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Characterization of a thermoelectric/Joule–Thomson hybrid microcooler

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ABSTRACT

Micromachined Joule–Thomson (JT) coolers are attractive for cooling small electronic devices. However, microcoolers operated with pure gases, such as nitrogen gas require high pressures of about 9 MPa to achieve reasonable cooling powers. Such high pressures severely add complexity to the development of compressors. To overcome this disadvantage, we combined a JT microcooler with a thermoelectric (TE) pre-cooler to deliver an equivalent cooling power with a lower pressure or, alternatively, a higher cooling power when operating with the same pressure. This hybrid microcooler was operated with nitrogen gas as the working fluid at a low pressure of 0.6 MPa. The cooling power of the microcooler at 101 K operating with a fixed high pressure of 8.8 MPa increased from 21 to 60 mW when the precooling temperature was reduced by the thermoelectric cooler from 295 to 250 K. These tests were simulated using a dynamic numerical model and the accuracy of the model was verified through the comparison between experimental and simulation results. Based on the model, we found the high pressure of the microcooler can be reduced from 8.8 to 5.5 MPa by lowering the precooling temperature from 295 to 250 K. Moreover, the effect of TE cooler position on the performance of the hybrid microcooler was evaluated through simulation analysis.

1. Introduction

Many electronic devices can benefit from operation at lower temperatures, which results in lower thermal noise [1,2], higher speed [3], larger bandwidth [4], or even superconductivity [5,6]. Micromachined Joule–Thomson (JT) coolers are attractive for cooling these electronics, because they have no moving cold parts and, therefore, can be scaled down to match the size and power consumption of these electronics. JT microcoolers produce cooling power by the expansion of a high-pressure gas through a flow restriction. This cooling power can be increased by pre-cooling the incoming high-pressure gas by the cold low-pressure gas in a counter flow heat exchanger (CFHX). The temperatures of the low- and high-pressure gas flows will approach closest at some location, referred to as the pinch-point. The maximum possible cooling capacity per unit of mass flow is the minimum isothermal enthalpy difference (Δh_{min}) between the low- and high-pressure gas flows over the temperature range spanned by the CFHX. For pure gases, Δh_{min} usually occurs at the warm end of the heat exchanger. The isothermal enthalpy difference increases with increasing high pressure and with decreasing warm-end temperature. Usually, a high pressure is needed to achieve sufficient refrigeration, which adds complexity to the development of a compressor for the closed-cycle operation of a JT cooler.

In order to deliver an equivalent cooling power with modest high pressures, the high-pressure gas can be pre-cooled at the warm-end entrance of the CFHX. Precooling can be realized by using thermoelectric (TE) coolers. TE coolers are semiconductor devices that can directly convert electricity into cooling power at an interface [7]. TE coolers offer similar advantages as JT coolers, such as compact structure, free of moving parts, high reliability and spot cooling. Compared to TE coolers, JT coolers can reach lower temperatures with higher efficiencies [8–10]. Lester [11] investigated the possibility of increasing the efficiency of a closed cycle JT cooler by using a TE cooler. Precooling by a TE cooler at 240 K was employed in a closed cycle JT microcooling configuration by Burger et al. [12] and Lin et al. [13]. Burger et al. developed a 169 K microcooler with a cooling power of 200 mW when it was operated with ethylene gas between 0.2 and 1.5 MPa. Lin et al. realized a 140 K JT microcooler operating with a five-component mixture between 0.07 and 1.4 MPa. An open JT system for cooling an infrared detector array was investigated by Bailey [14]. The run time of the system was extended by using TE precooling. This paper describes a hybrid microcooler that combines a 100 K JT cooler with a TE cooler to increase the cooling power or reduce

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the high pressure of the JT cooler. In the next section, the performance improvement of a JT cooler through TE precooling is analyzed based on the assumption of ideal operation of CHFXs and pre-cooler. The measurement set-up is described in Section 3 and the simulation of the performance of the hybrid microcooler is explained in Section 4. Section 5 discusses the measurement and simulation of the performance of the hybrid microcooler. The paper is closed with conclusions in Section 6.

2. Analysis

The schematic of a JT microcooler with a pre-cooler and the corresponding thermodynamic cycles drawn in a temperature-entropy plot are shown in Fig. 1. The cooling capacity (gross cooling power of the hybrid microcooler) $\dot{Q}_{load}$ is defined by:

$$\dot{Q}_{load} = (h_6 - h_5)\dot{m} = \Delta h_{6,5}\dot{m} \tag{1}$$

Here, h is specific enthalpy, and $\dot{m}$ is the mass-flow rate.

If there is no heat flow from the environment to the CFHX and assuming the JT expansion to be isenthalpic, then $\Delta h_{6,5} = \Delta h_{7,3}$. Extending the energy balance to the total CFHX, we can write:

$$\Delta h_{6,5}\dot{m} = \Delta h_{8,1}\dot{m} + \dot{Q}_{pre} \tag{2}$$

where $\dot{Q}_{pre}$ is the precooling power.

To analyze the efficiency of this hybrid microcooler, its coefficient of performance (COP) in the steady state is derived. Furthermore, it is assumed that there are no parasitics and all cooling energy of the TE cooler is used for precooling the high-pressure gas of the JT microcooler. The COP of the hybrid microcooler is defined as the ratio of the gross cooling power of the JT microcooler and the sum of the electric power, W_{TE}, supplied to the TE cooler and the change in Gibbs free energy of the working fluid of the JT microcooler during compression, as follows:

$$\mathrm{COP} = \frac{\Delta h_{6,5}\dot{m}}{W_{TE} + (\Delta h_{1,8} - T_h \Delta s_{1,8})\dot{m}} \tag{3}$$

where T_h is the ambient temperature.

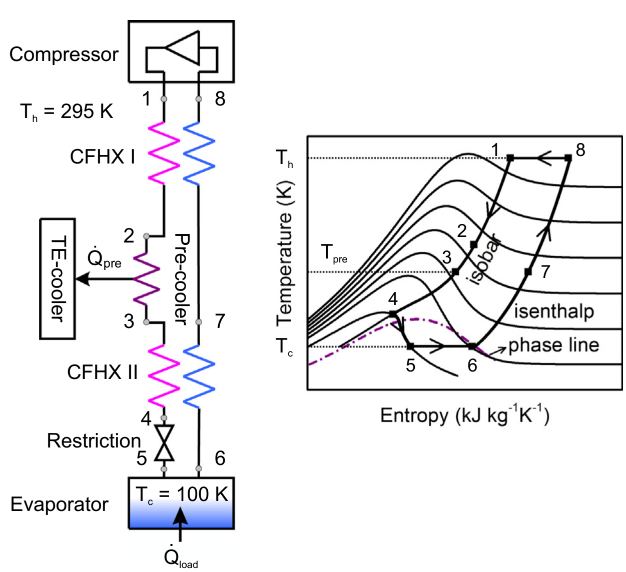

Fig. 1. A schematic of the Linde–Hampson cycle of a JT microcooler with a TE pre-cooler and a temperature-entropy diagram representing the thermodynamic ideal cycles of the hybrid microcooler.

The COP of the TE cooler is defined as the ratio of the gross cooling power of the TE cooler, used as precooling power, $\dot{Q}_{pre}$, to the electric power input to the TE cooler:

$$\mathrm{COP}_{TE} = \frac{\dot{Q}_{pre}}{W_{TE}} \tag{4}$$

The steady-state energy balance of the pre-cooler gives:

$$\dot{Q}_{pre} = \Delta h_{2,3}\dot{m} \tag{5}$$

Substituting Eqs. (2), (4) and (5) into Eq. (3) results in:

$$\mathrm{COP} = \frac{\Delta h_{8,1} + \Delta h_{2,3}}{\Delta h_{2,3}/\mathrm{COP}_{TE} + (\Delta h_{8,1} - T_h \Delta s_{8,1})} \tag{6}$$

The overall COP of a multi-stage TE cooler, is a function of the COP of each stage. We consider an n-stage TE cooler with the COP of each stage to be equal and denoted by COP^*_{TE}. Then, the overall COP_{TE} is [15],

$$\mathrm{COP}_{TE} = \left(\left(1 + 1/\mathrm{COP}^*_{TE}\right)^n - 1 \right)^{-1} \tag{7}$$

The COP of each stage of the n-stage TE cooler is given by an approximate expression [15]:

$$\mathrm{COP}^*_{TE} = n\left(\mathrm{COP}^S_{TE} + 0.5\right) - 0.5 \tag{8}$$

Here, it has been assumed that the temperature of each stage is equal to $(T^h_{TE} - T^c_{TE})/n$, where T^c_{TE} and T^h_{TE} are the cold- and warm-side temperatures of the TE cooler. Then COP^S_{TE} is given by [15,16]:

$$\mathrm{COP}^S_{TE} = \frac{T^c_{TE}\left((1+ZT)^{0.5} - T^h_{TE}/T^c_{TE}\right)}{\left(T^h_{TE} - T^c_{TE}\right)\left((1+ZT)^{0.5} + 1\right)} \tag{9}$$

where $ZT = S^2\sigma/\kappa$ is the figure-of-merit of the TE cooler, S, σ, κ and T are the Seebeck coefficient, the electrical conductivity, the thermal conductivity and the absolute temperature, respectively [17].

The hybrid microcooler discussed in this paper uses a two-stage TE cooler. Therefore, the COP of a two-stage TE cooler will be analyzed. Fig. 2a shows the COP of a two-stage TE cooler with the warm side at 295 K as a function of the cold-side temperature for several figures-of-merit. The COP increases with an increasing figure-of-merit at a fixed cold-side temperature and approaches the Carnot-cycle efficiency for an infinite ZT. The efficiency of the TE cooler for a constant figure-of-merit rapidly decreases with increasing temperature difference between the warm and cold side.

The relation between the COP of the hybrid microcooler and the precooling temperature is shown in Fig. 2b. The working fluid of the JT microcooler is nitrogen gas, and the high and low pressures of the nitrogen gas are 8.8 and 0.6 MPa, respectively. The COP of the hybrid microcooler increases with increasing figure-of-merit of the TE-cooler for a constant precooling temperature. At a constant figure-of-merit a lower precooling temperature is beneficial but at too low temperatures the COP decreases due to the decreasing COP of the TE cooler. Commercially available TE materials [16] have a figure-of-merit, ZT, of about 1. According to Fig. 2b the optimal precooling temperature with ZT equal to 1 is about 230 K and the corresponding COP is about 0.1.

Fig. 3a shows the gross cooling power of the hybrid microcooler per unit of mass-flow rate of nitrogen gas (kg s^{-1}) as a function of the precooling temperature for several high pressures. Here, the low pressure of the JT microcooler is set to a constant value of 0.6 MPa. This specific gross cooling power of the hybrid microcooler increases with increasing high pressure and decreasing precooling temperature. The specific gross cooling power of the hybrid