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Development of 4K Cryocooler for Space Application

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Abstract: A compact closed cycle cryocooler operating around 4K has been developed for space application. The prototype cooler consists of a Joule-Thomson (JT) system and a two-stage Stirling cycle cooler which is used to pre-cool the JT system. The typical cooling power is about 30 mW at 4.85K and the input power to the compressor is approximately 180W. This paper reports the results from preliminary test of the prototype cooler.

1. DESCRIPTION OF CRYOCOOLER SYSTEM

The flow diagram of the prototype cryocooler is shown in Figure 1. The major components are a pre-cooler, JT compressors, JT valve and five heat exchangers (Hex-1 to Hex-5). A two-stage Stirling cycle cooler is used to pre-cool a conventional JT system.

1.1 Pre-Cooling

In the pre-cooling process, the by-pass valve is opened. The helium gas in the JT system is diverted through the by-pass line to cool the 4K stage directly by the temperature of the pre-cooler. When the 4K stage temperature is close to the pre-cooler, the by-pass valve is closed and all the helium gas is diverted through the orifice.

1.2 Steady State Condition

The high pressure gas passes through five heat exchangers before expansion at JT valve. The first is the coaxial double tube heat exchanger (Hex-1) where the high pressure gas is cooled from the room temperature to around 100K by the returning low pressure gas. This is followed by a heat exchanger (Hex-4) at the first stage of the pre-cooler which take heat transfer between the high pressure gas in the JT system and the pre-cooler. A second coaxial heat exchangers (Hex-2) cools the high pressure gas from around 100K to 20K . This is also followed by a heat exchanger (Hex-5) at the second stage of the pre-cooler. Finally, the high pressure gas passes through a third coaxial heat exchanger (Hex-3), and the gas is cooled to low temperature for

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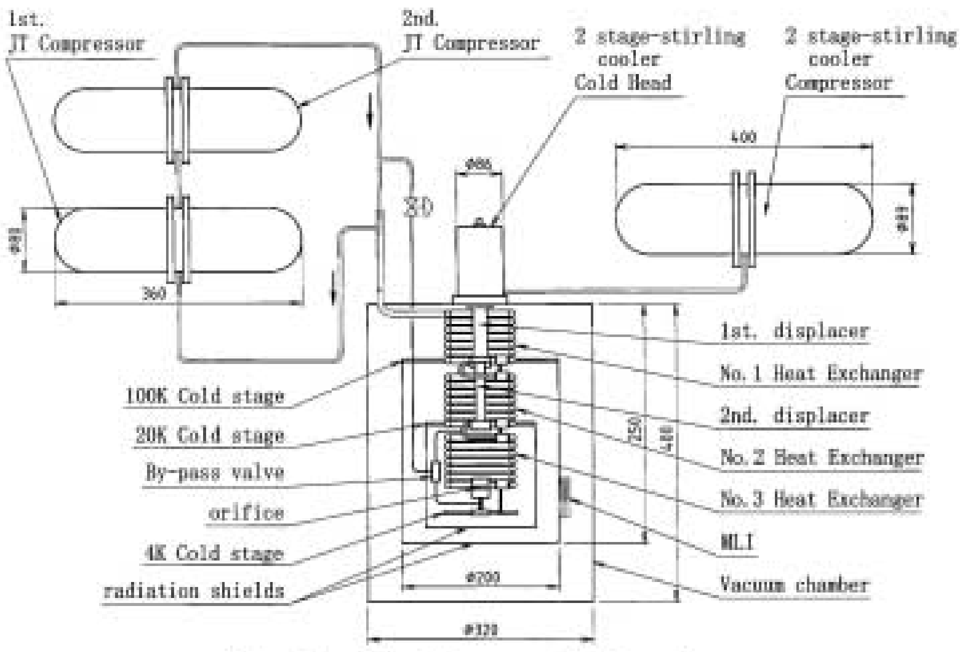

Fig. 1: Flow Diagram of 4K cooler

JT effect by the returning low pressure gas. Through the JT valve, the high pressure gas cooled by these five heat exchangers will be a saturated helium by JT effect.

2. COMPONENTS IN THE SYSTEM

2.1 Two-Stage Stirling Cycle Cooler (Pre-Cooler)

A photograph and a schematic drawing of the two-stage Stirling cycle cooler is shown in Figures 2 and 3. The cooler consists of a cold head unit with a two-stage displacer, a compressor and a gas feed connecting tube. The compressor has dual opposed pistons, to reduce the vibration levels. Each piston in compressor is directly coupled to moving coil of linear motor in the permanent magnet system. The permanent magnet system provides a constant field of 0.52T in the gap around the iron. In the gap, the coil connected to the piston move up and down driven by a.c. current through the coil. The operating frequency is around 15 Hz and the swept volume is about 9.5 cc. The cold head unit has a two-stage displacer moving up and down in the cylinder, driven by linear motor. The mechanism for the linear motor in the cold head is the same as in the compressor. The first and second regenerator consist of two different sizes of metal mesh. The cylinder is constructed from copper and stainless steel with a thin wall. The dimensions of the connecting tube are 3.2 mm in diameter and 250mm long. The nominal cooling capacity of the two-stage Stirling cycle cooler is 200 mW at 20K, and 1W at 100K. The total input power to the compressor and cold head is approximately 110W (Kyoya, Narasaki, & Ito 1994).

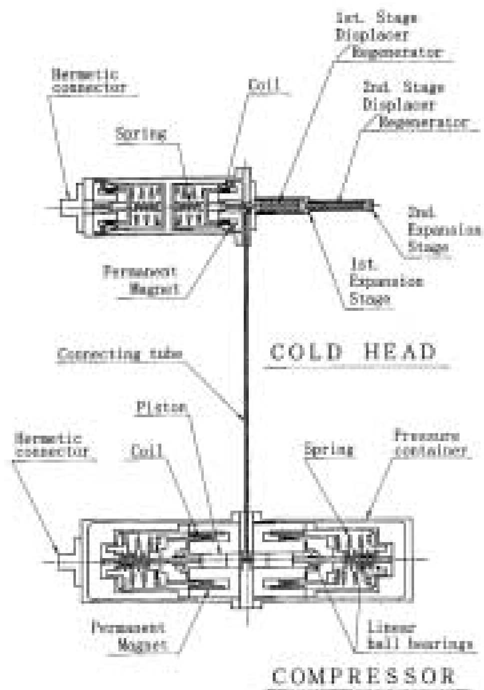

Fig. 2: Schematic Drawing of two-stage Stirling cycle cooler

Fig. 3: Photograph of two-stage Stirling cycle cooler

2.2 JT COMPRESSOR

The JT compressors are similar to the compressor for the Stirling cycle cooler described above, and consist of two units which are connected in series. Additional reed valves mounted in the head of each compressor are used to provide a one-way flow of helium gas. The operating frequency is around 30Hz. The JT compressors provide a high pressure of about 1.5 MPa, and a low pressure of about 0.1 MPa. The nominal helium gas flow-rate is 0.13 Nm3/h and the

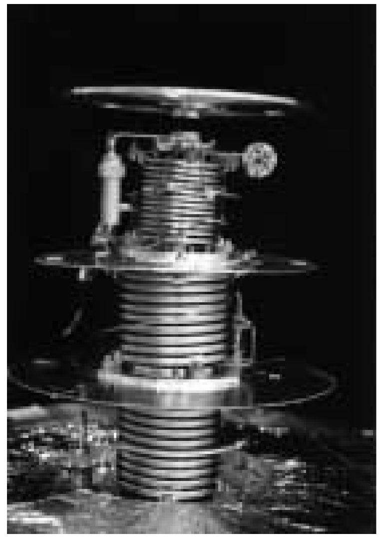

Fig. 4: Photograph of the JT system

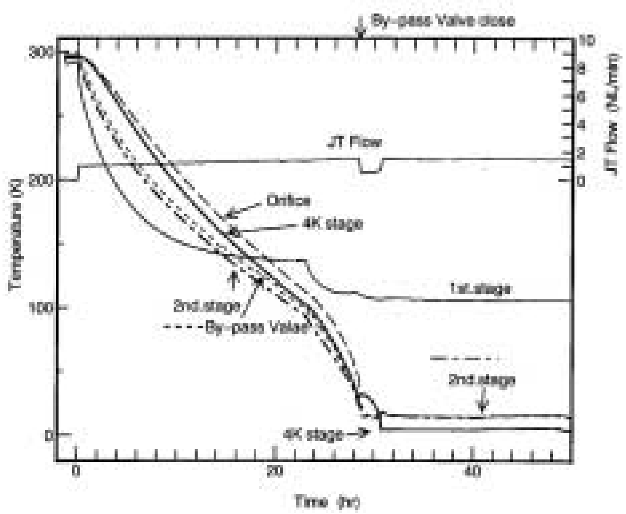

Fig. 5: Cool-down Operation (Orifice size 20 μm)

nominal input power to the JT compressors is 80W at the pressure ratio.

2.3 Heat Exchangers

There are two types of heat exchanger in the 4K cryocooler. Three coaxial double tube heat exchangers (Hex-1, 2, & 3) are used to cool the high pressure gas by the returning low pressure gas. These coaxial double tube heat exchangers run between room temperature and the first stage of pre-cooler, the first and second stage of pre-cooler, the second stage of pre-cooler and

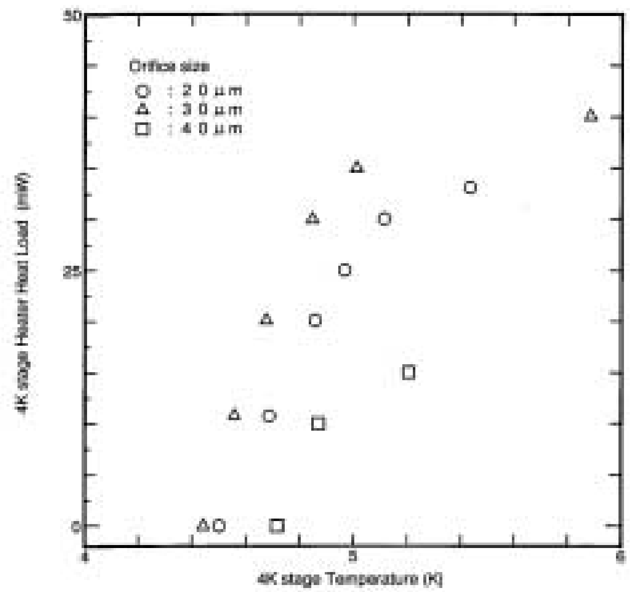

Fig. 6: Cooling Power at 4K stage

4K stage. Two coil type heat exchangers (Hex-4 and Hex-5) are mounted in the two cold stages of pre-cooler to take heat transfer between the high pressure gas in JT system and the two-stages of pre-cooler respectively.

Tin wall stainless steel tubes are adopted with optimized dimension on the efficiency over 97%.

A photograph of the JT system is shown in Figure 4.

2.4 JT Valve

The JT valve consists of a orifice and a by-pass line with a open/close valve. The orifice which has the size of 20∼30μm are made and tested. The open/close valve in the by-pass line is controlled by means of a gas pressure actuator and coil type spring. A capillary tube with length of about 1 m is connected between the open/close valve and the gas actuator at the room temperature.

3. TEST RESULTS

3.1 Cool-Down Operation

Figure 5 shows the experimental result of cool-down performance of the 4K cryocooler with orifice size of 20μm. At room temperature, Stirling and JT compressor are started and by-pass valve is opened. When the 4K stage temperature is below 90K, the input power to the Stirling compressor is increased and the input power to cold head is turned on. When the 4K stage temperature is below 30K, by-pass valve is closed and the gas is diverted through the orifice. Then input power to the Stirling and JT compressor are increased. The cool-down time is about 30∼40 hours.

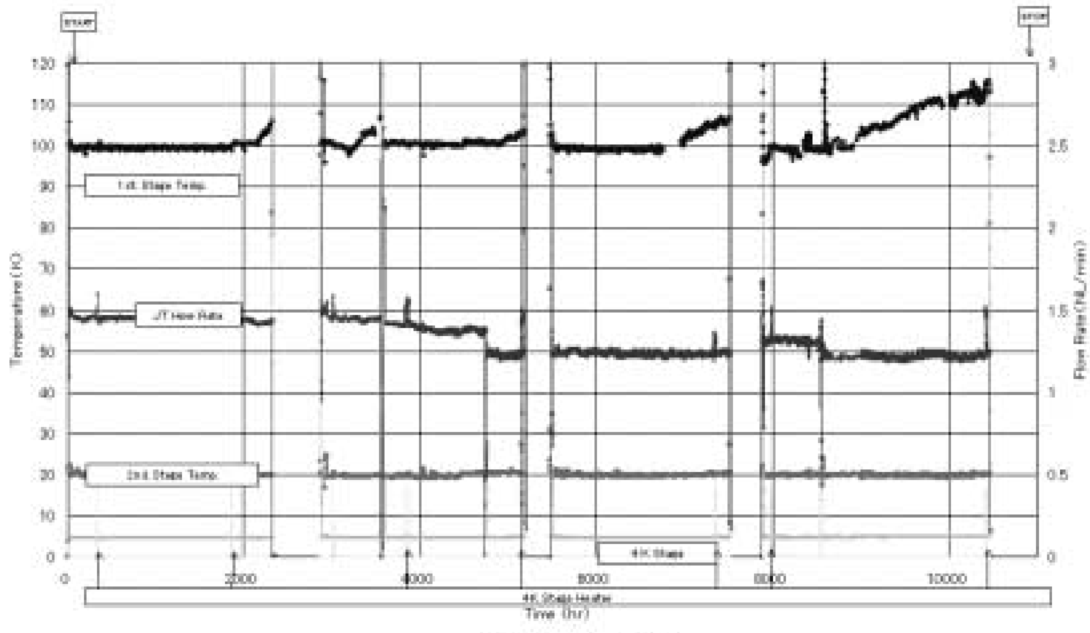

Fig. 7: Running Test

3.2 Cooling Power

Figure 6 shows the cooling power depended on the orifice size versus 4 K stage temperature with no heat load to the first and second stage under steady state conditions. In case of 30μm orifice size , the typical cooling power is about 30 mW at 4.85K. In case of 20μm orifice, when heat loads is added to each stages by electric heater, the cryocooler is balanced under steady state condition with 10.8mW/4.56K at 4K stage, 80mW/19.1K at second stage and 500mW/112.6K at first stage. The total input power to the compressors and cold head is nominally 180W.

3.3 Running Test

The result of long-term running test is shown in Figure 7. The result has shown the cooling capability lasts more than one year.

4. CONCLUSION

The prototype of 4K cryocooler for space application has been designed, fabricated and tested. The test results show that the prototype cooler has the capability with respect to cooling power required for space application. The effort to improve the performance and reliability of the 4K cryocooler is now being performed.

REFERENCES

Kyoya, M., Narasaki, K., & Ito, K. 1994, Cryogenics, 34, 431