Experimental Investigation of High-Efficiency 4K GM Cryocoolers

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ABSTRACT

The power consumption for a conventional 1W 4K GM cryocooler at Sumitomo Heavy Industries, Ltd. (SHI) is about 7 kW when the compressor is operated at 60 Hz and about 6 kW at 50 Hz. Recently, SHI developed a high-efficiency 4K GM cryocooler. The typical cooling capacity of 40 W at 38.4K for the first stage and 1.0 W at 4.04K for the second stage has been achieved. The compressor is operated at 50 Hz and the input power is 4.1 kW, which is about 30% less than that of a conventional 1W 4K GM cryocooler. The efficiency of a 4K GM cryocooler has been optimized by improving the configuration of the scotch yoke and reducing the losses in the rotary valves, the regenerators and the heat exchangers.

The cooling performance vs. the initial charging pressure, the orientation and the magnetic regenerator material amount were investigated. As the charging pressure increases, the temperature at the first stage decreases, while the effect on the second stage is small. When the cold head is tilted, the reduction of cooling capacity at both the first and the second stage is within 5% in any direction. With a 44 W heat load at the first stage and 1.0 W at the second stage, the temperature is 41.3 K at the first stage and 4.02 K at the second stage when the cold stage is installed downward. In a horizontal direction, the temperatures are 41.7 K and 4.05 K. In an upward direction, the temperatures are 42.7 K and 3.99 K. Since the second stage performance is strongly dependent on the regenerator efficiency, it is possible to further improve the performance by simply increasing the magnetic regenerator material. The second stage cooling capacity increases from 1.0 W at 3.99 K to 1.0 W at 3.86 K when the magnetic regenerator material is increased by about 50%.

The detailed experimental results will be reported in this paper.

INTRODUCTION

Since 1990, the efficiency of a 4K GM cryocooler has been continuously improved by optimizing the operation parameter[1,2] and valve timing[3].

It is well known that the 4K GM cryocooler has been used widely for cooling superconducting magnets, such as magnets in MRI systems. A large amount of power in an MRI system is consumed by the cryocooler. Especially at night, more than half the power is consumed by the cryocooler since no diagnosis is performed. The power consumption for an SHI conventional 1W 4K GM cryocooler is about 7kW when the compressor is operated at 60 Hz, and about 6kW at 50 Hz.

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Figure 1. Photo of an F-40 compressor.

Figure 2. Photo of a high-efficiency cold head.

Recently, in order to reduce the power consumption of the cryocooler, SHI developed a high-efficiency 4K GM cryocooler. A simulation model was built to estimate the cooling capacity and losses, and to optimize the operating parameters and the dimensions of key components. Using the simulation program, an experimental model of a high-efficiency cold head was designed, built and tested[4]. The cooling performance of the resulting high-efficiency cold head vs. initial charging pressure, orientation and magnetic regenerator material amount will be reported in this paper.

EXPERIMENTAL SYSTEM

A F-40 prototype compressor (Fig. 1) is used to drive the high-efficiency cold head (Fig. 2). In a high-efficiency cold head, the inner diameter and the length of the cylinder are the same as a SHI conventional 1W 4K GM cryocooler. The interface for mounting the cooling object is also the same as that of a conventional 1W 4K GM cryocooler. The parameters of the key components were designed using a numerical simulation program, and then further optimized by experiments. The valve timing and the configuration of the scotch yoke is optimized to improve the phase shift between the pressure and the displacement of the displacer. The dimensions and the regenerator material of the first stage regenerator are optimized in order to reduce the void volume and enhance the heat exchange coefficient. The magnetic material amount in the second stage regenerator is minimized in order to reduce magnetic noise and cost. The heat exchangers are optimized to reduce the pressure drop and to enhance the heat exchange coefficient.

EXPERIMENTAL RESULTS

Effect of Initial Charging Pressure

Figure 3a shows the power consumption with different initial charging pressures. The power consumption is measured with a heat load of 44W at the first stage and 1.0W at the second stage. All of the experimental results reported in this paper were measured when the compressor was operated at 50 Hz. In general, the power consumption increases as the initial charging pressure increases. The typical power consumption is about 4.1kW at 50 Hz with a charging pressure of 1.4 MPa.

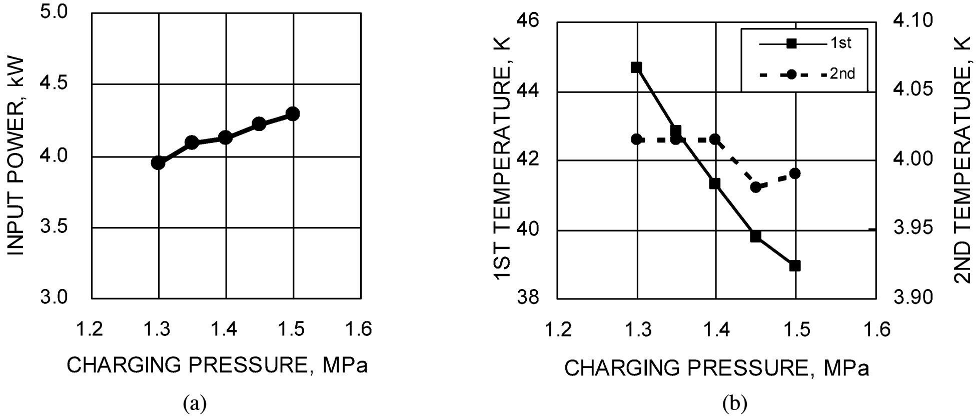

Figure 3. Effect of charging pressure with 44 W and 1.0 W heat loads. (a) input power; (b) temperatures.

Figure 3b shows the cooling temperatures with different charging pressures when the heat load is 44W at the first stage and 1.0W at the second stage. As the charging pressure increases, the temperature at the first stage decreases, while the effect on the second stage is small. At higher charging pressures, the mass flow rate from the compressor increases, which results in increasing the ideal cooling capacity. The net cooling capacity of the first stage is strongly dependent on the ideal cooling capacity, while the net cooling capacity of the second stage is mainly dependent on the regenerator efficiency. It is a typical behavior of a two-stage 4K GM cryocooler. The cooling capacity is 44W at 41.3K at the first stage and 1.0W at 4.02K at the second stage, with a charging pressure of 1.4 MPa. The input power is about 4.1 kW. This indicates that the cooling capacity of a high-efficiency GM cryocooler is similar to that of a conventional 1W 4K GM cryocooler with about 30% less input power.

Orientation Dependence

Since the second displacer of a high-efficiency cryocooler is similar to a conventional 4K GM cryocooler, it is expected that the cooling performance will be orientation-free. In order to confirm this behavior, the orientation dependence of the cooling performance was also investigated. Figure 4 shows the orientation dependence of the cooling performance when the heat load is 44 W at the first stage and 1.0 W at the second stage. The 0 deg. orientation angle corresponds with the cryocooler oriented vertically with the cold stage pointed downward. As shown in Figure 4, when the cold stage is installed downward, the temperature is 41.3 K at the first stage and 4.02K at the second stage, respectively. In the horizontal position, the temperatures are 41.7K and 4.05K. In the upward direction, the temperatures are 42.7K and 3.99K. When the cold head is tilted, the reduction of cooling capacity at both the first and the second stage is within 5% in any direction.

Effect of Magnetic Material Amount

In order to reduce cost, the amount of magnetic regenerator material in a high-efficiency 4K GM cryocooler is minimized. Since the second stage performance is strongly dependent on the regenerator efficiency, it is possible to further improve the performance by simply increasing the magnetic regenerator material. Figure 5 shows the second cooling temperature vs. the normalized amount of magnetic regenerator material. As shown in Figure 5, the second stage temperature with 1.0W heat load decreases from 3.99K to 3.86K when the amount of the magnetic regenerator material is increased by about 50%.

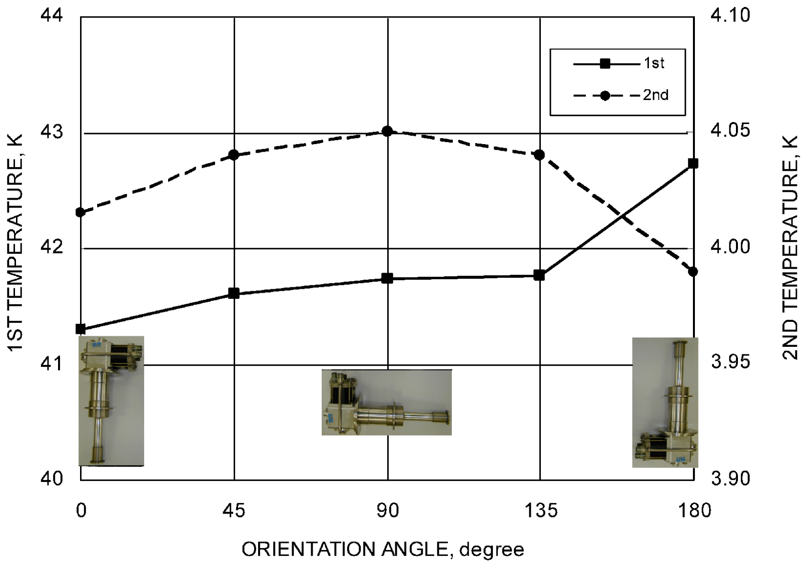

Figure 4. Orientation dependence of cooling performance.

Typical Cooling Capacity

Figure 6 shows a typical cooling load map for an experimental unit. The typical cooling capacity of 40 W at 38.4K at the first stage and 1.0W at 4.04K at the second stage, which is almost the same as that of an SHI conventional 1W 4K cryocooler, has been achieved. The compressor is operated at 50 Hz and the cold head is operated at 1.0 Hz. The initial charging pressure is 1.4 MPa. With 44W at the first stage and 1.0W at the second stage, the input power of the compressor is about 4.1kW, which is about 30% less than that of a conventional 1W 4K GM cryocooler.

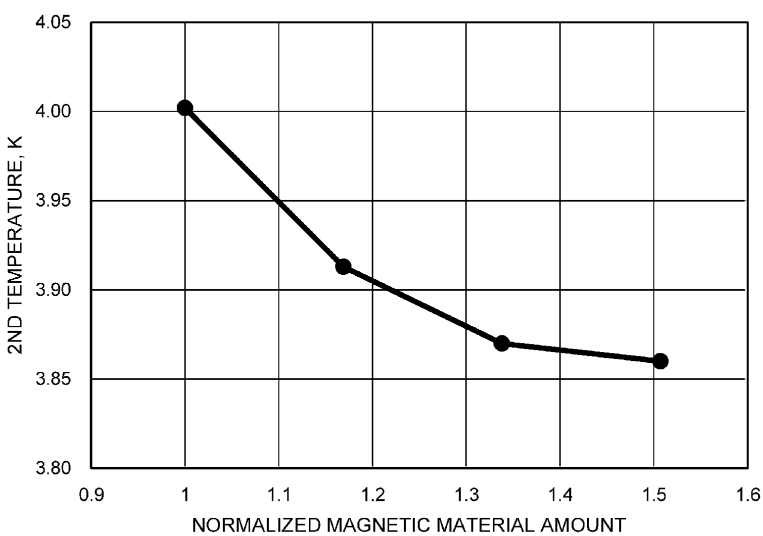

Figure 5. Effect of magnetic material amount in the second stage regenerator

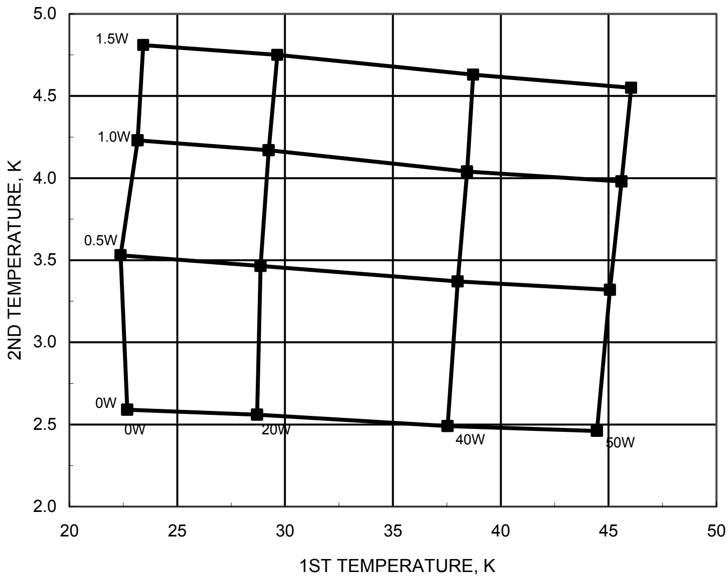

Figure 6. Typical cooling load map of a high-efficiency 1W 4K GM cold head with an F-40 compressor.

CONCLUSION

A high-efficiency 4K GM cryocooler has been developed. A typical cooling capacity of 40W at 38.4K at the first stage and 1.0W at 4.04K at the second stage has been achieved. The input power is reduced by about 30% compared to a conventional 1W 4K GM cryocooler.

As the charging pressure increases, the temperature at the first stage decreases, while the effect on the second stage is small.

When the cold head is tilted, the reduction of cooling capacity at both the first and the second stages is within 5% in any direction.

The second stage temperature with a 1.0W heat load decreases from 3.99K to 3.86K when the magnetic regenerator material is increased by about 50%.

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