Achievement of 120 W at 80 K by synchronous operation of two single-stage G-M cold heads driven by a 2 kW class compressor

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ABSTRACT

In order to improve the cooling capacity and efficiency of a Gifford-McMahon (G-M) cryocooler, synchronous operation of two single-stage G-M cold heads driven by a 2 kW class compressor was experimentally investigated. The pair of flexible hoses was branched into two pairs near the compressor, and then two pairs of hoses, each 10 m long, were connected to each cold head. Two synchronous modes, in-phase and reverse phase, were carried out. In the in-phase mode, two vertically moving displacers of the G-M cold heads reach top and bottom dead center simultaneously. In the reverse phase mode, when one of the displacers reaches top dead center, the other simultaneously reaches bottom dead center, and vice versa. The experimental results showed that two synchronous modes had almost the same cooling capacity in the measured temperature range. The cooling capacity achieved at 80 K was 123 W, which was 1.4 times larger than that of a single cold head operated with the same compressor. The relative Carnot efficiency was calculated to be 16%. These results prove that synchronous operation of two G-M cold heads is highly efficient at the temperature of liquid nitrogen.

INTRODUCTION

Regenerative cryocoolers with large cooling capacity and low power consumption can reduce the running cost of advanced systems in which they are attached. Gifford-McMahon (G-M) cryocoolers are considered representative regenerative cryocoolers, because they can cover temperatures from 4 to 80 K. For this reason, the G-M cryocoolers have been widely used for various applications, such as cryopumps for semiconductor production, cooling for super-conductors, and recondensing, heat exchanging and liquefying some gases. [1-3] However, the relative Carnot efficiency has not been increased, and its value is not enough.

In recent years, some G-M cryocoolers with large cooling capacity have been designed and developed, which have the cooling capacity of 600 W class at 80 K. The relative Carnot efficiency is calculated to be at the level of 10%. [4-8]

On the other hand, the simultaneous operation of two cold heads could be one of the candidates to achieve a high cooling capacity. This method has been reported in pulse tube cryocoolers. [9-12] Two pulse tubes are combined to achieve optimum phase control or to eliminate the need for a reservoir tank. As a report on several G-M cold heads in operation, Jakob G. et al. presented the multiple system consisting of three cold heads and two compressors, which achieved the cooling capacity of 290 W at 80 K and the relative Carnot efficiency of 8.0% in 2010. [13]

In this study, two single-stage G-M cold heads were operated synchronously driven by one compressor to improve the cooling capacity and efficiency. The following sections describe the setup of our experimental apparatus, two operating modes of the G-M cold head, and the experimental results including cooling capacity, relative Carnot efficiency, and so on.

EXPERIMENTS SETUP AND OPERATING MODE

Experimental setup

Figure 1 shows a schematic diagram of the experimental setup. To implement the synchronous operation, two single-stage G-M cold heads (RD125, Sumitomo Heavy Industry) were installed in each vacuum chamber. The regenerator material of these cold heads was modified by authors. To reduce radiation heat, the cold stage and cylinder were wound with superinsulation (not shown in Fig. 1). The reciprocating speed of each cold head was controlled by an external inverter. The calibrated thermometers and electric heaters were attached to each cold stage. A displacement sensor (LP40, LEVEX) was mounted on top of the G-M cold head (room temperature side) to monitor the displacement of the displacer.

The pair of flexible hoses was branched into two pairs near a 2 kW class compressor (SSC-1100, Suzuki-Shokan), and then two pairs of hoses, each 10 m long, were connected to each cold head. Six pressure gauges (PGM-50KD, KYOWA), three mass flow meters (HFM-301, KOFLOC) mounted on each flexible hose, and two displacement sensors were simultaneously sampled by an AD converter (PCD-430A, KYOWA). Compressor electrical input and cold head motor power dissipation were measured with power meters (PW3336, HIOKI). A photo of two G-M cold heads and vacuum chambers is presented in Fig. 2.

Operating mode of G-M cold head

Two synchronous modes, which we call in-phase and reverse phase, have been carried out. In the in-phase mode, two vertically moving displacers of the G-M cold heads reach top and bottom dead center simultaneously. In the reverse phase mode, when one of the displacers reaches top dead center, the other simultaneously reaches bottom dead center, and vice versa. Figure 3 shows schematics of the vertical position of two displacers and the on/off timing of gas switching valves.

EXPERIMENTAL RESULTS

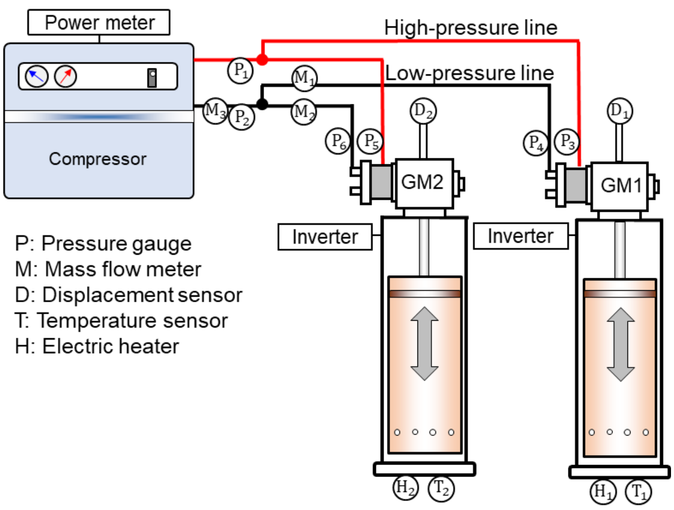

Figure 1. Schematic diagram of the synchronous operation, and the location of pressure gauges, mass flow meters, and displacement sensors.

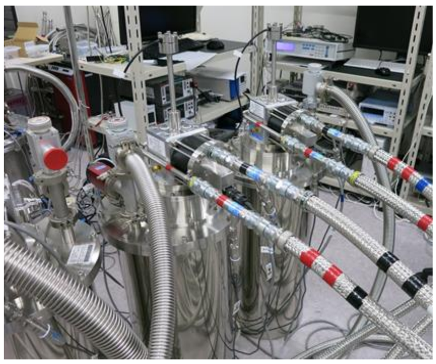

Figure 2. Photo of two G-M cold heads and vacuum chambers.

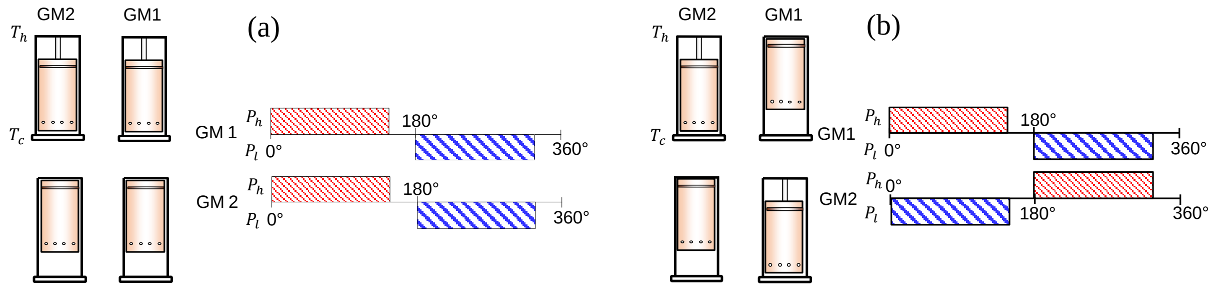

Figure 3. Diagrams of two operating modes and pressure gas switching valves, (a) in-phase mode, and (b) reverse phase mode. The hatched area represents the angle at which the gas switching valves are open. These valve timings are for illustrative purposes only.

The cooling capacity was measured under the following conditions: the initial charging pressure was 2.0 MPa, and the reciprocating speed of the cold head was 96 rpm. The vacuum in the vacuum chamber evacuated by the turbo molecular pump was less than 10^{-4} Pa.

Stand-alone operation (single head)

First, we confirmed the cooling capacity of two G-M cold heads by stand-alone operation (hereinafter called single head) as shown in Fig. 4. The maximum difference in cooling capacity was 7% in the measured temperature range from 18 to 85 K. In the following, as a single head, the cooling capacity, suction mass flow results are given as the average of two cold heads. From Fig. 4, the average cooling capacity at 80 K was 87 W.

Synchronous operation of two cold heads

Since the two cold heads were set in their own vacuum chambers as shown in Figs. 1 and 2, the average of two thermometers (T_1 and T_2) and the sum of two electric heaters (H_1 and H_2) were used to measure the cold stage temperature and cooling capacity, respectively. Figure 5 shows the results for in-phase mode and reverse phase mode, as well as single head cooling capacity. As shown, two synchronous modes have almost the same cooling capacity. The effect of the synchronous mode is seen above 40 K. The cooling capacity achieved at 80 K is 123 W, which is 1.4 times larger than that of the single head. Figure 6 presents the comparison with the calculated relative Carnot efficiency. The electrical input used for the calculation was the compressor power and the cold head motor power. All three curves are convex, with a peak around 50 K the maximum value of which is 18%. At 80 K, it is estimated to be 16% (total electrical input of 2.1 kW). The relative Carnot efficiency at 80 K of major cryocoolers was summarized by R. Radebaugh [14] as shown in Fig. 7. The 16% efficiency obtained in this study is also plotted (star shape). These results prove that this study of synchronous operation has demonstrated a very high efficiency compared to other G-M cryocoolers and almost the same as Stirling cryocoolers.

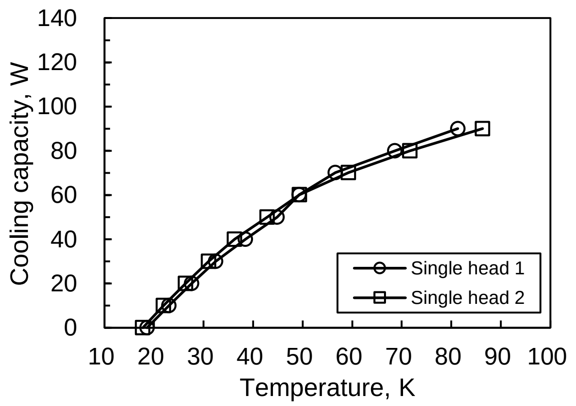

Figure 4. Comparison of two G-M single cold heads cooling capacity.

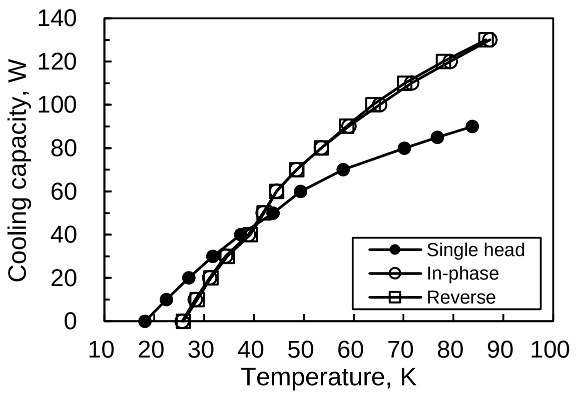

Figure 5. Cooling capacity results for in-phase mode, reverse phase mode of synchronous operation, and single head.

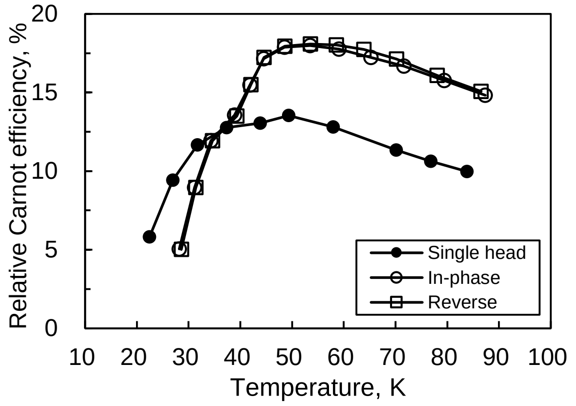

Figure 6. Temperature dependence of relative Carnot efficiency calculated from the cooling capacity results.

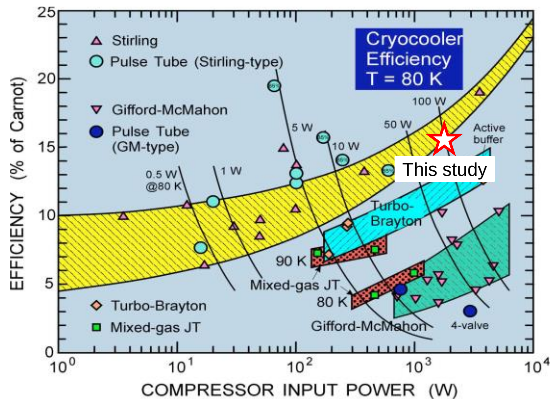

Figure 7. Comparison of relative Carnot efficiency at 80 K of major cryocoolers [14] and the synchronous operation of two G-M cryocoolers in this study (star shape).

Pressure and displacement measurements

Figure 8 shows the pressure waves on the high- and low-pressure lines, and the displacer displacement at 80 K: (a) is the single head operation, (b) and (c) are in-phase and reverse phase modes, respectively. The pressure gauges from P_3 to P_6 and the displacement sensors of D_1 and D_2 of Fig. 1 are used. Normalized displacement of 0 and 1 means that the displacer reaches bottom dead center (minimum expansion volume) and top dead center (maximum expansion volume). As shown in Fig. 8 (a), when the normalized displacement is 0, the high-pressure valve opens and the high-pressure line drops. Conversely, when the normalized displacement is 1, the low-pressure valve opens and the low-pressure line rises.

In the in-phase mode, Fig. 8 (b), the phase difference of two pressures is almost zero, however, two displacements have a difference of 60°. This phase difference occurs automatically after

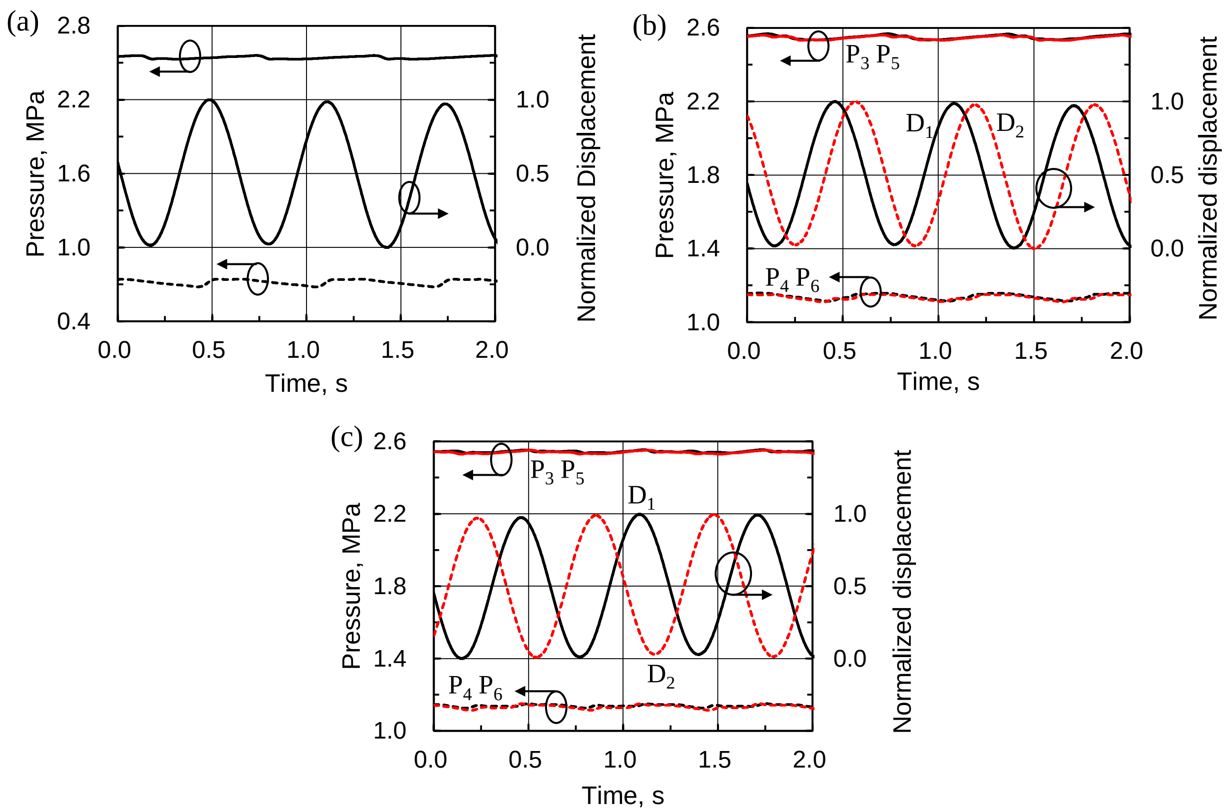

Figure 8. Pressure of high- and low-pressure lines and normalized displacement of displacer at 80 K: (a) single head, (b) in-phase mode, and (c) reverse phase mode. The location of pressure sensors (P_3-P_6) and displacement sensors (D_1, D_2) refer to Fig. 1.

cooling from room temperature. Similarly, in the reverse mode, Fig. 8 (c), the phase is automatically shifted from 180° to 220° after a cool-down start. Comparing the pressures, the high pressure is almost the same, and the low pressure is higher in two synchronous modes that lead to a decrease in the pressure ratio.

Mass flow measurements

Figure 9 shows the results of the suction mass flow at 80 K: (a) is the single head operation, (b) and (c) are in-phase mode and reverse phase mode, respectively. The plotting timing of the time axis corresponds to that in Fig. 8. The location of three mass flow sensors is shown in Fig. 1. The suction mass flow M_1 and displacement D_1 are values obtained from GM_1 cold head, and M_2 and D_2 are values obtained from GM_2 cold head. From the single head operation shown in Figs 8 (a) and 9 (a), the low-pressure valve opens when the displacer passes the top dead center, then the suction mass flow reaches the peak value.

In the in-phase mode, Fig. 9 (b), M_1 and M_2 have an inverse phase relationship. When M_1 reaches its maximum value, M_2 simultaneously reaches its minimum value. Note that a positive flow means helium is flowing toward to the compressor side, and a negative flow means helium is flowing toward to the cold head side. Interestingly, the waveform of M_3 is similar to that of single head shown in Fig. 9 (a). In the reverse mode, Fig. 9 (c), M_1 and M_2 have an inverse phase relationship, which is the same as in the in-phase mode, but the difference between the maximum and minimum values is large. Furthermore, the waveform of M_3 is more pulsating, having two peaks in a cycle. Consequently, the cooling capacity can be independent of the operating mode. In each operating mode, the movement of two displacers and the mass flow seem to automatically adjust to stable condition.

The comparison of the suction mass flow of the single head and two synchronous modes is shown in Fig. 10. The average of two mass flow meters (M_1 and M_2) was used for "In-phase (M_1, M_2)" and "Reverse phase (M_1, M_2)". These values are about half of the single head values above 40 K, but the mass flow of M_3 is about 1.8 times that of the single head. One reason for this large

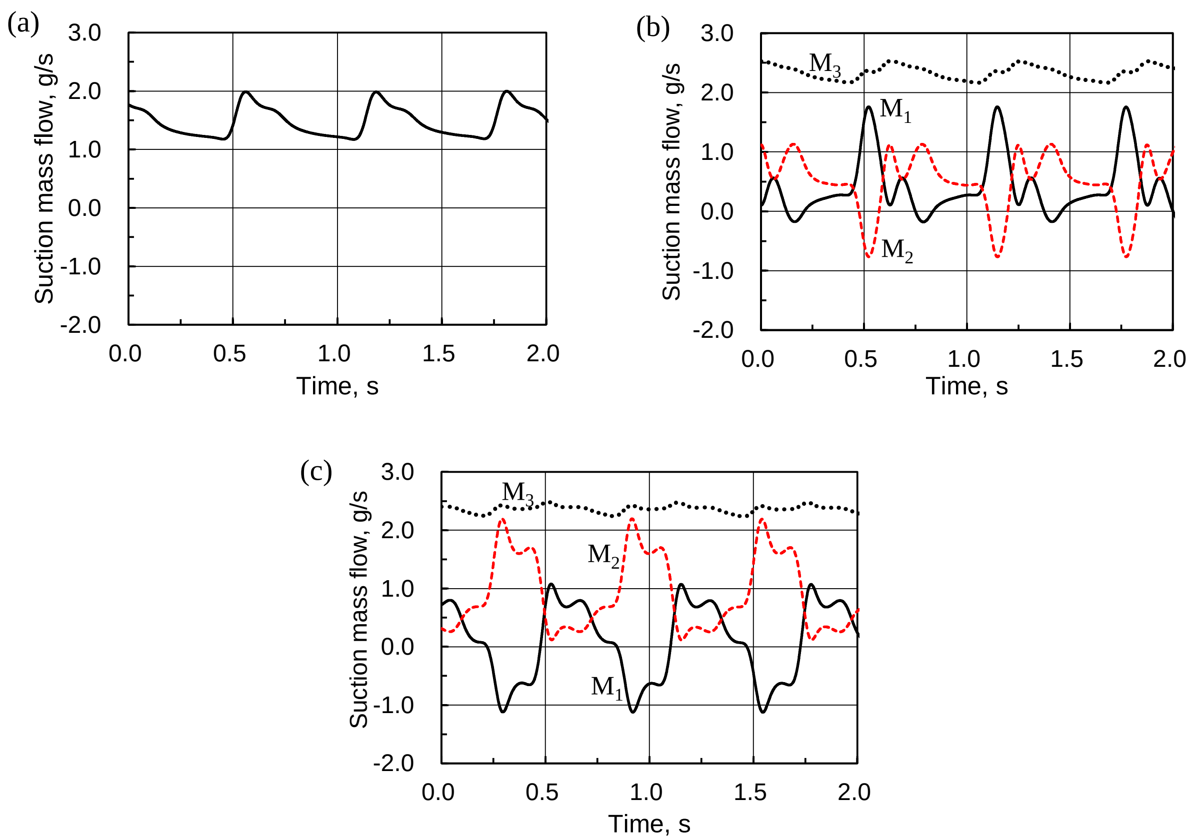

Figure 9. Results of suction mass flow measurement at 80 K: (a) single head, (b) in-phase mode, and (c) reverse phase mode. The location of mass flow meters (M_1-M_3) refers to Fig. 1.

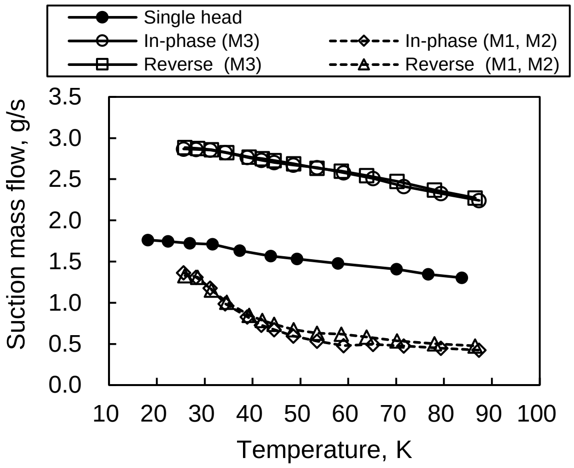

Figure 10. Temperature dependence of suction mass flow of single head, in-phase mode and reverse phase mode.

mass flow is probably a difference in pressure ratio. The pressure ratio at 80 K for single head and two synchronous modes was 3.0 and 2.2, respectively. From the compressor characteristics, a small pressure ratio results in a high mass flow. In two synchronous modes, although the mass flow decreases with increasing temperature, the movement of the two cold heads, including the displacers and gas switching valves, is considered to automatically compensate for the reduction in mass flow, resulting in improved cooling capacity above 40 K.

SUMMARY

The synchronous operation of two single-stage G-M cold heads driven by one compressor was experimentally investigated. Two operating modes, which we call in-phase and reverse phase modes, were tested. As a result, they showed the same cooling capacity. The achieved cooling capacity and the relative Carnot efficiency at 80 K were 123 W and 16%, respectively. In each operating mode, the displacement of two displacers and the mass flow seem to automatically adjust to stable condition, and the cooling capacity is predicted to be independent of the operating mode. This study proved that synchronous operation of two G-M cold heads is highly efficient at the temperature of liquid nitrogen. As a next step, the synchronous operation of two larger G-M cold heads will be tested.

ACKNOWLEDGMENT

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