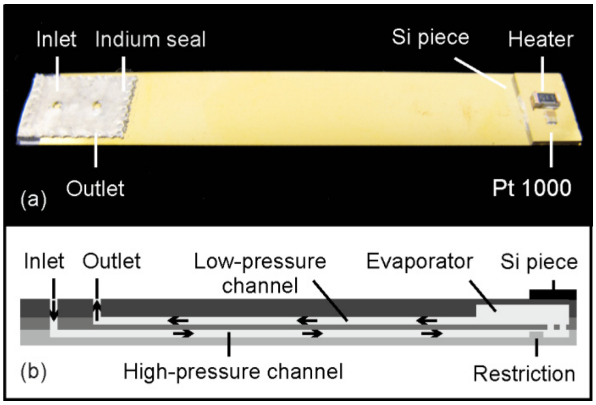

Fig. 2. Photograph (a) and cross-section (b) of the microcooler under test.

3. Results

3.1. Influence of moisture level in nitrogen gas

During the experiments, the cryo-filter cools down to the set-point temperature after preliminary cleaning by pumping the gas line. Then, the nitrogen gas is introduced into the cryo-filter and the microcooler with a high pressure of 8.7 MPa and a low pressure of 0.6 MPa. It is important that the moisture level in the nitrogen gas after the cryo-filter is not increased by any remaining water in the gas line connecting the cryo-filter to the microcooler. To prevent this, clogging experiments of the microcooler under the same conditions will be repeated until the mass-flow rate at any cold-end temperature during cool down does not change with time.

Fig. 3 shows the temperature and mass-flow rate of the microcooler when the cryo-filter temperatures are controlled at 150 and 180 K, respectively. During the cool down, the mass-flow rate increases with the decreasing cold-end temperate due to the temperature dependent gas properties (density and viscosity). The mass-flow rate at 110 K decreases with time is caused by the clogging. Compared to the initial mass-flow rate at 110 K with cryo-filter temperature of 150 K, the initial mass-flow rate at 110 K with cryo-filter temperature of 180 K is smaller. That is because the ice forms in the restriction once the temperature of the restriction is lower than the saturation temperature of the water in the nitrogen gas. Higher moisture level implies that the water molecules deposit in the restriction at higher temperature, resulting in more ice in the restriction, less mass-flow rate. The moisture levels at different cryo-filter temperatures are measured by controlling the cold-end of the microcooler at different temperatures. As shown in Fig. 4a, the mass-flow rate does not decrease as long as the cold-end is controlled at temperatures above 179 K when the cryo-filter is controlled at 150 K. Since the saturation pressure of water at 179 K is at 4.4 mPa (see Fig. 4b), we can estimate the molar fraction of water in the nitrogen gas passing through the microcooler to be about 0.5 ppb . By using the same method, the molar fraction of water in the nitrogen gas passing through the microcooler is measured with a value of about 5.6 ppb when the cryo-filter is controlled at 180 K.

Once the restriction reaches 110 K, the main deposition area shifts into the CFHX and the moisture level at the restriction is almost independent on the initial moisture level. That explains the reduction rate of mass-flow rate at

110 K is not determined by the initial moisture level of the nitrogen gas. The difference in the reduction rate of mass-flow rate at 110 K is due to the different initial mass-flow rates at 110 K. Higher mass-flow rate means that more water molecules deposit in the restriction, resulting larger reduction rate of mass-flow rate as show in Fig. 3b. The difference in the operating time at 110 K of the two measurements is caused by the different radiation losses of the mcirocooler. This will be further explained in details in the section 3.2.

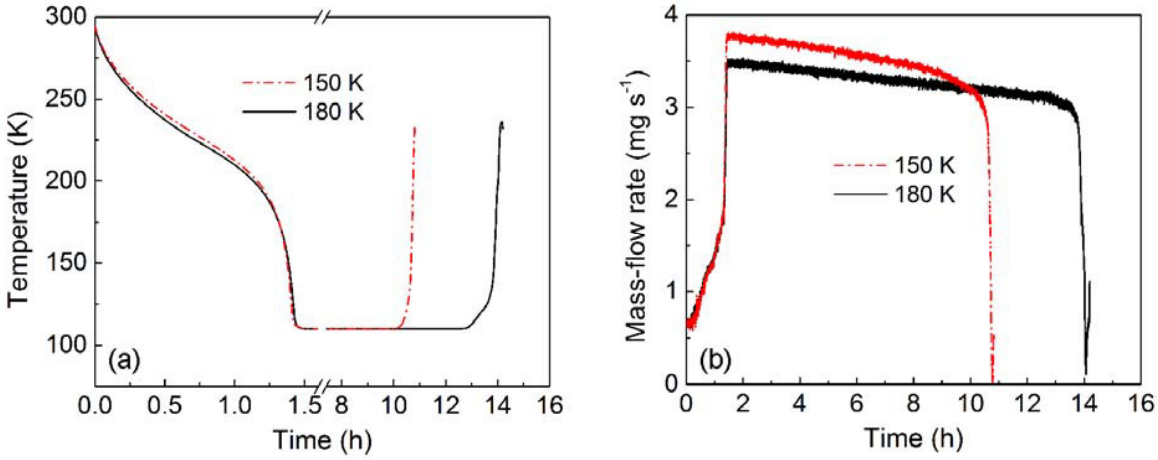

Fig. 3. Cold-end emperature (a) and mass-flow rate (b) of the microcooler versus time with cryo-filter temperatures of 150 and 180 K, respectively. The glass vacuum pressures of the measurements with cryo-filter temperatures of 150 and 180 K are 0.025 and 0.020 Pa, respectively.

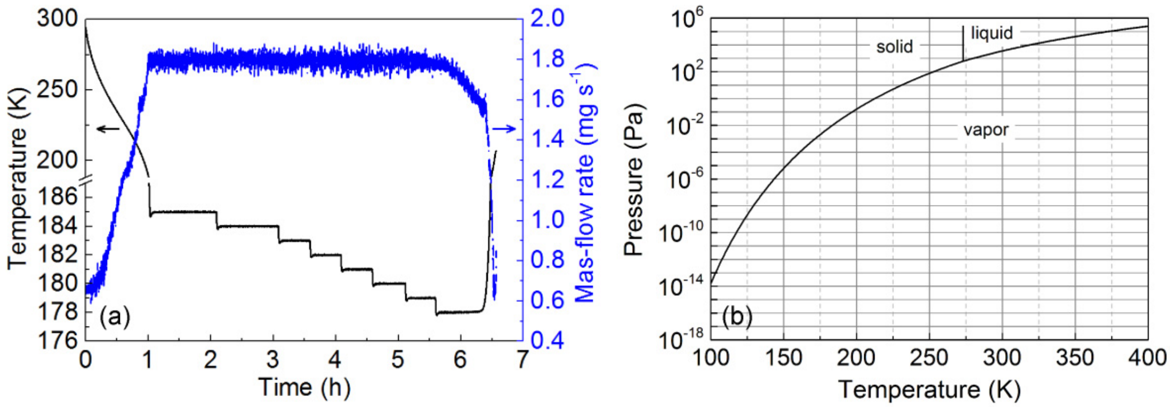

Fig. 4. (a) Cold-end temperature and mass-flow rate of the microcooler versus time with a cryo-filter temperature of 150 K. (b) Phase diagram of water (Lemmon).

3.2. Influence of cold-end temperature of microcooler

The Fig. 5a shows the mass-flow rates of the microcooler with different cold-end temperatures when the cryo-filter temperature is controlled at 150 K. With the cold-end reaching the set-point temperatures (110, 120 and 130 K), the mass-flow rate starts to decrease due to the clogging until the microcooler has no net cooling power left and subsequently the warming up of the microcooler. For the linear decrease phase, the reduction rate in mass-flow rate increases with the cold-end temperate increasing from 110 to 130 K. Based on the discussion in section 3.1, we know that the main deposition area is in the CFHX when the cold-end temperate is less than 179 K. The moisture level at the restriction is dependent on the restriction temperature, which increases with the restriction temperature approaching 179 K. That explains why the clogging rate increases with the cold-end temperature increasing from 110 to 130 K.

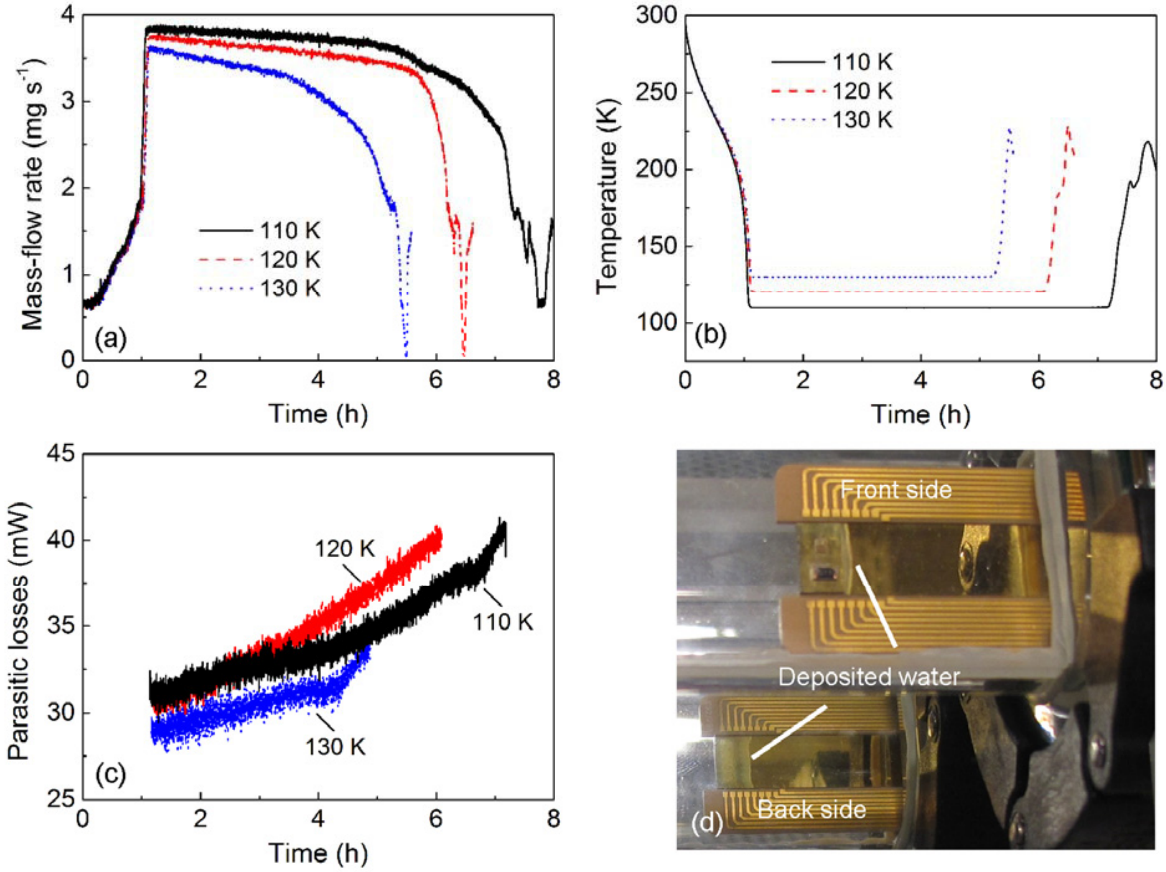

Fig. 5. Mass-flow rate (a), cold-end temperature (b), and parasitic losses (c) of the microcooler versus time at different cold-end temperatures. Photograph of the deposited water molecules (white spot) on the surface of the front and back side of the microcooler (d). The microcooler is operated with a high pressure of 8.7 MPa and a low pressure of 0.6 MPa. The cryo-filter temperature is controlled at 150 K. The glass vacuum pressure of the three measurements is 0.006 Pa.

The rapid decrease in the mass-flow rate is caused by the change in temperature profile and the relation between the ice height and the mass-flow rate. Fig. 5c shows parasitic losses of the microcooler when the cold-end temperatures keep constant at set point temperatures. The parasitic loss is the difference between the gross cooling power and the measured net cooling power. The gross cooling power is the product of the measured mass-flow rate and the enthalpy difference of the high- and low-pressure nitrogen gas, which is 16.6 kJ/kg when the microcooler is operated between 0.6 and 8.7 MPa. The parasitic loss at each set point temperature increases with time, which is caused by the increasing radiation loss between the microcooler and the surrounding gas. The radiation loss is a function of the emissivity of the microcooler surface and the temperatures of the chamber and the microcooler. The microcooler under test is covered with a thin gold layer with the emissivity of about 0.02. The radiation loss increases with the increasing amount of the water molecules that deposit on the outside surface of the microcooler (see Fig. 5d). The radiation loss causes high restriction temperature and high moisture level at the restriction, resulting in high clogging rate The microcooler can keep 110 K for about 10 hours in the measurement described in Fig. 3 when the cryo-filter is controlled at 150 K. Under the same operating pressures, the microcooler can only keep 110 K for about 7 hours in the measurement described in Fig. 5. The difference is caused by different radiation loss. On the other hand, the mass-flow rate through the restriction is inversely proportional to the restriction length for viscous laminar flow in the restriction driven by certain pressure difference. If the opening of the restriction becomes locally too small, the restriction works as an orifice with choked flow, and the mass-flow rate is independent on the restriction length. Compared to the laminar flow, the choked flow has a higher mass-flow rate with the same opening of the restriction.

4. Conclusions

The performance of a microcooler for a long-term operation is investigated. Moisture has influence on a microcooler in two ways: moisture in the nitrogen gas and moisture in the vacuum. The microcooler is operated with nitrogen gas with different moisture levels. During the cool down, a high moisture level results in a low mass-flow rate. Once the microcooler reaches the set cold-end temperature, most of the water molecules deposit in the CFHX and the moisture level at the restriction is almost independent on the inlet moisture level of the microcooler. A high cold-end temperature implies a high the moisture level at the restriction, which results in a high reduction rate of the mass-flow rate. Moreover, the long-term operation of the microcooer is also determined by the moisture level in vacuum chamber. Water molecules in the vacuum chamber deposit the outer surface of the microcooler, resulting in high emissivity of the microcooler and high radiation loss. The radiation loss reduces the time that the microcooler can keep at a certain cold-end temperature. Besides, the radiation loss causes the increase in the temperature along the restriction, which leads to the increase in the clogging rate and the reduction in the operating time. To increase the operation time of a microcooler at a certain temperature, both the moisture level of the nitrogen gas and the vacuum environment should be reduced as low as possible. In addition, trapping most of the water molecules in the CFHX by decreasing the temperature along the restriction is beneficial to extend the operation time of the microcooler.

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