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Miniature J-T cryocooler using argon and nitrous oxide mixture

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Abstract-- **Miniature J-T cryocooler using nitrogen or argon has been widely adopted in cooling infrared sensor for space/military application and cryosurgery. Argon or nitrogen, however, has relatively low specific cooling power compared to nitrous oxide, but the ultimate operating temperature is much lower than nitrous oxide. On the other hand, nitrous oxide has large specific cooling power, but the operating temperature is limited to its boiling point (>183 K). To compromise the different characteristics of these gases, the performance of miniature J-T cryocooler using argon and nitrous oxide mixture is investigated in this paper. Three different compositions of mixture (25/75, 50/50, and 75/25 molar fraction) are blended and tested. The results are compared with the experiments of pure argon and pure nitrous oxide. The experimental results show some encouraging potentiality of mixed refrigerant J-T cryocooler. The critical clogging problem, however, was observed with argon and nitrous oxide mixture, and the lowest achievable temperature with this mixture was limited to the freezing point of nitrous oxide. The paper discusses detailed clogging process of the mixture and suggests an alternative.**

1. INTRODUCTION

J-T cryocooler is an attractive refrigerator for miniaturization due to its simple structure. Moreover, there is neither a vibration nor an electromagnetic interference at the cold end, so numerous J-T cryocoolers have been adopted in cooling infrared sensor for space/military application and cryosurgical operation [1]-[3]. In those applications, high pressure gas like hundreds of bar of argon or nitrogen is usually used to obtain low temperature.

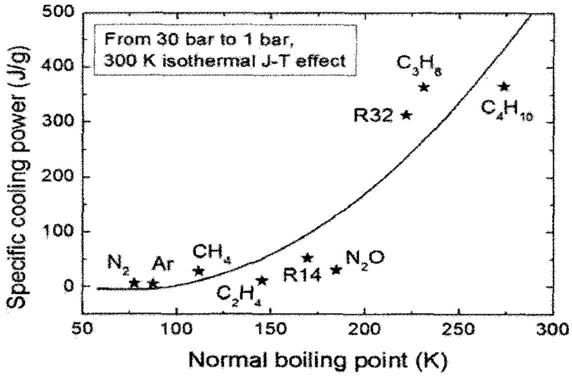

Fig. 1. Specific cooling power of various J-T refrigerants with regard to their normal boiling point.

Those cryogenic gases, however, have relatively small specific cooling power (J/g or J/mol) compared to high boiling point refrigerant like nitrous oxide. Usually, low boiling point refrigerant has small cooling power, and high boiling point refrigerant has large cooling power. As shown in Fig. 1, the specific cooling power of refrigerant, which is calculated by the enthalpy difference of high pressure state and low pressure state at the same temperature, is increased as its normal boiling point increases. The specific cooling powers are calculated in the operating pressure range varied from 30 bar to 1 bar, which is generally used in typical J-T cryocooler in a closed system. This characteristic of J-T refrigerant was noticed by several researchers [4]-[5]. Therefore, J-T cryocooler using low boiling point refrigerant can achieve low ultimate operating temperature, which is equal to its boiling temperature at the expansion stage, at steady-state operation, and the one using high boiling point refrigerant can cool down fast during transient operation.

J-T cryocooler using mixed refrigerant of argon and nitrous oxide was investigated to compromise the advantages of two kinds of refrigerant, which are low final temperature and fast cool-down time. Three different

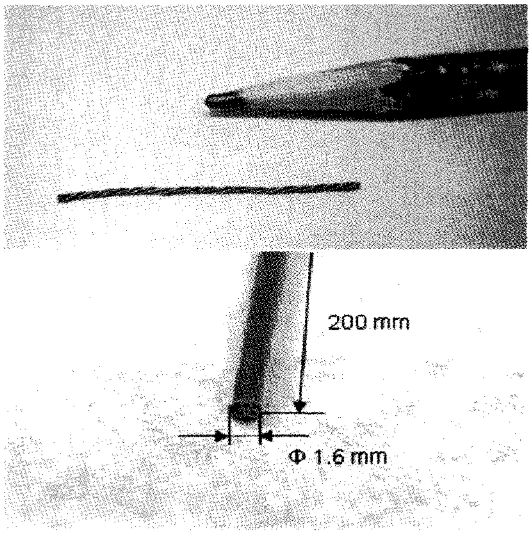

Fig. 2. Triplet heat exchanger for J-T cryocooler.

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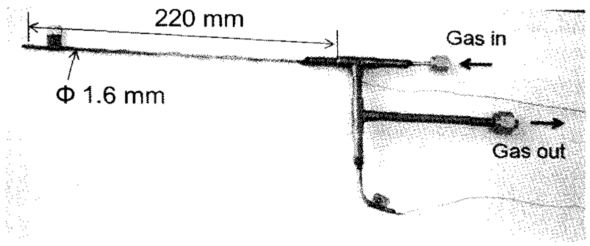
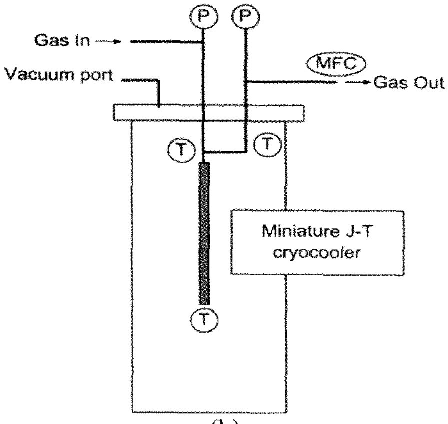


Fig. 3. Miniature J-T cryocooler.



(b)

Fig. 4. Schematic diagram of experimental apparatus.

compositions of mixture were blended to research the characteristics of mixture by comparing the performances of J-T cryocooler. The experimental results are presented and discussed in this paper.

2. EXPERIMENTAL APPARATUS

2.1. Miniature J-T cryocooler

The miniature J-T cryocooler, with its potentiality for cryosurgery probe, was fabricated in 1.6 mm diameter and 220 mm length. Triplet heat exchanger, composed of three wound tube bundle, is adopted for the heat exchanger as shown in Fig. 2 and the end of each tube is crushed for expansion device. The performance of triplet heat exchanger had been investigated in previous research, and it had shown satisfactory result for miniature J-T cryocooler [6].

2.2. Experimental procedure

The miniature J-T cryocooler depicted in Fig. 3 was installed in an evacuated cryostat as shown in Fig. 4. The experimental tests of pure argon and pure nitrous oxide were conducted to check the performance of J-T cryocooler, and they are compared to that of J-T cryocooler using mixed refrigerant. Three kinds of argon and nitrous mixture are blended to have molar fractions of 25/75 (argon/nitrous oxide), 50/50, and 75/25, respectively. Every experiment was conducted at the fixed operating pressure conditions (from 30 bar to atmosphere) and with the fixed geometry of J-T cryocooler for fairness.

TABLE I
INSTRUMENTS FOR MEASUREMENTS.

	Type	Range	Accuracy
Inlet pressure	SENSOTEC (FPA)	0 ~ 68.9 bar	±0.1% F.S.
Outlet pressure	SENSOTEC (FPA)	0 ~ 34.5 bar	±0.1% F.S.
Inlet temperature	E type thermocouple	3 ~ 953 K	±1.8 K
Outlet temperature	E type thermocouple	3 ~ 953 K	±1.8 K
Cold end temperature	E type thermocouple	3 ~ 953 K	±1.8 K
Mass flow rate	Bronkhost (F-201C)	0 ~ 100 slpm (He)	±0.5 slpm

2.3. Measurements

Inlet and outlet pressures of J-T cryocooler were measured, and three E-type thermocouples were used to measure the temperatures of inlet, outlet and cold end. Mass flow rate was also quantified at the exit by mass flow controller. All measuring devices used in the experiments are described in Table 1.

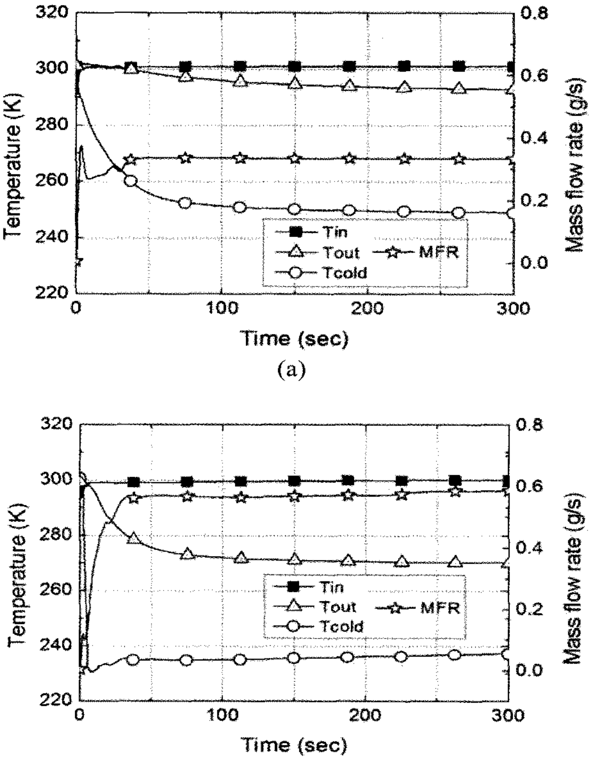
3. RESULTS AND DISCUSSIONS

3.1. Pure gas experiments

The cool-down curves of 30 bar argon and nitrous oxide are depicted in Fig. 5. The cold end temperature, mass flow rate, and heat exchanger effectiveness of argon were 248 K, 0.34 g/s, and 82.4%, respectively, at steady state. The cold end temperature is very high compared to its optimum operation (~88 K). The specific cooling power of 30 bar argon is much smaller (5.4 J/g) than that of nitrous oxide (32.5 J/g). For its optimum operation, the operating pressure of argon should be much higher than 30 bar to overcome heat invasion and to lower cold end temperature by liquefying argon gas at the cold end of cryocooler. Also, the geometry of cryocooler, which consists of heat exchanger and expansion device, should be modified as the operating pressure changes [3]. Nevertheless, all the experiments were performed with given geometry of J-T cryocooler and at fixed operating pressure for fair comparison. The optimization of J-T cryocooler involves different operating condition (different geometry of J-T cryocooler or different operating pressure), and it can make the comparison of mixtures biased.

The cold end temperature, mass flow rate, and heat exchanger effectiveness of nitrous oxide test were 238 K, 0.59 g/s, and 51.4%. The cold end temperature of pure nitrous oxide was also high because the performance of heat exchanger is greatly degraded due to large mass flow rate. The mass flow rate is increased as the density of fluid is increased in the fixed geometry and operating pressure, which is shown in equation (1). Nitrous oxide has much larger density than argon in a given operating condition, so the mass flow rate of nitrous oxide is much larger than that of argon.

$$\Delta P = f\frac{L}{D}\frac{G^2}{2\rho} \sim \frac{\mu L}{\rho D^2}\left(\frac{\dot{m}}{A}\right) \quad \text{for laminar flow,} \qquad (1)$$
$$\sim \frac{\mu^{0.25} L}{\rho D^{1.25}}\left(\frac{\dot{m}}{A}\right)^{1.75} \quad \text{for turbulent flow}$$



(a)

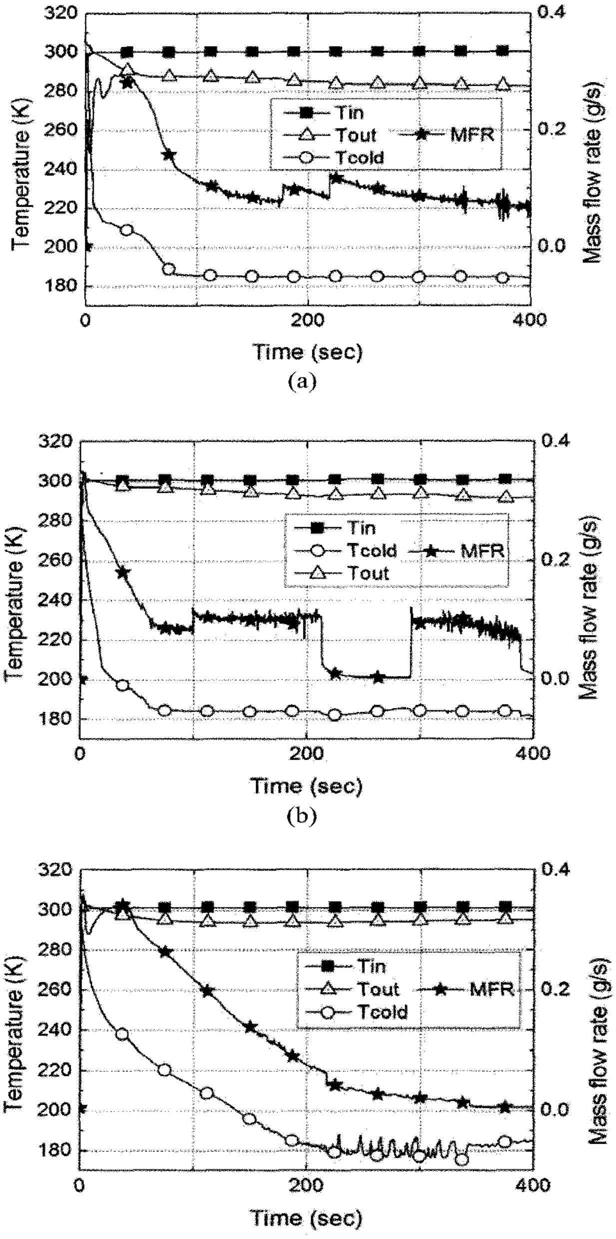
(b)

Fig. 5. Cool-down curves of pure gases: (a) argon 30 bar and (b) nitrous oxide 30 bar.

The NTU (Number of Transfer Unit) of heat exchanger is proportional to the reciprocal of mass flow rate, so the performance of heat exchanger is degraded as the mass flow rate increases. That means that the mass flow rate should be reduced by decreasing flow area of expansion device or lowering the operating pressure for optimum operation of nitrous oxide. It was proved by the additional experiment with reducing operating pressure to 15 bar. The cold end temperature and heat exchanger effectiveness were 185 K and 97.6% in the experiment, but the cool-down curve is not presented in this paper since it is beyond the scope of this paper, which is fixing the operation condition for simple comparison of characteristic of mixture.

3.2. Mixture experiments

The cool-down curves of mixtures are plotted in Fig. 6. It is observed that the cold end temperatures are much lower than those of pure gases. The reasons can be found from the existence of argon. The J-T effect of argon is bigger as temperature goes down [7]. Argon component of mixture is cooled so lower temperature than pure argon test with the aid of nitrous oxide that the cold end temperatures of mixtures are lower than those of pure gases. The acceleration pressure drop owing to phase change in heat exchanger also contributes to lowering temperature by reducing the mass flow rate. The lowest temperatures of 25/75, 50/50, 75/25 mixtures instantaneously reached 185 K, 181 K, and 177 K, respectively.



(a)

(b)

(c)

Fig. 6. Cool-down curves of mixture: (a) 25/75, (b) 50/50, and (c) 75/25 (Ar/N_2O based on molar fraction).

The cold end temperatures of two experiments (50/50 mixture and 75/25 mixture) were about 182 K, which is almost equal to the freezing point of nitrous oxide, and the mass flow rates were very small with some fluctuation. Therefore, it is suspected that the expansion device is clogged by solidified nitrous oxide, and intermittently cleared by gaseous argon. The peculiar difference in mass flow rates fluctuation of two experiments is also observed. It cannot be definitely explained at this time, but it is presumably originated from the portion of argon. The expansion device is not completely clogged by solidified nitrous oxide because of strong flow inertia of gaseous argon. Hence, the flow cannot be clogged completely but periodically. In 75/25 mixture, the solidified nitrous oxide at the expansion device is more frequently clogged than in 50/50 mixture because the flow inertia of gaseous argon becomes weaker as the fraction of argon is decreased. The actual mass flow rate of 75/25 mixture might more frivolously fluctuate than the measured value, but it is not reflected in the measurement because there is substantial space between the cold end of J-T cryocooler and the exit. It is presumed that the temperature of 75/25 mixture might be affected by this fluctuation, so it abruptly fluctuates around 182 K while that of 50/50 mixture does not.

TABLE II
FREEZING POINT AND IDEAL COOLING POWER OF MIXTURES.

	Molar fraction (Ar / N_2O)	Freezing Point (K)	Ideal cooling power (J/g)
Mixture #1	25 / 75	157.7	24.22
Mixture #2	50 / 50	133.1	16.84
Mixrure #3	75 / 25	108.4	10.57

The cold end temperature is usually designed to be higher than the averaged freezing point of mixture based on molar fraction [5], [8]. It is a conservative method since a clogging is generally occurred at lower temperature than the averaged freezing point due to a so-called freezing point depression. In the beginning of this research, the freezing points of mixtures were expected as Table 2 by calculating averaged freezing point. The clogging, however, occurred with the mixture of argon and nitrous oxide. The reason is that the freezing point of nitrous oxide is too high (182 K) compared to the boiling point of argon. Hence, argon gas cannot be liquefied even when nitrous oxide is solidified, so the expansion device is clogged with frozen nitrous oxide. The estimation by averaging the freezing point of refrigerant can be used only when solid-liquid equilibrium, not solid-gas equilibrium. Therefore, it is inferred that the mixture should be made of fluids, whose phase temperature is evenly distributed, with consideration of their phase equilibrium at low temperature. If propane whose triple point (85.5 K) is below the normal boiling point of argon (87.3 K) is mixed with argon, the J-T cryocooler can achieve much lower temperature without clogging problem.

The slopes of cool-down curves in mixture experiments are steeper than the one of argon, but not as much as that of nitrous oxide. As shown in Fig. 6, the temperature drop at the beginning of the operation is the fastest in 25/75 mixture, then 50/50 mixture, and then 75/25 mixture. This can be explained by the cooling power of mixture calculated in Table 2. The mixture with more nitrous oxide has larger cooling power than the mixture with more argon, so the cooling speed has been increased with fixed cooling load as nitrous oxide component increases.

4. CONCLUSION

Miniature J-T cryocooler using nitrogen or argon has been widely adopted in cooling infrared sensor for space/military application and cryosurgery. It requires very highly pressurized gas for fast cool-down since nitrogen or argon has very small specific cooling power. On the other hand, high boiling point refrigerant like nitrous oxide has much larger specific cooling power than argon, but the operating temperature is limited to its boiling point. In this paper, miniature J-T cryocooler using argon and nitrous oxide mixture is investigated to research the characteristic of mixture. Miniature J-T cryocooler is fabricated in a 1.6 mm diameter using triplet heat exchanger. Three different compositions of mixture were blended and compared with pure gas experiments.

In pure gas experiments, the performances of J-T cryocooler were not good since the operating conditions were not optimized.

In the mixture experiments, it is observed that the cold end temperatures decrease rapidly, and they are much lower than those of pure gases, which show the encouraging potentiality of mixed refrigerant J-T cryocooler. The cold end temperature, however, is limited to the freezing temperature of nitrous oxide with clogging problem at the expansion device. The reason for clogging due to the fact that nitrous oxide has relatively high freezing temperature with small liquid existence temperature range. This problem can be eliminated by substituting nitrous oxide by other component, and further research is on going.

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