Triplet 열교환기를 사용하는 소형 J-T 냉동기

Miniature J-T Refrigerator Using Triplet Heat Exchanger

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Abstract: Most J-T (Joule-Thomson) refrigerators use a Giaque-Hampson type heat exchanger due to its excellent thermal performance and compactness. The cryoprobe (cryosurgical probe) treating prostate cancer usually has a dimension of 17 gauge (1.6 mm diameter), so it does not have enough space to bear a Giaque-Hampson type heat exchanger. In this paper, the triplet heat exchanger is adopted as the heat exchanger of cryoprobe, and the performance is investigated with an experimental test. The result shows that the triplet heat exchanger can be substituted for Giaque-Hampson type heat exchanger in the application of cryosurgery.

Key Words: heat exchanger, J-T refrigerator, cryosurgery.

1. INTRODUCTION

A J-T refrigerator has attractive features for miniaturization. It is free from vibration and electromagnetic interference since there is no moving part at the expansion stage, and has short cool-down time with simple structure. There have been numerous works on developing miniature J-T refrigerator applied for cooling infrared sensor in spacecraft and military application, HTS application, and cryosurgery [1-4]. A cryoprobe with a miniature J-T refrigerator applied to prostate cancer cryosurgery should be fabricated in an especially small scale (about 17 gauge needle size, 1.6 mm outer diameter) for comfortable surgical operation. This tiny space for narrow flow passage is inconvenient to adopt a Giaque-Hampson type heat exchanger, which has been usually used in most J-T refrigerator systems due to its compactness and thermally excellent performance [1, 5].

The triplet heat exchanger is to be adopted in a miniature J-T refrigerator for cryosurgical probe. It consists of three stainless steel wound tubes of 0.55 mm outer diameter (Figure 1) and a shell tube of 1.6 mm outer diameter The dead volume occupied by mandrel of a Giaque-Hampson type heat exchanger is removed in this case, and the mass flow rate of the working fluid and the heat transfer area are increased in the triplet heat exchanger. To obtain high heat transfer coefficient and effective heat transfer area, three tubes wound together, and the wound tube bundle has 1.2 mm outer diameter so that they are snuggly inserted into the shell tube of 1.6 mm outer diameter. Therefore, the 1.6 mm cryoprobe using the triplet heat exchanger can be constructed to have a larger cooling power than the one using Giaque-Hampson type heat exchanger for the same length.

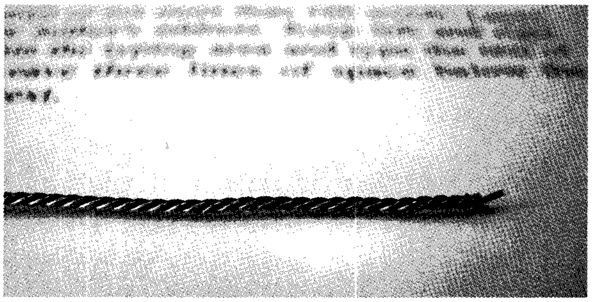

Fig. 1. Triplet heat exchanger.

2. FABRICATION OF MINIATURE J-T REFRIGERATOR

Fabrication of triplet heat exchanger

The schematic diagram of the triplet heat exchanger is described in Figure 2. The tubes are wounded by the fitting in Figure 3 with three 0.6 mm holes on the one side and a 3.2 mm hole on the other side. By using the fitting, the triplet heat exchanger is neatly fabricated with uniform winding pitch. The length of triplet heat exchanger is reduced by 5 % of the original tube length with winding process, which can be controlled by the winding pitch. If the winding pitch becomes smaller, the length is shortened, but tubes are excessively distorted that the inner tube diameter deforms. With this fabrication method, the triplet heat exchanger can be constructed with much ease and low cost.

Fabrication of expansion part

Self-regulating flow restriction device is widely

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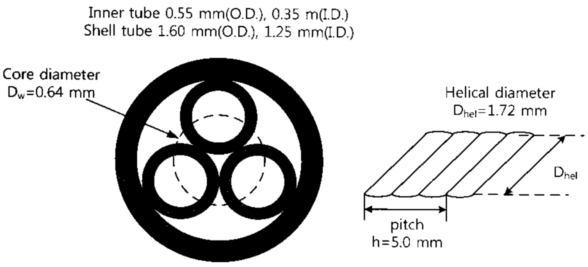


Fig. 2. Schematic diagram of the triplet heat exchanger.

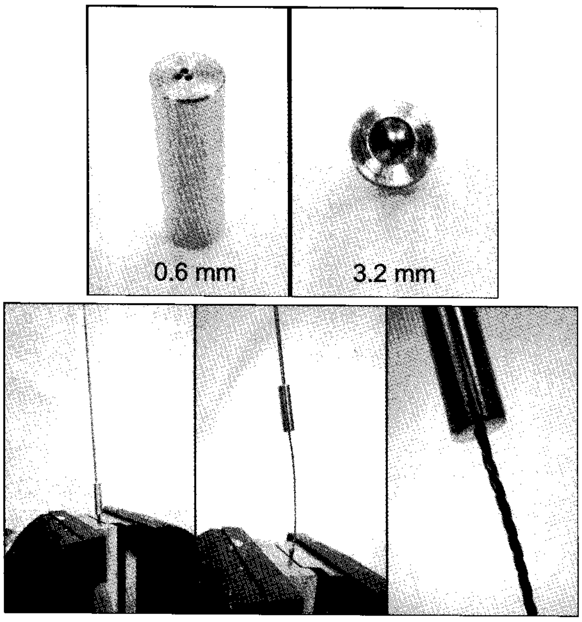


Fig. 3. Tube fitting for winding.

used in recently developed J-T refrigerator since it can optimally control the mass flow rate with regard to its cold end temperature [1, 6]. The performance of J-T refrigerator can be promoted with the aid of a self-regulating device. It, however, is not applicable for the small sized J-T refrigerator, so fixed type expansion device is fabricated by crushing the tubes. The thickness gauge was used to regulate the expansion dimension fairly. This fabrication method was verified by several pressure drop tests, and it showed quite good manageability. The cross-section of 10 mm length-crushed tube is assumed to have a square-shape with 0.05 mm height and 0.50 mm width.

3. EXPERIMENTAL SETUP

The experimental apparatus is depicted in Figure 4, and its photograph in Figure 5. The inlet pressure, outlet pressure, cold end temperature, outlet temperature, and mass flow rate are measured with the instruments listed in Table 1. The inlet temperature is set as ambient temperature (299 K), and 0.5 micron sintered metal filter (Swagelok TF series) is connected just before the inlet port to prevent the cryoprobe from clogging with particles like a scrap of tube burr or residual dust in the tube.

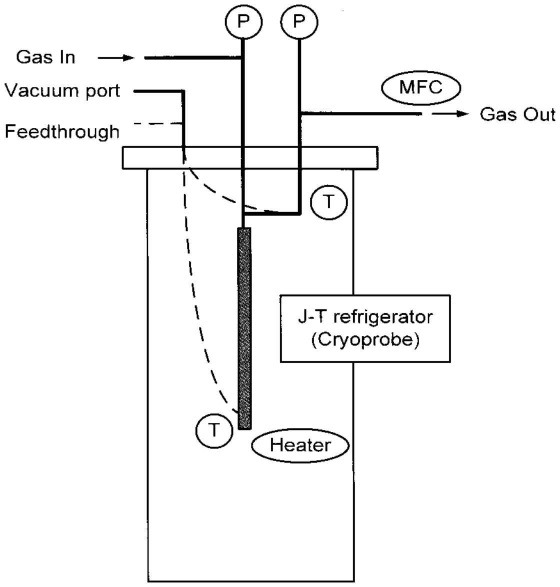
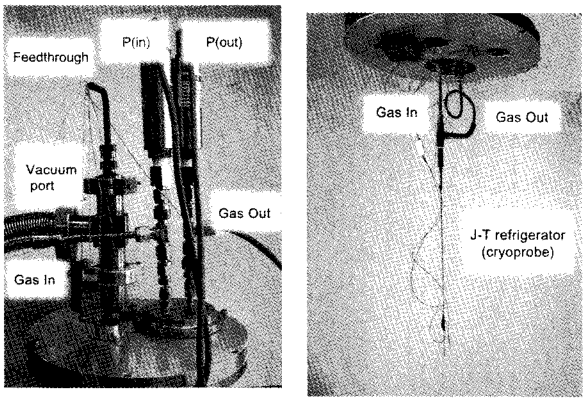


Fig. 4. Schematic diagram of experimental setup.



(a) (b)

Fig. 5. Pictures of experimental apparatus; (a) upper part and (b) lower part.

Table 1. Instruments for experiments.

	Type	Range	Accuracy
Inlet pressure	Swagelok (S model) / SENSOTEC (FPA)	0 ~ 345 bar / 0 ~ 69 bar	±0.1% F.S.
Outlet pressure	SENSOTEC (FPA)	0 ~ 34.5 bar	±0.1% F.S.
Cold end temperature	E type thermocouple	3 ~ 953 K	±1.8 K
Outlet temperature	E type thermocouple	3 ~ 953 K	±1.8 K
Mass flow rate	Bronkhost (F-201C)	0 ~ 100 slpm (He)	±0.5 slpm

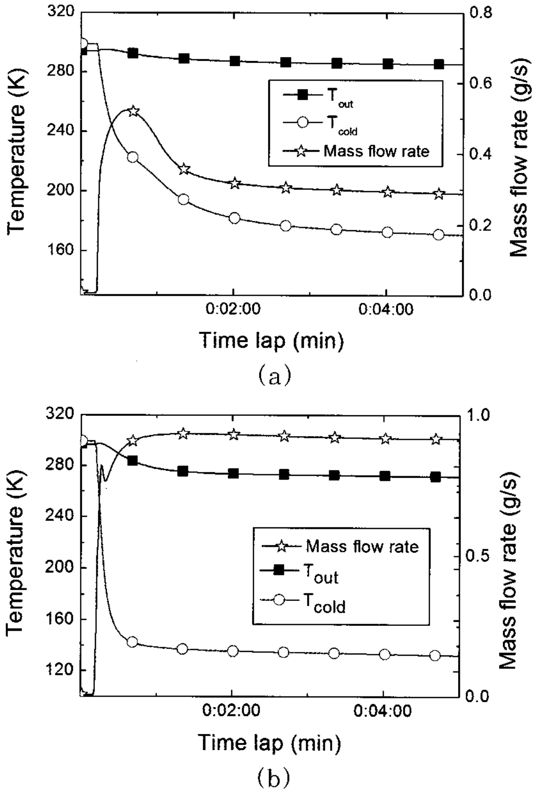
The cryoprobe is fabricated in the size of 1.6 mm diameter and 210 mm length including cold end. Since the cooling power of the cryoprobe is small due to size restriction, it is sensitive to heat invasion. To minimize heat leak through radiation and convection, the experimental apparatus is shielded by MLI (Multi-Layer Insulation) and placed in a vacuum cryostat.

4. RESULTS

The experimental results using argon are shown in Figure 6. With 50 bar argon, the cold end temperature reached 177 K for 150 seconds cool-down, and it went down to 171 K for 5 minutes cool-down. The steady mass flow rate was 0.29 g/s, and the heat exchanger effectiveness was calculated as 88.6% with the measured temperatures. The experiment using 100 bar argon was also conducted. The cold end temperature was recorded 139 K for 50 seconds cool-down, and the lowest temperature was 132 K. The steady mass flow rate was 0.91 g/s, and the heat exchanger effectiveness was calculated as 83.4%.

The experimental results with 30 bar nitrous oxide are shown in Figure 7. The steady cold end temperature was 235 K for 15 seconds short cool-down time, the mass flow rate was 0.54 g/s, and the heat exchanger effectiveness was expected to be 54.4%.

The cooling powers with respect to cold end temperature were measured after cool-down tests, which are described in Figure 8.



(a)

(b)

Fig. 6. Cool-down curve of (a) 50 bar argon and (b) 100 bar argon.

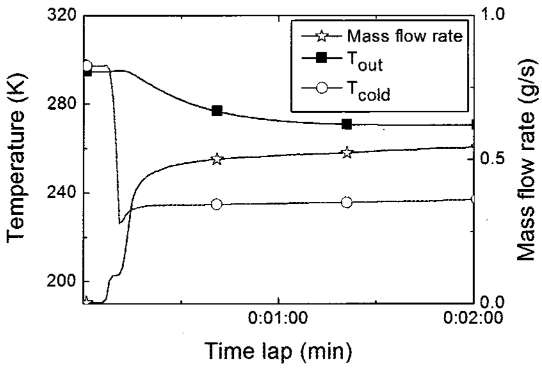


Fig. 7. Cool-down curve of 30 bar nitrous oxide.

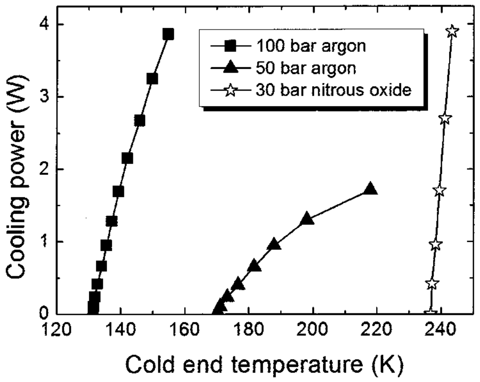


Fig. 8. Cooling power of cryoprobe.

5. DISCUSSION

The cryoprobe using triplet heat exchanger shows satisfactory results during the experiments, but not for the heat exchanger effectiveness in the experiments using 30 bar nitrous oxide. The reason is that the triplet heat exchanger was roughly designed for the case of using 50 bar argon. The performance was expected to be also good in 30 bar nitrous oxide experiment, but the thermal and hydraulic characteristic of two-phase flow with nitrous oxide is much peculiar compared to single gas flow with argon. The performance is believed to be enhanced by developed cryoprobe design which has a smaller expansion part for diminished mass flow rate with the consideration of two-phase flow in micro-channel.

For the cooling power of cryoprobe depicted in Figure 8, the cooling powers of 100 bar argon and 30 bar nitrous oxide are less sensitive to cold end temperature, but the one of 50 bar argon is varied with regard to its cold end temperature. This phenomenon is due to the liquefaction of working fluids. For the experiments of 100 bar argon and 30 bar nitrous oxide, the working fluids are partly liquefied, so the fraction of liquid absorbs heat load without temperature variation. In the case of 50 bar argon test, the argon after expansion is in the superheated vapour state where the gas temperature increases as much as heat is supplied.

The pressure after expansion can be estimated with the results of 100 bar argon and 30 bar nitrous oxide. The evaluated pressures are about 22 bar for argon and 10 bar for nitrous oxide, which means the pressure drop of outlet heat exchanger is so large that the cold end temperature is much higher than the saturated temperature of atmosphere. As mentioned, this triplet heat exchanger was not designed for the case of 100 bar argon or 30 bar nitrous oxide, so the mass flow rates are larger than optimized value. If the mass flow rate decreases by raising flow resistance of expansion part, the cold end temperature could be lower with high value of heat exchanger effectiveness.

6. CONCLUSION

The miniature J-T refrigerator for cryosurgery should be formed in the dimension of 17 gauge (1.6 mm diameter), that is inconvenient to adopt conventional heat exchanger like a Giaque-Hampson type heat exchanger. The triplet heat exchanger, which is composed of three tubes wound together, is adopted for the development of cryoprobe. The fabrication method is very easy and low-cost. To investigate the performance of cryoprobe using triplet heat exchanger, the experimental tests were conducted with argon and nitrous oxide. The result shows that the triplet heat exchanger can be used in compact heat exchanger for miniature J-T refrigerator.

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