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Optimum design of infrared detector's micro-cooler with entropy generation minimization

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HIGHLIGHTS

- Optimization of Joule-Thomson micro coolers (as one of the important micro cooling cycle in many industrial and non-industrial devices) based on minimization of irreversibility.
- The considerable cooling system is divided into some layer, include of the hot gas layer, cold gas layer, the buffer layer, top layer and the upper layer and each layer divided into some cell.
- The energy balance (include of convective heat transfer and enthalpy flow) was applied to each cell and the set of governed equations was solved with the suitable method.
- The comparison of the current study with experimental results, show the very good accuracy of performing modelling.
- The irreversibility analysis and evaluation of the total entropy generation rate were evaluated.

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ABSTRACT

In this paper, an optimization of Joule-Thomson micro coolers, used in the infrared detector is performed based on minimization of irreversibility. These types of coolers have various applications in many industrial and non-industrial devices. One of the major applications of these coolers is the micro cooling system in infrared detectors. In this paper, the considerable cooling system is divided into some layer, include of the hot gas layer, cold gas layer, the buffer layer, top layer and upper layer and each layer divided into some cell. Then the energy balance (include of convective heat transfer and enthalpy flow) was applied to each cell and set of governed equations was solved with the suitable method. The comparison of the current study with experimental results shows the good accuracy of performing modeling. In the next section, irreversibility analysis was performed and the total entropy generation rate was evaluated. In the last section, optimization of the considered system is performed for minimizing of entropy generation and volume.

1. Introduction

Cryogenic micro coolers are used in many electronic devices, such as optical detectors, low-noise amplifiers, and superconducting devices, because these devices need low temperature for thermal noise reduction. Most of the infrared detectors use Joule-Thomson cycle as a cooling cycle because these coolers do not contain any moving parts and thus are suitable for the micro scale cooling system. According to the important application of micro coolers, many types of research are performed on this subject. Analysis of the Hampson-type Joule-Thomson (J-T) cooler is performed by Maytal in 1994 [1]. In this study, the effect of heat and mass transfer between working fluid, tube and other part were not considered. Transient numeric and experimental analysis of the Hampson-type Joule-Thomson (J-T) cooler are performed by Chou et al. [2–4]. In numeric modeling of considered cooler, 1-D numerical simulation of momentum and energy transport equations are performed and effect of secondary flow; torsion effect was not considered. Primarily development of the self-regulating Hampson-type Joule-Thomson (J-T) cooler by control mechanism is performed by Chien et al. (1996) [2,4]. In this paper, Chien used transient simulation similar to Chou's simulation. Fabrication of 10 mW JT cold stage cooler was performed by Lerou [5–7]. In this project, the cold stages were made by MEMS technology. The effect of using multi-component working fluid in JT cycle was investigated by Little [8,9] for the first time. This idea successfully employed by Marquardt et al. [10] for small cryo coolers used in

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Nomenclature

A	heat transfer area [m^2]	P_{ch}	perimeter of channel [m]
A_{cross}	cross-sectional area [m^2]	$\dot{Q}$	heat flow [W]
AR	aspect ratio [–]	Q_{Cond}	conductive heat flow [W]
C	geometric constant [–]	Q_{conv}	convective heat flow [W]
c_p	specific heat capacity [J kg^{-1} K^{-1}]	Re	Reynolds number [–]
D_h	hydraulic diameter [m]	S_{gen}	entropy generation [J K^{-1} s^{-1}]
f	friction factor [–]	T	temperature [K]
H	enthalpy [J]	$\bar{T}_h$	fluid mean temperature [K]
$\dot{H}$	transfer of enthalpy flow [W]	T_c	wall temperature [K]
H_{ch}	height of fluid channel [mm]	ΔT	temperature difference between two fluid [K]
k	thermal conductivity of a fluid [W m^{-1} K^{1}]	dT	temperature difference between two point of one fluid [K]
L	length of fluid channel [mm]	v	fluid velocity [m s^{-1}]
l	length [m]	v_m	mean fluid velocity [m s^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]	ρ	density [kg m^3]
Nu	Nusselt number [–]	μ_{JT}	Joule-Thomson coefficient [K Pa^{-1}]
P	pressure [Pa]	WC	width of the CFHX [mm]
P_h	pressure at high pressure side [kPa]	W	width of fluid channel [mm]
P_c	pressure at low pressure [kPa]		
ΔP	pressure drop [Pa]		

sensors and medical applications. In another research, Little [11] check the capability of the J-T cooler to provide cooling power in CMOS, NMOS and other electronics. A comprehensive research on the effect of various compositions of mixed coolants on the performance of cryo cooler systems were examined by Longsworth [12], Boiarsky [13] and Alexeev [14] The effect of Flammable and non-flammable gas mixture was discussed in the patents of Kahtri [15], Boiarski [16] Maytal et al. [17] optimized a gas mixture up to 30 MPa pressure. Their analysis showed that it is possible to find a mixture of nitrogen and hydrocarbons with the higher enthalpy difference than argon, but with a boiling point close to nitrogen. Sobel [18] presented a new mixture of argon and neon for open-cycle cryo cooling system for reaching a temperature below 80 K with non-flammable working fluid. Ng et al. [19] and Xue et al. [20] present the experimental and numerical simulation of Joule-Thompson cycle in the steady-state condition. In this study, argon gas used as the working fluid. Chien et al. [21] and Chou et al. [22] performed the one-dimensional transient numerical simulation of the Joule-Thompson cooler with nitrogen working fluid. Hong et al. [23] evaluated characteristics of a Joule-Thompson cryo cooler with E-NTU method. Ardhapurkar and Atrey [24] introduce the new correction factor to calculate the heat transfer area on the cold side of J-T cryo cooler. Fredrickson [25] has modeled the Joule-Thomson cryo cooler that used in the cryosurgical probe. Topkar and Atrey [26] present new steady-state numerical simulation of the heat exchanger in the Joule- Thomson cryo cooler. In this model, prediction of the pressure and temperature distribution in high-pressure and low-pressure streams along the length of the cooler was performed. For this purpose, the steady-state model of the heat exchanger for Joule-Thompson cryocooler is used and the effects of various parameters of the heat exchanger are studied. Hong et al. [27] used an E-NTU method to predict the thermodynamic characteristics of the heat exchanger in the Joule-Thomson refrigerator. The steady-state performance simulation of J-T cooler's heat exchanger was performed by Hong et al. [28] with argon and nitrogen working fluid. Hong et al. [29] examine the J-T cooler with the gas pressure up to 12 MPa with the suitable experimental study.

In the current paper, the Joule-Thomson micro coolers, used in infrared detectors, are analyzed based on the first and second law of thermodynamic. For this purpose, the considered cooling system is divided into some layer; include the hot and cold gas layers, the buffer layer, top layer and the upper layer. Each layer divided into some cell and the energy balance (include of convective heat transfer and enthalpy flow) was applied to each cell. The set of governing equations was solved with suitable methods and temperature distribution in micro cooler is specified. The comparison of the current study with experimental results shows good accuracy of the numerical model. Then, the total entropy generation in micro cooler is evaluated using suitable analytical correlations. In the last section, multi-objective optimization of J-T system is performed and optimum micro cooler's geometry is obtained by minimizing two important functions: entropy generation and volume.

2. Description of problem

2.1. System definition

The cryogenics systems are usually used for extremely low-temperature production (below 120 K) in infrared detectors. The required cooling heat loads in these systems can be produced based on various thermodynamic cycles. The Linde-Hampson cooling cycle (with Joule-Thomson expansion) is one of the major cooling cycles that used in micro cooler systems. The schematic view of the J-T cooling cycle is shown in Fig. 1. First, the working fluid is pressurized by a compressor1 in an isothermal process (point 1–2 in Fig. 1). Then the compressed working fluid flow through J-T cycle's main heat exchanger (counter flow heat exchanger). In this heat exchanger, the heat exchanges between high pressure working fluid (at point 2) and low-pressure fluid (point 5) are performed and high pressure working fluid cool down. Then the high-pressure cold working fluid enters to throttle valve, undergoes isenthalpic expansion to the low-pressure side and converts to the vapor-liquid mixture. In the evaporator, two-phase working fluid absorbs heat from surrounding and converts into vapor.

In J-T micro coolers, the isenthalpic expansion process has important effects on cooling system performance. In this process, change in working fluid's temperature can be evaluated by the Joule-Thomson coefficient. If this coefficient is positive, the gas cools and if negative, the gas heats up during the expansion.

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_h \quad (1)$$