

A Numerical Study on Operating Characteristics of a Miniature Joule-Thomson Refrigerator

Yong-Ju Hong^{1,*}, Seong-Je Park¹, and Young-Don Choi²

¹ Korea Institute of Machinery & Materials, Daejeon, 305-343, Korea

² Department of Mechanical Engineering, Korea University, Seoul, 136-701, Korea

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Abstract-- Miniature Joule-Thomson refrigerators have been widely used for rapid cooling of infrared detectors, optoelectronic device, and integrated circuits of micro electronics. The typical J-T refrigerator consists of the recuperative heat exchanger with the double helical tube and fin configuration, J-T nozzle, a mandrel, Dewar and a compressed gas storage bottle. In this study, to predict the thermodynamic behaviors of the refrigerator with a compressed gas storage bottle during the cool-down time, numerical study of transient characteristics for a J-T refrigerator was developed. A simplified transient one-dimensional model of the momentum and energy equations was simultaneously solved to consider the thermal interactions of the each component of the refrigerator. To account for effects of the thermal mass of the solid, the heat capacities of the tube, fins, mandrel and Dewar are considered. The results show the charged gas pressure of the gas storage bottle has significant effects on the performance of the J-T refrigerator. At the elevated gas pressure of the gas storage bottle, the large capacity of the compressed gas storage does not need to get the fast cool-down performance of the J-T refrigerator in the cool-down stage.

1. INTRODUCTION

Miniature Joule-Thomson (J-T) refrigerators, which are used in open-cycle mode, have been widely used for rapid cooling of many military applications because they have special characteristics of fast cool-down, constant operating temperature, operability over wide range of ambient conditions, simplicity of operation, portability, relative low price and etc..

The cooling of the J-T refrigerator is based on the J-T effect where the temperature of a gas decreases through an expansion to low pressure. To ensure the rapid cooling to the cryogenic temperature, the J-T effect could be amplified by using an expanded gas to cool incoming gas within a recuperative heat exchanger. The thermodynamic performance of the J-T refrigerator highly depends on the hydraulic and heat transfer characteristics of the recuperative heat exchanger.

The cooling system consists of the J-T refrigerator contained in Dewar. Typical open-cycle J-T refrigerator is composed of the counter flow heat exchanger, J-T nozzle,

a mandrel, a gas filter and a compressed gas storage bottle (reservoir). The heat exchanger has the double helical tube and fin or the matrix tube configuration. The cool-down time, the temperature at the cold end, the running time and the gas consumption are the important indicators of the performance of the J-T refrigerator.

Ng et al. [1] and Xue et al. [2] reported the experimental and numerical study of the J-T refrigerator for steady-state characteristics with the argon gas. Chua et al. [3] developed the geometry model of the Hampson-type cryocooler and the steady state governing equations were solved numerically. Hong et al. [4] predicted the steady state performance of the heat exchanger for the elevated pressure of the argon and nitrogen gas.

Hong et al. [5] reported the experimental study of J-T refrigerator with the gas pressure up to 12 MPa for the cool-down characteristics. Numerical studies of the J-T refrigerator for transient characteristics with one dimensional transient model were reported by Chou et al. [6], Chien et al. [7], and Hong et al. [8], but their works were only for a J-T refrigerator that does not contain effects of a compressed gas storage bottle.

In this study, a simplified one-dimensional model of momentum and energy transport for the J-T refrigerator was adopted to predict the transient thermodynamic behaviors of the J-T refrigerator with a compressed gas storage bottle during the cool-down time. In the analysis, to consider the thermal interactions of each component of the refrigerator, the momentum and energy equations for the high pressure gas, the low pressure gas, and a compressed gas storage, energy equation for the tube, fins, the Dewar, and the mandrel were simultaneously solved.

2. GOVERNING EQUATIONS

A schematic diagram of the J-T refrigerator with double helical tube and fins is shown in Fig. 1, which consists of the counter flow heat exchanger with the double helical tube and fin, J-T nozzle, a mandrel, Dewar and a compressed gas storage bottle. In this analysis, the flow control mechanism is not considered, because it is very difficult to determine the transient heat interaction between the low pressure gas and the flow control mechanism.

* Corresponding author: yjhong@kimm.re.kr

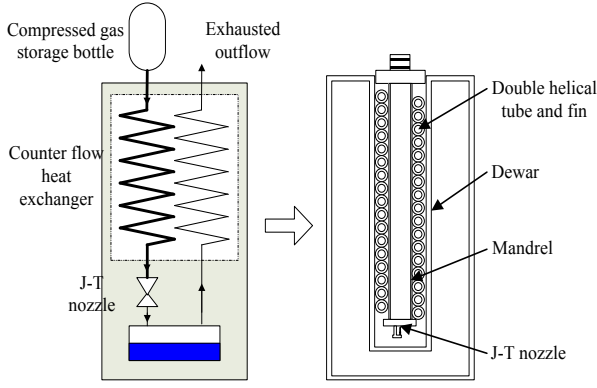


Fig. 1. Schematic diagram of the J-T refrigerator.

The high pressure gas from the compressed gas storage bottle flows inside the tube whilst the low pressure gas flows on the outside but in opposite direction. To simulate the heat and fluid flow in the J-T refrigerator, a one-dimensional heat and flow model is used for the compressed gas storage bottle, the flows inside and outside of the double helical tube and fin around the mandrel. To account for effects of the thermal mass of the solid, the heat capacities of the tube, fin, mandrel and Dewar are considered.

The governing equations for the conservation of mass, momentum, and energy for each part of the J-T refrigerator are discretized for finite volume method (FVM), coupled and solved numerically using the SIMPLE algorithm [9]. The thermodynamic properties of the gas from the REFPROP [10] were used to account for the real gas effects of the elevated pressure of the nitrogen gas. The governing equations for the compressed gas storage bottle, the high pressure gas, low pressure gas, the double helical tube and fin, mandrel, and the inner part of the Dewar are as follows:

- Compressed Gas in the Storage Bottle

The discharge process of the compressed gas storage bottle is assumed to be the isothermal process. The density of the gas in the storage (ρ) can be written as

$$\frac{\partial \rho}{\partial \tau} = -\frac{\dot{m}}{V} \quad (1)$$

Where \dot{m} denotes the mass flow rate of the gas, τ and V denote time and volume of the storage bottle, respectively.

- High Pressure Gas

The continuity, momentum and energy equation for the high pressure gas along the helical direction (ξ) of the tube can be written as

$$\frac{\partial \dot{m}}{\partial \xi} = 0 \quad (2)$$

$$\frac{\partial \rho u u}{\partial \xi} = -\frac{\partial P}{\partial \xi} - \frac{2f\rho u^2}{d_h} \quad (3)$$

$$\rho A_h \left[\frac{\partial C_p T_h}{\partial \tau} + u \frac{\partial C_p T_h}{\partial \xi} + \frac{\partial (u^2/2)}{\partial \xi} \right] = -h_h (\pi d) (T_h - T_t) \quad (4)$$

(1) where u is the velocity of gas; P is the pressure of gas; f is the fanning friction factor; d is the inner diameter of the passage; A is the cross-sectional area for the gas flow; C_p is the specific heat of the gas; T is the temperatures; h is the heat transfer coefficient; and subscript h and t denote the high pressure gas and tube. The fanning friction and heat transfer coefficient for the high pressure gas was calculated by the empirical equation suggested by Timmerhause and Flynn [11] for a helix tubular pipe.

- Low Pressure Gas

The continuity, momentum and energy equation for the low pressure gas along the longitudinal direction (x) of the refrigerator can be written as

$$\frac{\partial \dot{m}}{\partial x} = 0 \quad (5)$$

$$\frac{\partial \rho u u}{\partial x} = -\frac{\partial P}{\partial x} - \frac{2f\rho u^2}{d_l} \quad (6)$$

$$\rho A_l \left[\frac{\partial C_p T_l}{\partial \tau} + u \frac{\partial C_p T_l}{\partial x} + \frac{\partial (u^2/2)}{\partial x} \right] = -h_l A_{p,l} (T_l - T_t) - h_l A_{p,f} (T_l - T_f) \quad (7)$$

where A_p denote the peripheral area; d_l is the hydraulic diameter of the passage; and subscript l, f, m and d denote the low pressure gas, fin, mandrel and Dewar, respectively. The fanning friction for the low pressure gas was calculated by the empirical equation suggested by Timmerhause and Flynn [11], and the heat transfer coefficient was calculated by the empirical equation for a bank of in-line tubes [12].

- Double Helical Tube and Fin

The energy equations for the double helical tube (t) and fin (f) along the helical direction could be written as

$$m_t C_t \frac{\partial T_t}{\partial \tau} = k_t A_t \frac{\partial^2 T_t}{\partial \xi^2} + h_h A_{p,ht} (T_h - T_t) + h_l A_{p,lt} (T_l - T_t) + 2 \frac{k_f k_f}{k_f W_f + k_t t} W_f L_f (T_t - T_f) \quad (8)$$

$$m_f C_f \frac{\partial T_f}{\partial \tau} = k_f A_f \frac{\partial^2 T_f}{\partial \eta^2} + h_l A_{p,ft} (T_l - T_f) - 2 \frac{k_t k_f}{k_f W_f + k_t t} W_f L_f (T_t - T_f) \quad (9)$$

where m is mass; C is specific heat; k is the thermal conductivity; W is the width of the fin; t is the thickness of the fin; L is the length of the fin; and subscript ti and to denote the inner side and outer side.

- Mandrel

The mandrel is cooled by the low pressure gas along the outside surface and the inside surface is considered adiabatic. Therefore the energy equation along the axial direction can be written as

TABLE I
PARAMETERS OF THE SIMULATION.

Parameters		Value
Geometric dimensions	Diameter of helix	4.070 mm
	Inner diameter of tube	0.3 mm
	Outer diameter of tube	0.5 mm
	Pitch of tube	0.95 mm
	Number of turn of tube	42
	Height of fin	0.2 mm
	Pitch of fin	0.132 mm
	Thickness of fin	0.08 mm
	Number of fin per revolution of tube	55
	Simulation parameters	Case (I) : charged gas pressure of the storage bottle (volume of bottle : 200cm ³)
	Case (II) : capacity of the compressed gas storage bottle (charged gas pressure : 40MPa)	100, 200, 300, 400, 500 cm ³

$$m_m C_m \frac{\partial T_m}{\partial \tau} = k_m A_m \frac{\partial^2 T_m}{\partial x^2} + h_l A_{p,m} (T_l - T_m) \quad (10)$$

- Dewar

The Dewar is cooled by the low pressure gas along the inside surface and the outside surface has the radiation heat transfer. This is given by

$$m_d C_d \frac{\partial T_d}{\partial \tau} = k_d A_d \frac{\partial^2 T_d}{\partial x^2} + h_l A_{p,d} (T_l - T_d) + \frac{\sigma}{(1/\varepsilon_d + A_{amb}/A_{do}(1/\varepsilon_{amb} - 1))} (\pi d_{do}) (T_d^4 - T_{amb}^4) \quad (11)$$

where σ is Stefan-Boltzmann constant; ε is the emissivity and subscript *do* and *amb* denote the outer side of the Dewar and ambient.

- J-T nozzle

The mass flow rate and change of the enthalpy through the J-T nozzle can be written as

$$\dot{m} = C_d \sqrt{\gamma \rho_{nz} P_{nz}} A_{nz} \left[\frac{2}{\gamma} + 1 \right]^{(\gamma+1)/(2(\gamma-1))} \quad (12)$$

$$\dot{i}_{out} = \dot{i}_{in} \quad (13)$$

where C_d is the discharge coefficient of the nozzle; γ is the ratio of the heat capacity; i is enthalpy; and subscript *nz* denotes nozzle.

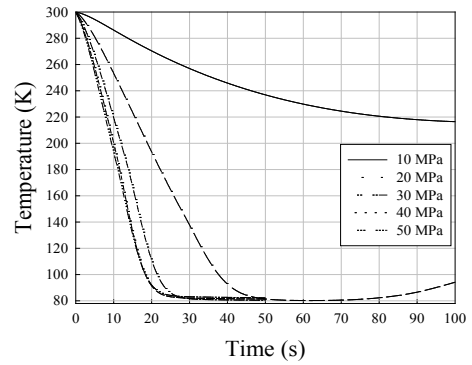
- Thermodynamic Properties of the Gas

The thermodynamic properties of the nitrogen gas are obtained from REFPROP which makes use of the Helmholtz energy equation. The viscosity and thermal conductivity are determined with the pure fluid model.

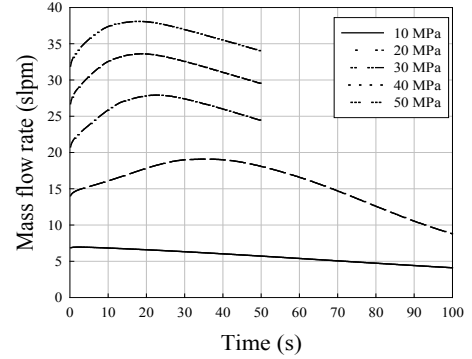
3. RESULTS AND DISCUSSION

Simulations were carried out for the constant capacity of the compressed gas storage bottle with 5 different charged pressures of the gas (Case I) and constant charged pressure of the gas with 5 different volumes of the bottle (Case II). The geometric dimensions and simulation parameter of the

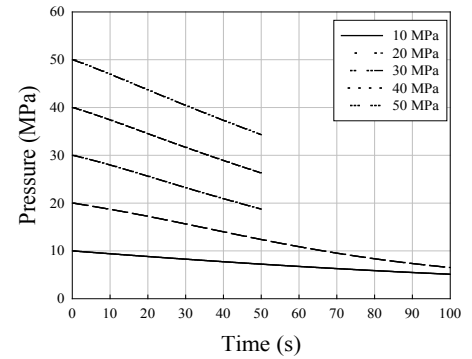
J-T refrigerator are delineated in the Table 1. To ensure that results are independent of the time step, in the simulation, the time step of 0.01 second was used [8]. The total physical times of the simulation are limited to 50 seconds for the charged gas pressure of 30, 40, 50 MPa and 200 seconds for the charged gas pressure of 10, 20 MPa, respectively. Fig. 2 shows transient variations of the temperature of the cold end of the Dewar, the mass flow rate of the nitrogen gas, and the pressure of the compressed gas storage bottle for case (I). The refrigerator with the constant supply gas pressure of 10 MPa reaches the steady state with the temperature of below 90 K [8], but the refrigerator with the charged gas pressure of 10 MPa does not reach to the temperature of below 90 K as shown in Fig. 2 (a). There exist no increase of the mass flow rate of the gas during cool-down stage and the mass flow rate does not depend on the temperature of the cold end.



(a) Temperature of the cold end



(b) Mass flow rate of the gas



(c) Pressure of the storage bottle

Fig. 2. Effects of the charged gas pressure of the gas storage bottle on the cool-down characteristics, Case (I).

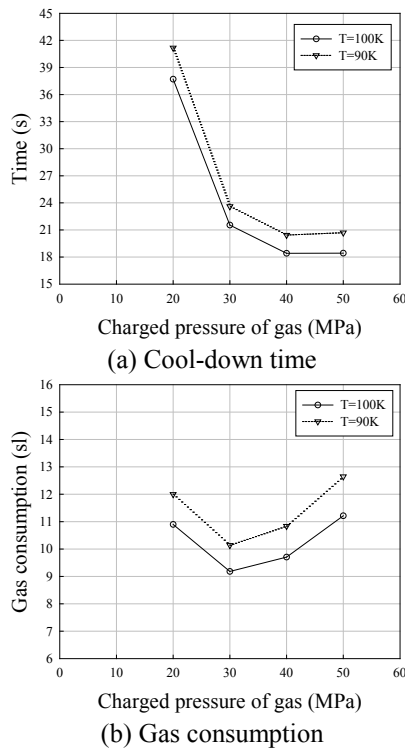


Fig. 3. Cool-down time and gas consumption for case (I).

Above the pressure of 10 MPa, the refrigerator reached the temperature of below 90 K. It is seen that as the charged gas pressure of the compressed gas storage bottle increases up to 40 MPa, the cool-down rate of the cold end of the Dewar increases. It is seen that as the temperature of the cold end decreases, the mass flow rate of the gas increases as shown in Fig. 2 (b). At the higher charged gas pressure of the compressed gas storage bottle, faster decreases of the pressure occur due to the larger mass flow rate as shown in Fig. 2 (c). The cooling capacity of the J-T refrigerator would increase the supply pressure increases, because the J-T refrigerator with higher supply pressure has the larger mass flow rate of the gas and the larger enthalpy difference between inlet and exhaust of the J-T refrigerator. Lowest temperatures do not reach to the temperature of the normal boiling point of the nitrogen due to the increase of the pressure at the exit of the J-T nozzle as shown in Fig. 2 (a). At the end of the operation, the decrease of the pressure of the gas storage bottle results in the decreases of the cooling capacity of the refrigerator, so the temperature of the cold end increases as shown in Fig. 2 (a).

Fig. 3 shows the cool-down time and the gas consumption of the J-T refrigerator until the temperature of the cold end reaches to the temperature of 100 K and 90 K. Up to the charged gas pressure of 40 MPa, the cool-down time decreases significantly. The cool-down time of the refrigerator with the pressure of 50 MPa increase more than that of the refrigerator with the supply pressure of 40 MPa as shown in Fig. 3 (a). It is obvious that the charged gas pressure of the gas storage bottle should be about 40 MPa

to achieve the fast cool-down of the J-T refrigerator. There exist lower limits of the pressure of the given gas storage bottle to get the cooling of the Dewar. When the refrigerator has the pressure of 40 MPa, the cool-down times are 18.4 second for the temperature of 100 K and 20.4 second for the temperature of 90 K, respectively. The refrigerator has the minimum of the gas consumption at the pressure of 30 MPa as shown in Fig. 3 (b). The gas consumption of the nitrogen decreases as the pressure increase up to the pressure of 30 MPa. At the high pressure of above 30 MPa, the gas consumption increases as the supply pressure increases. These results are similar to that of the J-T refrigerator with the constant supply pressure of the nitrogen [8]. The J-T refrigerator with the elevated pressure of the nitrogen has a large amount of the enthalpy difference and the mass flow rate, but the large mass flow rate through the heat exchanger results in the large ineffectiveness of the heat exchanger.

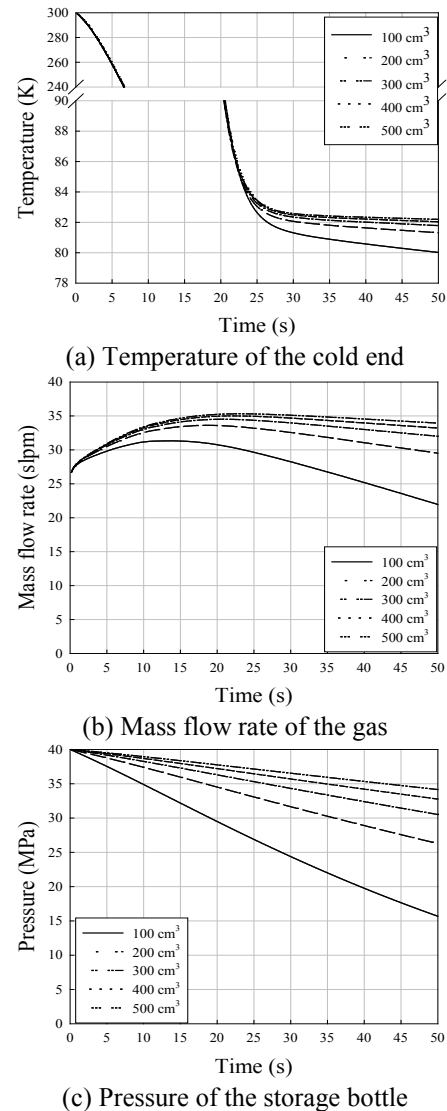


Fig. 4. Effects of the capacity of the gas storage bottle on the cool-down characteristics.

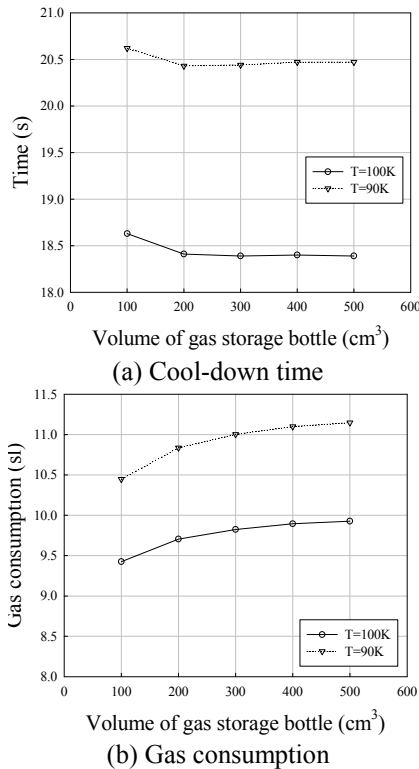


Fig. 5. Cool-down time and gas consumption for case (II).

These phenomena reduce the cooling capacity of the J-T refrigerator. So, at the pressure of above 40 MPa, the refrigerator has a large consumption of the gas during the cool-down stage. Finally, it is obvious that the charged gas pressure of the gas storage bottle has significant effects on the performance of the J-T refrigerator.

Fig. 4 shows transient variations of the temperature of the cold end of the Dewar, the mass flow rate of the gas, and the pressure of the gas in the storage bottle for case (II). At the elevated pressure, the capacity of the storage bottle has little effects on the initial cool-down rate of the J-T refrigerator as shown in Fig. 4 (a). The lowest temperature of the cold end decreases as the capacity of the bottle decreases. The maximum of the mass flow rate of the gas increases as the capacity of the bottle as increases as shown in Fig. 4 (b). After the cool-down stage, the mass flow rate of the gas is gradually reduced. The drop of the pressure of the bottle of 1,000 cm³ is smaller than those of the other capacity of bottle in spite of the large mass flow rate of gas as shown in Fig. 4 (c). The low pressure of the bottle results in the small mass flow rate. The small mass flow rate through the heat exchanger gives rise to the small pressure drop of the low pressure gas and the low pressure at the exit of the J-T nozzle. This tendency in the pressure drop forms the higher saturated temperature of the gas than the normal boiling point, and the gradual decrease of the temperature of the cold end after the cool-down stage.

Fig. 5 shows the cool-down time and the gas consumption of the J-T refrigerator until the temperature of the cold end reaches to the temperature of 100 K and 90 K.

Above the volume of 200 cm³, increase of the capacity of storage bottle give rise to the small increase of the gas consumption, but no reductions in the cool-down time. So, at the elevated pressure of the gas, it is obvious that the large capacity of the compressed gas storage does not need to get the fast cool-down performance of the J-T refrigerator in the cool-down stage.

4. CONCLUSIONS

In this study, simulations were performed to investigate effects of the compressed gas storage bottle on the performance of the J-T refrigerator. From the results, the followings can be concluded.

The charged gas pressure of the gas storage bottle should be about 40 MPa to achieve the fast cool-down of the J-T refrigerator. There exist lower limits of the pressure of the given gas storage bottle to get the cooling of the Dewar. The charged gas pressure of the gas storage bottle has significant effects on the performance of the J-T refrigerator. At the elevated gas pressure of the gas storage bottle, the large capacity of the compressed gas storage does not need to get the fast cool-down performance of the J-T refrigerator in the cool-down stage.

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