Experimental Research on the JT Cycle of Hybrid 4.5K JT Cryocooler

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Abstract. Key Laboratory of Space Energy Conversion Technologies of TIPC, CAS has developed a 4.5K Joule-Thomson (JT) cryocooler precooled by a multistage pulse tube cooler. In this paper, series of experimental research is carried out to explore the performance of the JT cooler at different operating conditions. When only the power consumption of JT compressors is considered, the coefficient of performance (COP) of the JT cycle is proposed to evaluate the performance of JT cycle. Experimental research is carried out to investigate the influence of supply pressure and JT orifice on cooling capacity and especially the COP of JT cooler. Experimental results suggest that cooling power of JT cooler increases as supply pressure increases and higher COP are gained because of rising flow resistance of JT orifice. Then JT orifices of different diameters are experimentally studied to explore the effect of flow resistance of JT orifice on the performance of JT cooler.

1. Introduction
Cryogenics and its applications in space have made a remarkable amount of progress over the last decades. Many mechanical cryocoolers operating at temperature above 10K have been launched. Such coolers are pulse tube coolers, Stirling coolers and so on. When temperatures below 6K are needed, the efficiency of pulse tube cryocooler and Stirling cryocooler drops dramatically due to the invalidation of regenerative material. Therefore, in view of its flexibility and relatively higher efficiency, JT cryocooler is widely used in space exploration at temperatures below 6K. In fact, nearly all the space applications of mechanical cryocoolers working at 4.5K, having been launched or under development are hybrid JT cryocoolers. For instance, mechanical cryocooler used in Planck is a 4He JT cooler precooled by adsorption cryocooler.[1] James Webb Space Telescope (JWST) uses a three-stage pulse tube cryocooler to precool JT loop.[2,3] In Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) and Space Infrared Telescope for Cosmology and Astrophysics (SPICA), two stage of Stirling cooler is used to provide precooling for JT cooler.[4-6] However, research of all these hybrid JT coolers focus on satisfying the requirement of certain space detectors, and few research has been done specifically on the JT cycle.

Our laboratory has developed a 4.5K JT cooler precooled by a three-stage pulse tube cryocooler to satisfy the demands of future space exploration.[7] And compared to Stirling cryocooler, high frequency pulse tube cooler has the advantages of light weight, low vibration and electromagnetic interference and especially long life. Based on the 4.5K hybrid JT cooler developed by our laboratory,
the JT cycle is experimentally studied and discussed in detail to find out how to improve its performance.

In this paper, special attention is paid to the performance of JT cycle, so a commercial two-stage GM cryocooler instead of the multistage pulse tube cryocooler is used as precooler for the purpose of shortening experimental time and maintaining the two stage of precooling temperature fixed at 80K and 15K.

2. The hybrid JT cooler system

The hybrid JT cooler is composed of two thermally coupled parts: the multistage pulse tube cryocooler and the JT loop, as shown in Figure 1. The pulse tube cryocooler provides precooling for JT cycle at 80K and 15K respectively.

In this paper, a two-stage GM cryocooler is used to precool JT cycle at the same temperature to shorten experimental time. On the other hand, the GM cryocooler is able to provide additional cooling power for JT cycle. As mass flow rate of JT cycle increases, the two stages of precooling temperature can maintain constant by adjusting the electrical heaters that attached at the cold ends of GM cooler. The JT cycle is driven by two oil-free linear compressors, which makes it suitable for space application. High pressure gas passes through the inner tube of the three counter-flow heat exchangers where it is cooled by the low pressure returning gas. And two additional heat exchangers mounted on cold end of the precooler provide precooling for JT cycle. When helium gas reaches JT orifice, it has been cooled to nearly 5K. The JT orifice is detachable calibrated restriction that allows the high pressure gas to expand into low pressure JT return line. A fraction of the helium gas will condense into liquid during the expansion process. Cooling capacity of the hybrid JT cooler is the heat that is absorbed by vaporizing the liquid helium. Besides, the buffer tanks are used to balance the pressure between the JT compressors and two stages of cold shields are installed in this hybrid cooler to decrease heat leakage of radiation.

3. Experimental results and discussion

The cooling capacity of the 4.5K JT cryocooler is determined by the mass flow rate of JT cycle. And mass flow rate is determined by JT orifice, charge pressure, JT compressors and so on. In this section, series of experiments are carried out to investigate the influence of JT orifice and supply pressure on cooling capacity and COP of the JT cooler.

Since the main purpose of this study is to explore the performance of JT loop when its operating condition changes, COP of the JT cooler is defined as follows.
\[ \text{COP} = \frac{Q_0}{W_{JT}} \]  

(1)

Where \( Q_0 \) is the cooling capacity at 4K stage, \( W_{JT} \) is the power consumption of JT loop. Experimental research is carried out to investigate the influence of these factors on the performance of JT cooler. In experimental research, the suction pressure of the first stage JT compressor is fixed at about 0.13MPa to maintain that temperature at evaporator is 4.5K.

3.1. Influence of the supply pressure

Mass flow rate of JT cycle is determined by the supply pressure when the suction pressure and diameter of orifice is fixed at 0.13MPa and 30μm, respectively. And supply pressure is affected by JT compressors and charge pressure.

Table 1 shows the difference between one stage of compression and two stage of compression when the charge pressure is the same. The limitation of compression ratio for single stage compressor is the piston stroke of the compressor. When input power increases further the piston may hit the cylinder, so two-stage compression is used to increase supply pressure. Besides, another function of the secondary compressor is to maintain suction pressure fixed at 0.13MPa when supply pressure increases. As can be seen, two-stage compression gains 10.2mW cooling power at 4.5K, nearly 4mW more than one-stage compression. In other words, when a second stage compressor is used in the JT cycle, additional 4mW cooling capacity is gained at the cost of only 6.2W input power. Although the second stage compressor consumes additional power, it discharges the helium gas at higher pressure. And eventually mass flow rate increases.

The efficiency of the compressor is the ratio of the work done by the piston and the input electrical power. The efficiency of the compressor used in this study is about 65% and varies very little as charge pressure changes. Therefore, the input electrical power is used to evaluate the performance of JT cycle.

Table 1. Influence of the second compressor when charge pressure is 0.5MPa.

|                | cooling capacity | power consumption (W) | COP of JT cycle | supply pressure (MPa) | mass flow rate \( q_m \) (mg/s) |
|----------------|------------------|------------------------|------------------|-----------------------|----------------------------------|
| One-stage      | 6.3mW@4.5K       | 17.2                   | 0.0366%          | 0.5                   | 2.6                              |
| Two-stage      | 10.2mW@4.5K      | 23.4                   | 0.0436%          | 0.65                  | 3.2                              |

When two stages of compressors are used, the first stage compressor consumes a little more power than one stage compression to maintain that temperature at evaporator is 4.5K. Besides, when only the power consumption of JT cycle is considered, the COP of two-stage compression is much higher than one-stage compression. Thus, all the discussion in following parts adopts two-stage compression.

Figure 2. Influence of charge pressure on supply pressure.
Mass flow rate and cooling capacity                  b)Power consumption and COP

Figure 3. Performance of JT cycle at different supply pressure.

Charge pressure is another factor that influences supply pressure, as shown in Figure 2, supply pressure increases as charge pressure increases. When supply pressure increases, both mass flow rate and cooling capacity increase, as shown in Figure 3 a). Although power consumption increases at the same time, COP of JT cycle increases with rising supply pressure, as presented in Figure 3 b).

All in all, cooling capacity of JT cooler increases as supply pressure rises. We can attribute the improvement of cooling power to the rising mass flow rate. But the increase of COP demonstrates that there is another factor that deeply affects the performance of the JT cycle. In fact, as mass flow rate rises with increasing supply pressure, the flow resistance of JT orifice rises. That is to say, when flow resistance of JT orifice increases, more cooling power is achieved at the cost of per unit power. In other words, more cooling power is gained when the same power is consumed. Thus, COP of JT cycle is improved as flow resistance increases.

3.2. Influence of the JT orifice

JT orifice is one of the critical components of JT cooler. And higher flow resistance of JT orifice is preferred due to the research above. So, orifices with diameter of 25μm, 30μm and 38μm are experimentally studied in this part. In the experimental study, suction pressure is fixed at 0.13MPa and charge pressure varies to make sure that mass flow rate is about 4.7 mg/s.

When mass flow rate is same, the flow resistance of smaller orifice is higher. And Figure 4 a) shows that cooling capacity of JT cooler decreases and power consumption increases as diameter of JT cooler increases. That means orifice with higher flow resistance gains more cooling capacity and consumes relatively less electrical power. So COP of JT cooler increases as diameter of JT orifice decreases, as shown in Figure 4 b).

When the mass flow rate is fixed, the discharge pressure will decrease a little as diameter of the orifice increases. But in this case, the flow resistance is determined by the dimension of JT orifice. The flow resistance of the JT orifice decreases with increasing diameter of JT orifice. Therefore, more electrical power is consumed by the JT compressor to maintain the suction pressure fixed at 0.13MPa and more cooling capacity is measured at the evaporator. That is to say, flow resistance of JT orifice influences the COP of the JT cycle. Thus, cooling capacity decreases as diameter of JT orifice increases when mass flow rate is the same. In the extreme case, when the JT orifice is larger than 60μm, we can hardly achieve any cooling capacity with mass flow rate of 4.7 mg/s.
4. Conclusions
Based on the hybrid 4.5K JT cryocooler developed by our laboratory, experimental research is carried out on the influence of stage of compression, charge pressure and JT element to explore the performance of the JT cycle. Cooling capacity and COP of JT cooler improve with rising supply pressure due to the increase of mass flow rate. And COP of JT cycle increases as diameter of orifice decreases. Flow resistance of JT orifice is one of the key factors that affect the performance of the 4.5K JT cooler.

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