Influence of Ambient Temperature on Performance of a Joule-Thomson Refrigerator

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ABSTRACT

Miniature Joule-Thomson refrigerators consist of a counter flow heat exchanger with double helical tubes and fins, nozzles, a mandrel and a dewar. Typical performance factors for the Joule-Thomson refrigerator are cool-down time, cold end temperature, running time and gas consumption. The above performance factors depend on operating conditions such as the pressure of the gas, thermal environment and etc.

In this study, effects of the ambient temperature on the thermal performance of the Joule-Thomson refrigerator were investigated by numerical analyses. Effectiveness-NTU approach was adopted to predict the thermodynamic behaviors of the heat exchanger of the Joule-Thomson refrigerator. A one dimensional isentropic model was used to calculate the mass flow rate through the nozzle.

In the results, the Joule-Thomson refrigerator in the low ambient temperature has a large cooling capacity and mass flow rate for a regulated supply pressure of the gas. But, the low ambient temperature results in the decrease of the initial pressure of the gas in the vessel. The Joule-Thomson refrigerator, which is installed in the low ambient temperature condition, has a negative aspect in the pressure of the gas, but a positive aspect in the cooling effect. Hence, it has the cooling capacity for achieving fast cool-down.

INTRODUCTION

Miniature Joule-Thomson (J-T) refrigerators have been widely used for rapid cooling of infrared detectors, probes of cryosurgery, thermal cameras, missile homing head and guidance system, due to their special features of simple configuration, compact structure and rapid cool-down characteristics. Nitrogen (NBP 77.35 K) and argon gas (NBP 87.3 K) are typically used as cryogen due to their easy availability, low cost and ability to achieve a relatively low cryogenic temperature.

The J-T refrigerator consists of a counter flow heat exchanger with a double helical tube and fins, a nozzle, a mandrel and dewar as shown in Figure 1. The cooling power of the J-T refrigerator is generated by the isenthalpic expansion of the high pressure gas through the throttling process. The cooling effect can be amplified by using an expanded gas to cool incoming gas within a recuperative heat exchanger. Cool-down time, temperature at the cold end,
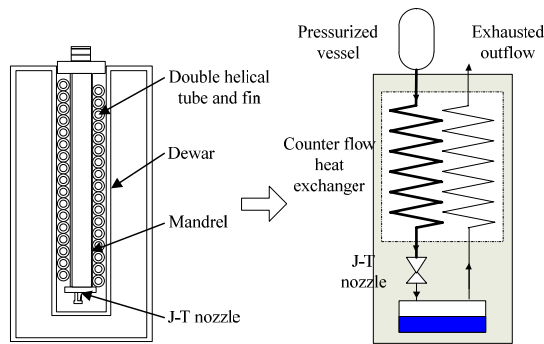
Figure 1. Schematic diagram of the J-T refrigerator

running time and gas consumption are the important indicators of the performance of the miniature J-T refrigerator.

The above performance factors depend on operating conditions such as the pressure of gas, thermal environment and etc. To cool from an initial temperature to a cryogenic temperature, the net refrigeration produced by the J-T refrigerator must meet or exceed the heat to be removed from the cold end components over the temperature range.

In order to insure fast cool-down, the design of the Dewar should minimize the thermal mass of the J-T refrigerator system[1]. The thermal mass depends on the initial temperature of the system. In the operation of the J-T refrigerator in the high ambient temperature, the J-T refrigerator should overcome a large thermal mass and heat load.

In general, the J-T refrigerator has a pressurized vessel in military applications. The change of the ambient temperature results in the initial pressure of the gas in the vessel, and effects of the gas pressure have significant effects on the performance of the J-T refrigerator.

Hong, et al.[2] reported the experimental study of the J-T refrigerator with the gas pressure up to 12 MPa. Experimental results show that the J-T refrigerator has a rapid cool-down rate at the cold ambient condition.

Chua, et. al.[3] developed the geometry model of the Hampson-type cryocooler with the argon gas and the steady state governing equations were solved numerically. Ng et al.[4] and Xue et al.[5] conducted the experimental and numerical study of the J-T refrigerator for steady-state characteristics with the argon gas. Hong, et. al.[6] adopted the effectiveness-NTU approach to predict the thermodynamic behaviors of the heat exchanger of the J-T refrigerator with different pressures and mass flow rate of the nitrogen and argon gas. The flow rate through the nozzle is relevant to the operation condition of the J-T refrigerator. Maytal[7] proposed an isentropic model to calculate the mass flux of the gas through a nozzle.

In this study, effects of the ambient temperature on the thermal performance of the Joule-Thomson refrigerator were investigated by numerical analysis.

ANALYSIS MODEL OF THE J-T REFRIGERATOR

The J-T refrigerator has a convectional double helical tube and fin configuration. The heat exchanger has two passages for high pressure gas and a common passage for low pressure gas. The outer diameter and the length of the heat exchanger are 9.5 mm and 24 mm, respectively.

Effectiveness-NTU approach[6] was adopted to predict the thermodynamic behaviors of the heat exchanger of the J-T refrigerator. A one dimensional isentropic model[7] was used to calculate the mass flux of the gas through the nozzle. Analyses were carried out for the argon gas with the gas pressure from 10 MPa to 60 MPa and the ambient temperature from -40°C to +60°C.
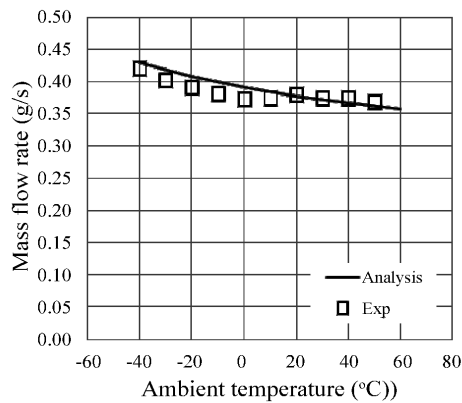
Figure 2. Comparison of the mass flow rate

In order to validate the analysis model, the mass flow rate of the argon gas from analysis was compared with that of the experiment[2]. The calculated mass flow rate follows the trend of experimental results as shown in Figure 2.

RESULTS AND DISCUSSION

In general military applications, the gas comes from a pressurized vessel. The change of the ambient temperature results in the initial pressure of the gas in the vessel. So the J-T refrigerator, which is installed in cold or hot ambient conditions, had variations in the cooling performance.

The cooling capacity of the J-T refrigerator is given by the product of the mass flow rate of the gas and the cooling effects (enthalpy difference between supply gas and exhaust gas of the refrigerator), and therefore increases of mass flow rate of the gas give rise to increases of the cooling capacity. In an ideal J-T refrigerator with the argon gas, the cooling effect increases as the supply pressure of the gas increases up to the pressure of 55 MPa. But, the larger mass flow rate of the gas causes the degradation of the effectiveness of the heat exchanger.

Figure 3 shows effects of the supply pressure of the gas on the performance of the J-T refrigerator. Analyses were carried out for the argon gas with a supply pressure of 10 MPa – 60
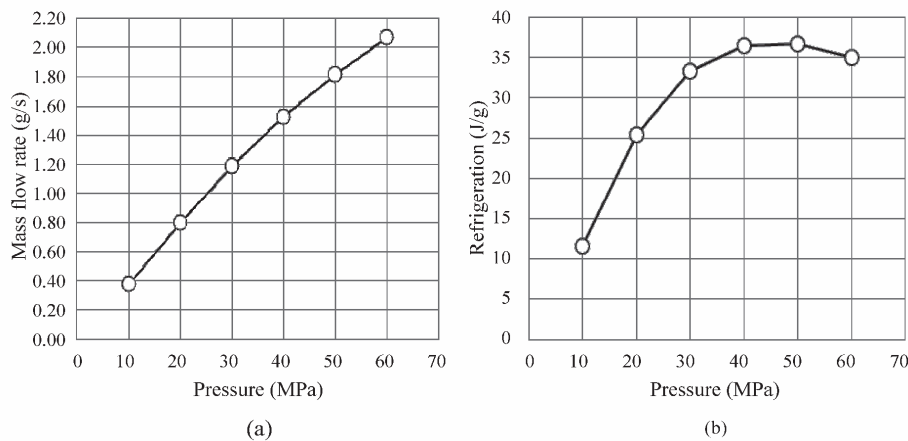

(a)   (b)

Figure 3. Effects of the pressure of the gas: (a) mass flow rate and (b) cooling effects

MPa and an ambient temperature of 20°C. Up to the supply pressure of 40 MPa, the J-T refrigerator with the gas high pressure has a high mass flow rate and a high cooling effects. Above a pressure of 40 MPa, the gas mass flow rate increases as the gas pressure increases, but the cooling effect does not increases. At the elevated pressure of the gas, the large mass flow rate comes from the pressure of the gas, and the increase of the cooling capacity mainly comes from the increase of the mass flow rate.

In the present study, to investigate effects of the ambient temperature on the performance of the J-T refrigerator, analysis was carried out previously for the constant supply pressure of the gas and the ambient temperature from -40°C to +60°C

Performance of the Refrigerator with a Regulated Pressure of the Gas

Figure 4 shows effects of the ambient temperature on the J-T refrigerator performance with a regulated supply pressure of argon gas. At a given gas supply pressure, as the ambient temperature increases, the gas mass flow rate and the cooling effect decrease, so the cooling capacity decreases rapidly.

At a high ambient temperature, the thermal mass of the Dewar and the J-T refrigerator would be increased. These phenomena will result in a slow cool-down characteristics of the J-T refrigerator at high ambient temperature.
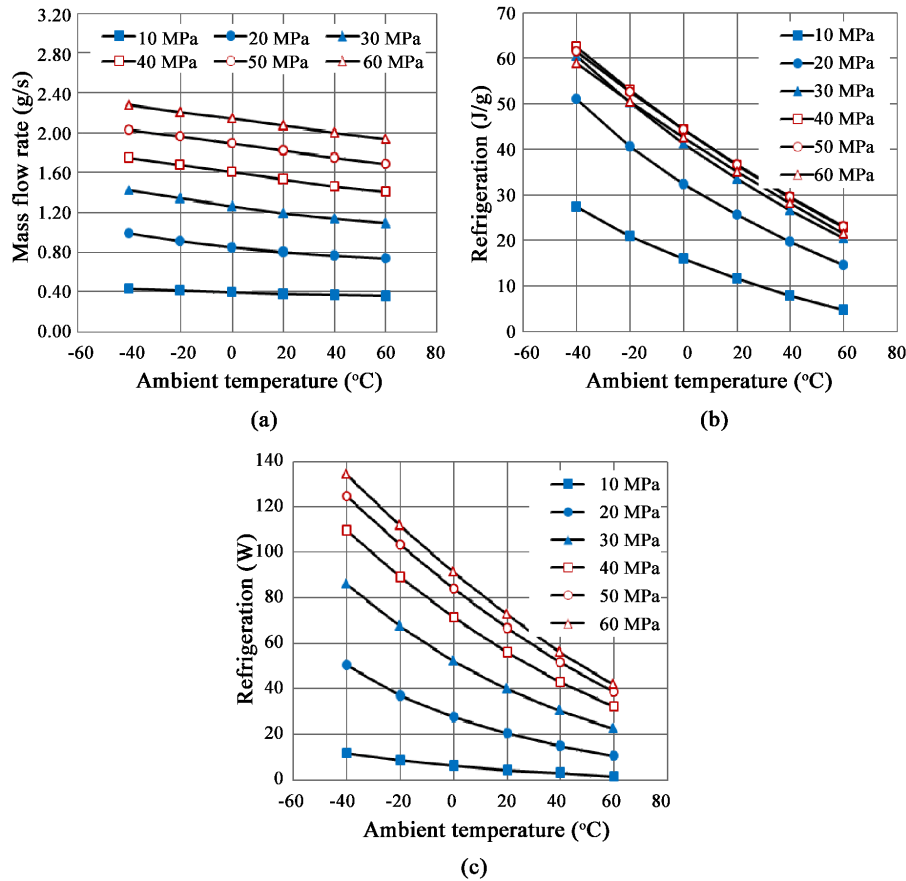

(a)

(b)

(c)

Figure 4. Effects of the ambient temperature for the regulated pressure of the gas: (a) mass flow rate, (b) cooling effects, and (c) cooling capacity

In the experiment[2], the cool-down period of the J-T refrigerator at the ambient temperature of +40°C is 5 - 6 times longer than that at the ambient temperature of -40°C. By estimation, the thermal mass of the Dewar and the J-T refrigerator at the ambient temperature of +40°C is raised by a factor of 1.6 times. So, during cool-down period, the cooling capacity of the J-T refrigerator at the ambient temperature of +40°C might be estimated 3 - 4 times lower than that at the ambient temperature of -40°C.

In present analysis, at the ambient temperature of -40°C, the J-T refrigerator with the gas pressure of 10 MPa has the cooling capacity of 11.7 W as shown in Figure 4. Otherwise the J-T refrigerator has the cooling capacity of 2.9 W at the ambient temperature of +40°C. These results show agreement with the experimental results.

Figure 5 shows the pressure-enthalpy diagram of the J-T refrigerator for different ambient temperatures. It is obvious that the J-T refrigerator in the cold ambient condition has a large cooling effect due to the outcome of the isenthalpic expansion from the low gas temperature at the inlet of the J-T nozzle. The increase of the mass flow rate mainly comes from the low temperature of the gas at the inlet of the J-T nozzle.

Performance of the Refrigerator with a Pressurized Vessel

In the cool-down period, the change of the ambient temperature results in a change in the gas supply pressure in the vessel. Figure 6 illustrates the calculated variation of the argon gas pressure with a change in the temperature. The gas pressure in a pressurized vessel increases as the ambient temperature increases. There is a two-fold increase in the pressure over the charging pressure range of 10 - 50 MPa.

Figure 7 shows the effect of the ambient temperature on the performance of the J-T refrigerator in a pressurized vessel. In the figure, pressure represents the gas charging pressure. By contrast to the case of the regulated pressure of the gas, the mass flow rate for the given pressure increases as the ambient temperature increases. These increases in the mass flow rate result from the pressure rise as shown in Figure 6. In the cold ambient condition, the J-T refrigerator has no great change in the aspect of the cooling effect by comparison with the case of the regulated pressure of the gas. But, at the pressure of 60 MPa and hot ambient condition, there is the rapid degradation in the cooling effect due to the decline in the performance of the heat exchanger.
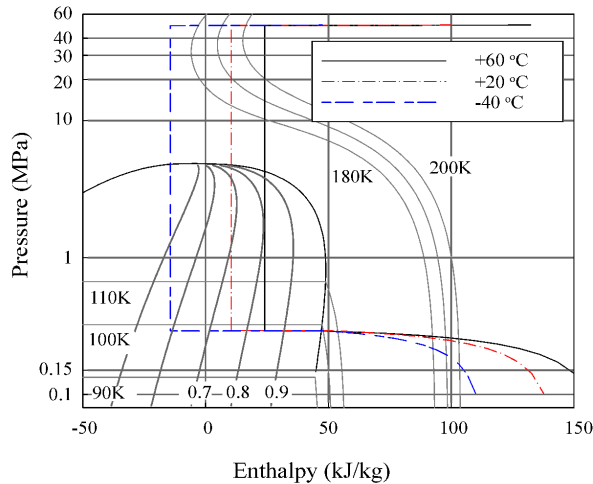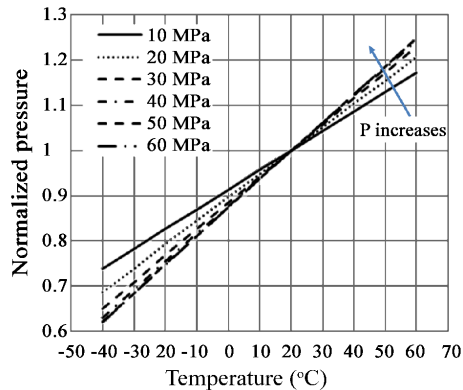

Figure 5. P-H diagram of the J-T refrigerator.

Figure 6. Variation of the pressure with the change of the ambient temperature
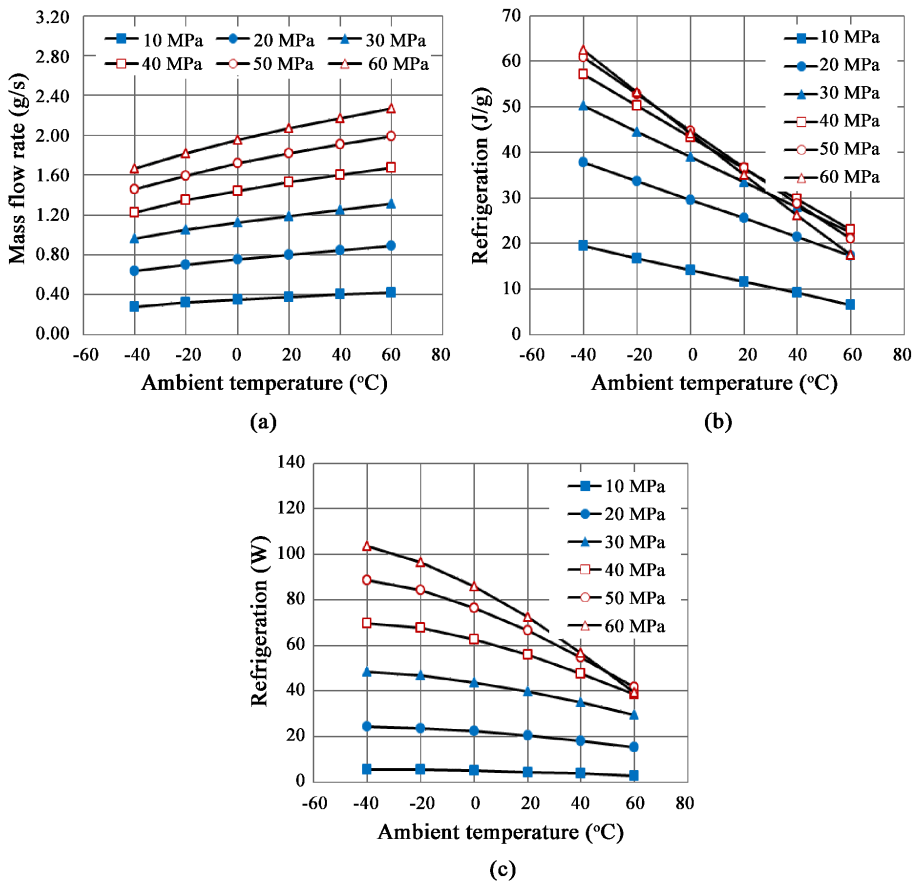

Figure 7. Performance of the J-T refrigerator with a pressurized vessel: (a) mass flow rate, (b) cooling effects, and (c) cooling capacity.

The J-T refrigerator in the low ambient temperature has the large cooling capacity. But, the low ambient temperature results in the decrease of the initial pressure of the gas in the vessel. It

could be concluded that the J-T refrigerator, which is installed in the low ambient temperature condition, has a negative aspect in the pressure of the gas, but a positive aspect in cooling effect. So the J-T refrigerator has the big cooling capacity for achieving fast cool-down.

SUMMARY

In the present study, the effectiveness-NTU approach and the isentropic model were adopted to predict the thermodynamic behaviors of the J-T refrigerator, and performances of the J-T refrigerator in different ambient temperatures were investigated.

For a regulated supply pressure of the gas, the J-T refrigerator for a given supply pressure in the cold ambient condition has the large mass flow rate and the big cooling effect. These phenomena result in the high cooling capacity. On the other hand, for a gas supplying from a pressurized vessel, the J-T refrigerator in the cold ambient condition has the small mass flow rate due to the change of the gas pressure in the vessel. But the J-T refrigerator has the high cooling capacity on account of the big cooling effect. So the J-T refrigerator has a rapid cool-down characteristics in the cold ambient condition.

ACKNOWLEDGMENT

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