Joule-Thomson microcooling developments at University of Twente

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Abstract. The development of Joule-Thomson microcoolers has been an on-going and successful research project at the University of Twente for many years. The aim of the research is to develop small and fully integrated cryogenic cooling systems for cooling small electronic devices such as pre-amplifiers and infrared sensors, in order to improve their performance. In the foregoing years, we have successfully developed single-stage microcoolers (typically cooling to 100 K) and two-stage microcoolers (typically 30 K) using standard micromachining technologies. In the present paper, we emphatically discuss recent developments in the Twente microcooling project among which microcoolers with a double expansion of the high pressure flow (reducing the 100 K to 83 K operating temperature), microcoolers operating with hydrocarbon gas mixtures, and microcoolers with an ejector, the three new developments aiming at lower cold end temperatures, lower operating pressure ratios and/or higher efficiency. Besides, utilization of microcoolers for cooling electronics and clogging phenomenon in microcoolers will also be introduced.

1. Introduction

Following the development of microelectromechanical systems technology, many electronic devices are being reduced in size. For many electronic devices, colder is better. At lower temperatures, electronic devices such as infrared detectors [1] and low-noise amplifiers (LNAs) [2] operate with a lower signal-to-noise ratio and better overall performance than they do at room temperature. Superconducting devices such as SQUIDs [3] need cryogenic temperatures to operate. But in order to make cryogenic electronics more widespread, micro-sized cryogenic coolers need to become cheaper and more reliable.

Joule-Thomson (JT) cryocoolers are suitable for miniaturization because they have no cold moving parts and therefore can be scaled down to match the sizes and power consumptions of devices to be cooled. Several studies on the miniaturization of JT cryocoolers deal with the optimization of the counterflow heat exchangers (CFHX) and the various techniques for manufacturing the cold stage [4–11]. Micromachining technology [12] has been identified as one of the most promising technologies in this respect because of its high fabrication accuracy and possibility of batch processing.
Pioneering work on the miniaturization of JT cryocoolers was done by Little et al. in the 1980s [5, 13]. They fabricated cryocoolers out of glass wafers using an abrasive etching process. The abrasive etching process is a relatively inaccurate and low resolution process when compared to the chemical etching technique which will be discussed in section 2. The smallest cryocooler produced by Little et al. consisted of four glass wafers and had dimensions of 15.0 x 2.0 x 0.5 mm$^3$. The cryocooler had a cooling power of 25 mW at 101 K when operated with nitrogen at a high pressure of 165 bar. Besides, Little presented a seven-wafer stack two-stage JT cryocooler but the details of the design were not reported [14]. He affirmed that seven-wafer stack two-stage cryocoolers were much more difficult to fabricate with acceptable yields and good efficiency than his earlier single-stage cryocoolers built from a four-wafer stack [15]. Crucially different from the work of Little, all microcoolers presented in section 2 consist of a stack of three glass wafers, single-stage as well as two-stage coolers. At the University of Twente, the miniaturization of JT cryocoolers was investigated since 1995. The development of cryocoolers include the development in fabrication technology and thermodynamic modeling. Fabrication technology went through three stages, namely, handmade, semi-micromachined, and fully-micromachined. Holland et al. [8] presented two handmade coolers with glass tube heat exchangers. In both coolers a tube-in-tube CFHX was used, one with a length of 270 mm, the other 105 mm. The tubes were made of fused silica glass with inner/outer diameters of 0.1/0.36 mm and 0.53/0.67 mm, respectively. The restrictions of the coolers can be tuned at the room temperature side of the cooler. Operated with nitrogen gas between 0.1 and 10.0 MPa, the lowest temperature of 82 K can be obtained by both coolers with different mass-flow rates. Burger et al. [16] explored the possibility to fabricate JT cooler parts by means of micromachining technology. They realized a semi-micromachined cooler, of which flow splitter, condenser and restriction/evaporator were micromachined, whereas the heat exchangers still were glass tubes. All the three micromachined parts were glued together with tube-in-tube CFHXs to form a whole cooler. They combined the semi-micromachined cooler with a sorption compressor and in that way produced a closed-cycle cooling system. With a precooling temperature of 238 K, the cooling system could reach a stable temperature of 169 K with a cooling power of about 200 mW when the system was operated with ethylene between 0.1 and 2.0 MPa. In follow-up projects, micromachining technology was further explored and fully-micromachined coolers based on different cooling cycles were designed through modeling and realized by using micromachining technology only. The fully-micromachined coolers will be described in detail in section 2. Section 3 discusses the utilization of these microcoolers. The clogging phenomenon in these microcoolers will be discussed in section 4.

2. Fully-micromachined coolers

2.1. Single-stage cooler

The fully-micromachined single-stage cooler developed at University of Twente consisted of a stack of three glass wafers as shown in figure 1a. Borosilicate glass D263T is chosen as the fabrication material. Considering pressure requirements, mechanical properties of the glass, and manufacturability, the thicknesses of the top wafer, middle wafer and bottom wafer are chosen as 400, 145 and 175 µm, respectively. The high and low-pressure lines (rectangular channels) are etched in separate glass wafers with supporting pillars for keeping the maximum stress within acceptable limits. These gas channels are separated by a middle glass wafer, thus constituting a CFHX. One end of the CFHX contains inlet and outlet ports for gas connections and the other end consists of a restriction and an evaporator. The single-stage cooler (see figure 1b) was fabricated using standard micromachining technology. The slits in the restrictions were buffered hydrofluoric acid (HF) etched, and the gas channels in the CFHX were HF etched. The evaporator slits and feedthroughs were powder blasted. Next, the three wafers were fusion bonded to one stack. Separate microcoolers were obtained by a combination of dicing and
powder blasting through the stack with a suitable mask. This approach allows the fabrication of many such microcoolers at low cost. The last step was to deposit a 0.2 µm layer of gold on the microcooler to increase the reflectivity of the surface. The bonding and powder blasting processes were the critical steps that currently mainly determine the production yield.

Operated with nitrogen gas between 0.6 and 8.0 MPa, a cold end temperature of 100 K was obtained with cooling powers in the range of 10-130 mW, depending on the size of the restriction and the cooler [11, 17]. When the single-stage coolers were operated with methane gas at a low pressure of 0.4 MPa, a cold end temperature of 140 K can be obtained. The cooling powers were in the range of 28-110 mW, depending on the high pressure, the size of the restriction and the cooler [17].

2.2. Two-stage cooler
The JT expansion process generates cooling only if the initial temperature, prior to expansion, is below the maximum inversion temperature of the working fluid. As a rule of thumb the maximum inversion temperature is about 10 times the normal boiling point of the working fluid. Thus the expansion of gases such as nitrogen, methane and ethylene at ambient temperature will generate cooling but hydrogen, neon, and helium will not. In order to reach temperatures near the boiling points of the latter three gases, a precooling stage is required to precool these gases from ambient temperature to a temperature below their respective maximum inversion temperature.

We have analyzed hydrogen and neon gas for reaching 30 K in theory and hydrogen has the best performance. The working fluid for the precooling stage is also optimized, resulting in nitrogen gas as the best choice. The pre-cooler, which is a heat exchanger thermally connecting the nitrogen and the hydrogen stages is an important component and careful design is crucial because the size and required mass-flow rate of the nitrogen stage is determined by the pre-cooler thermal performance [18].

The geometry of the two-stage microcooler is shown in figure 2a. For each stage, the high and low-pressure lines were etched in the middle and bottom wafers. In each stage, the high-pressure line ends in a flow restriction, which is extended to the evaporator volume and connected to the low-pressure line. Thus, a CFHX is formed by the high and low-pressure channels and the thin intermediate glass wafer. In order to increase the heat transfer between pre-cooler and the first evaporator, they are integrated into a compact design with a relatively large heat-transfer area. Here, the low-pressure fluid of the first stage, after expansion, absorbs heat from the high-pressure fluid of the second stage [19].
Figure 2. Two-stage microcooler geometry. (a) Exploded view of the two-stage microcooler. (b) Photograph of the two-stage microcooler.

Similar to the single-stage microcooler development, the two-stage microcooler (as shown in figure 2b) was fabricated using micromachining technology only. When the microcooler was operated with nitrogen gas between 0.1 and 8.5 MPa in the first stage and hydrogen gas between 0.1 and 7.0 MPa in the second, the two stages cool down to about 94 and 30 K, respectively. In changing the pressure settings, the cooling power can more or less be exchanged between the two stages. These typically range from 21 to 84 mW at 95 K at the nitrogen stage, corresponding to 30 to 5 mW at 31-32 K at the hydrogen stage [20].

2.3. Cooler with double expansion
The cold-end temperature of a JT cooler is determined by the boiling temperature of the working fluid in the evaporator, which depends on the pressure in the evaporator. This pressure is determined by the outlet pressure of the low-pressure channel and the pressure drop along that channel. With a fixed outlet pressure, a lower cold-end temperature can be realized by decreasing that pressure drop in the low-pressure channel. This can be established by a decrease in the

Figure 3. Schematic of the Linde-Hampson cooling cycle with double JT expansion and the corresponding gas cycle drawn in the temperature-entropy diagram.
mass-flow rate, a decrease in the length of the CFHX channel or an increase in the hydraulic diameter of the CFHX channel. However, the gross cooling power of a JT-cooler is reduced when the mass-flow rate is decreased. And a smaller channel length or a larger hydraulic diameter will both lower the heat exchanger efficiency, which increases the thermal conduction through the material from the warm to the cold end and thus will reduce the net cooling power.

A double-expansion cycle in a JT cooler is an ingenious way to reach a lower temperature without a loss in the gross cooling power of the cooler. In this method, the reduction of the pressure drop is realized by diminishing the mass-flow rate in the low-pressure channel, and the reduction in the gross cooling power due to the decreasing mass-flow rate is compensated by lowering the temperature of the high-pressure gas. A schematic of the JT cooler with double expansion is shown in figure 3. It consists of two CFHXs and two restrictions. The high-pressure gas after passing CFHX I is split into two gas streams. In one gas stream, most of the gas flows through the first restriction (R I) to the low-pressure channel of CFHX I (2→3→8). Due to the pressure drop in the low-pressure channel, the gas does not follow the isobaric line (3→8'). The second gas stream flows to CFHX II and then to the second restriction (R II) (2→4→5). Because the mass-flow rate through the second restriction is small, the pressure drop along the low-pressure channel connected to the second restriction is relatively small. Therefore, this small amount of gas nearly follows the isobaric line (6→8) and thus a lower cold-end temperature can be obtained.

A microcooler with double expansion was realized by micromachining technology as shown in figure 4. The outer dimensions of the microcooler design with a double expansion are 60.0 x 9.5 x 0.72 mm$^3$. The microcooler was operated with nitrogen gas at a high pressure of 8.0 MPa and a low pressure of 0.1 MPa. The microcooler cooled down from 295 to 83 K in 12 minutes and had a cooling power of 88 mW at 85 K.

2.4. Cooler with gas mixtures
Compared to pure gas, mixed gases provide equivalent cooling power with significantly lower pressure ratio and mass-flow rate. This simplifies the development of a compressor for closed-cycle operation of a JT cooler. We intend to investigate a gas mixture JT cooler that can cool down to 150 K starting with an ambient temperature range from 250 to 350 K. Three gas mixtures were optimized separately for three set ambient temperatures of 250, 300, and 350 K. Each gas mixture consisted of three components and the composition of each mixture was optimized by maximizing the COP of the cold stage with a cold end temperature of 150 K, operating pressures between 0.1 and 1.0 MPa. The properties of the mixtures were obtained from the SUPERTRAPP computer code developed at NIST [21]. It was found that one of the
three mixtures (composed of methane, ethane and neopentane) had the highest COP over the temperature range from 150 to about 300 K. To investigate the feasibility of the mixture at warm-end temperature up to 350 K, the COP of a hybrid system was analyzed. The hybrid system was composed of a JT cold stage operated with the mixture and a thermoelectric cooler. The thermoelectric cooler cools the incoming mixture from the respective warm ambient temperature to 300 K. The COP of the hybrid system had the highest COP over the temperature range from 300 to 343 K. Therefore, the mixture can be used as the working fluid of the cold stage in the entire temperature range. The performance of the mixture was tested by using a microcooler. Operated with the mixture between 0.2 and 0.9 MPa, the microcooler under test cooled down from 295 to 130 K in about 20 min with a precooling temperature of 283 K.

2.5. Cooler with an ejector

The performance of a JT cooler can be improved through the optimization of the working fluid, the operating pressures, the JT restriction and the CFHX. Besides these parameters, the performance can be improved by replacing the JT restriction with a work-producing device, changing the isenthalpic expansion to an isentropic one. This change will reduce the enthalpy of the working fluid entering the evaporator and produce work to reduce the required power of the compressor. The work-producing device could be a reciprocating, rotary, or turbine expander, but such devices have moving parts, resulting in vibration. Due to the moving parts, these devices are prone to damage by low quality two-phase flow.

We propose to introduce an ejector, as a work-producing device, into the Linde-Hampson cycle to improve the performance of a cryocooler. The working process of the Linde-Hampson cycle with an additional ejector is shown in figure 5. In the cycle, the high-pressure gas flows through the CFHX I, then is split into two streams (at point 2), one flowing through CFHX II for the isenthalpic expansion through the restriction (point 3 to 4) and the other flowing through the ejector. Inside the ejector, the high-pressure gas (the primary fluid) expands through a nozzle to create low pressure, and then mixes with the secondary fluid from the CFHX II (at point 6) in the mixing section. The mixed gas recovers a pressure in the diffuser section and flows to the

![Figure 5. The schematic of Linde-Hampson cycle with an ejector and corresponding temperature versus entropy diagram.](image-url)
CFHX I at the medium pressure (at point 7), rather than the low pressure of the evaporator. The process of the ejector is depicted roughly by the blue dotted lines in the temperature versus entropy diagram shown in figure 5. The discussion on the efficiency improvement realized by the ejector has been described in another study [22].

We are currently analyzing the incorporation of an ejector in the Linde-Hampson cycle to reach a temperature of 70 K. Nitrogen gas was selected as the working fluid and the corresponding saturation pressure at 70 K is 0.035 MPa. The outlet and inlet pressures of the compressor were selected as 8.0 and 0.1 MPa. It was further assumed that the pressure drop in the CHFX was negligible. Based on the energy conservation analysis, the entrainment ratio of the ejector, defined as the ratio between the secondary and the primary mass flow rates, increases as the temperature of point 7 increases from 100 to 295 K (see figure 6). This suggests that it is better to place the ejector at a relatively low temperature because a lower entrainment ratio is easier to realize under the assumption that the performance of the ejector is not related with temperature. However, at low temperatures there will be condensation droplets in the ejector, and the influence of these droplets on the performance of the ejector is under study. The position of the ejector also depends on the performance of the ejector at certain operating conditions, which is the core of the design.

3. Utilization of microcoolers for cooling electronics

The application potential of the microcooler coupled with electronic devices has been demonstrated by cooling an yttrium barium copper oxide film through its superconducting phase transition by using a 30 K two-stage microcooler [19]. This work demonstrates the application potential of the microcooler for integration with electronic devices, such as infrared detectors, LNA's and superconducting sensors. The utilization of the microcooler in cooling a LNA was investigated by using a 115 K single-stage microcooler [23]. The performance of an antenna system can be improved by cooling the LNA stage in order to reduce the noise figure. By cooling the LNA from 295 to 115 K, the average noise figure decreases from 0.83 to 0.50 dB, corresponding to a reduction in the average noise temperature of the LNA from 61 to 35 K. The telescope sensitivity is proportional to the ratio of the active area to the noise temperature of the entire receiver. This implies that the active area of a telescope with certain sensitivity can be reduced about 43% by using JT microcooling.

Figure 6. Entrainment ratio as a function of temperature of point 7 shown in figure 5.
4. Clogging phenomenon in microcoolers
The miniaturization of JT cryocoolers results in various interesting challenges. An important aspect of these microcoolers is the deposition of small amounts of water vapour. Ice crystals form and at some moment may clog the coolers. The mechanism of clogging was investigated through experimental observation and theoretical analysis by using a microcooler operating with nitrogen gas [24]. It was 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. During cool-down, ice crystals were depositing in the JT restriction area and these reduced the mass-flow rate. Once the microcooler reached the set cold-end temperature, the main deposition area shifted into the CFHX and the deposition rate at the restriction was almost independent on the inlet moisture level of the microcooler [25]. Two measures were proposed and verified experimentally to reduce the clogging rate: firstly, to decrease the water fraction in the supply gas using a getter filter and secondly, to shift the location of the major deposition of water molecules from the restriction to the CFHX by changing the temperature profile along the microcooler [24, 25].

5. Conclusions
Joule Thomson microcooling developments at University of Twente were introduced, which include microcoolers based on different cooling cycles, utilization of microcoolers for cooling electronics and mechanism of clogging in microcoolers. Microcoolers are challenging with respect to their thermodynamic modeling as well as their realization. The realization of microcoolers historically went through three stages, namely, handmade, semi-micromachined, and fully-micromachined. Fully-micromachined coolers based on different cooling cycles were introduced including: single-stage cooler, two-stage cooler, cooler with double expansion, cooler with gas mixtures and cooler with an ejector. The single-stage cooler is based on the Linde-Hampson cooling cycle. A two-stage microcooler is designed and realized to reach temperatures near the boiling points of gases with maximum inversion temperatures below ambient temperature. Compared to a single-stage cooler, coolers with double expansion, coolers with gas mixtures and coolers with an ejector have lower cold end temperatures, operating pressure ratios and/or higher efficiency. The utilization of microcoolers in cooling LNAs was investigated and the average noise figure decreases due to cooling, which implies that the sensitivity of a telescope can be increased or the active area of a telescope with certain sensitivity can be reduced by using microcooling. The mechanism of clogging was explained and two measures to reduce the clogging rate were discussed.

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