Performance analysis of the active magnetic regenerative refrigerator for 20 K

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ABSTRACT

An active magnetic regenerative refrigerator (AMRR) with the conduction cooled high temperature superconducting (HTS) magnet is fabricated and experimentally investigated. Key components of the AMRR are two-stage multi-layered active magnetic regenerator (AMR), conduction cooled HTS magnet, and the helium gas flow system. Since magnetic refrigerants are only effective in the limited temperature range near their Curie temperatures, the layered structure with four magnetic materials ($GdNi_2$, $Gd_{0.1}Dy_{0.9}Ni_2$, $Dy_{0.85}Er_{0.15}Al_2$, $Dy_{0.5}Er_{0.5}Al_2$) is employed on the AMR to increase its temperature span. The AMR is designed to operate with the temperature range between 80 K and 20 K. The HTS magnet, being cooled down by a two-stage Gifford-McMahon (GM) cryocooler, produces maximum magnetic field of 3 T for the AMR. DC power supply, a solenoid current switch and an external dump resistor are used for a continuous ramping operation of the HTS magnet. Oscillating helium flow in the AMR is induced and controlled by the helium compressor and four solenoid valves. This paper presents the experimental results of the AMR system operating between 80.8 and 21.8 K and discusses technical issues on the results.

INTRODUCTION

An AMRR is a type of magnetic refrigerator which utilizes magneto-caloric effect (MCE) for refrigeration. Early magnetic refrigerator such as an adiabatic demagnetization refrigerator (ADR) has been only employed to obtain sub-Kelvin temperature [1]. However, adoption of an active magnetic regenerator concept has enabled researchers to use MCE for refrigeration with a large temperature span. An AMR system can achieve much larger temperature lift than that of ADR by effectively utilizing a magnetic refrigerant as a regenerator and as an active magnetic component. Due to its advantage, an enormous number of AMRRs operating at room temperature have been reported [2-4]. However, only a few AMRRs working below liquid nitrogen temperature have been developed and investigated over the past several decades [5 - 11].

Since the energy interaction of MCE is an inherently reversible process, AMRR has high thermodynamic potential to improve the efficiency of hydrogen liquefaction. In order to achieve wide temperature span of an AMR, large magnetic entropy change over broad temperature range is indispensable [12]. Although an AMR can operate at larger temperature span than adiabatic temperature rise of a magnetic refrigerant, the temperature span is still limited because sufficiently large MCE of a typical magnetic refrigerant appears over limited temperature range. For instance, Numazawa et al. [8] experimentally investigated single layered AMRs with three different kinds of magnetic refrigerants (GGIG, $HoAl_2$, and $DyAl_2$) and the maximum temperature span of 12 K was achieved at the maximum magnetic field of 1.8 T. Moreover, they proposed three stage of AMR to cover the temperature span between 77 K and 20 K. Limitation of a single AMR can be overcome by using a multi-layered AMR. Two stage, two-layered AMR [10, 11] is reported in the previous research with the operating temperature span of 50 K.

An AMR requires magnetic field variation during operation. A superconducting magnet is an appropriate candidate as a magnetic field generator for a cryogenic device such as a hydrogen liquefier. Previous research groups [8, 9] used direct current (DC) superconducting magnet to apply the necessary magnetic field to the AMR. The magnetic field variation of the AMR was possible by relative displacement between the AMR and the magnet. However, continuous movement of an experimental device in cryogenic environment often undermines its reliability. For a static AMRR, alternating current (AC) low temperature superconducting (LTS) magnet was selected by previous researchers [10, 11] to create magnetic field variation. During the AMR experiment, expensive liquid helium was filled in the cryostat to remove heat from the LTS magnet caused by AC loss. Using liquid helium is neither an attractive nor efficient way for creating 20 K which enables a potential refrigeration system to liquefy hydrogen. In order to fabricate a cryogen-free system, a conduction cooled high temperature superconducting magnet must be prepared for being operated above 20 K. This paper describes an AMRR operating between 80 K and 20 K with the conduction cooled HTS magnet. The AMR system including the AMR, the HTS magnet and the helium oscillating flow system is presented and the experimental results are discussed.

EXPERIMENTAL SETUP

Conduction cooled HTS magnet system

The HTS magnet system employed in this paper is a modified version of the previously studied magnet [13]. Figure 1 shows the overall HTS magnet system. Ramping current generated by a DC power supply (KLN 40-76, Kepco) is applied to the magnet by passing through the

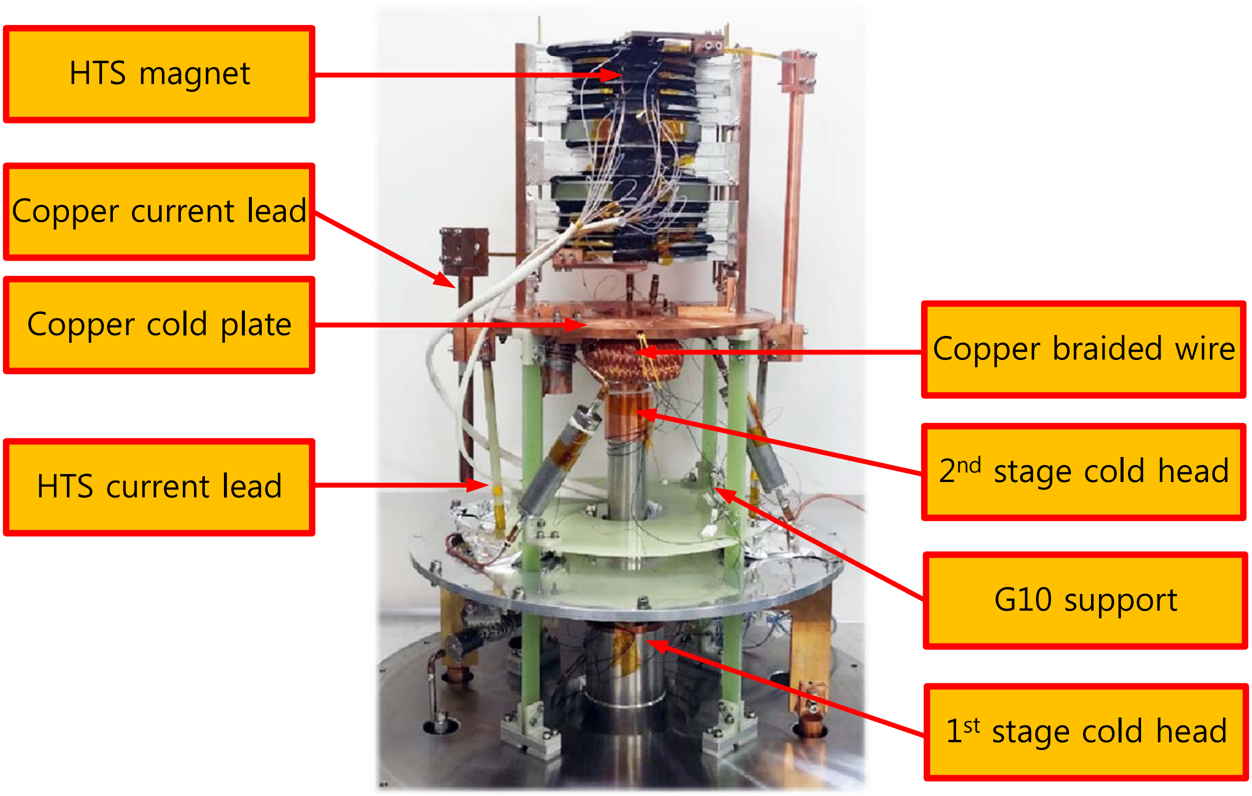


Figure 1. A photo of the HTS magnet system

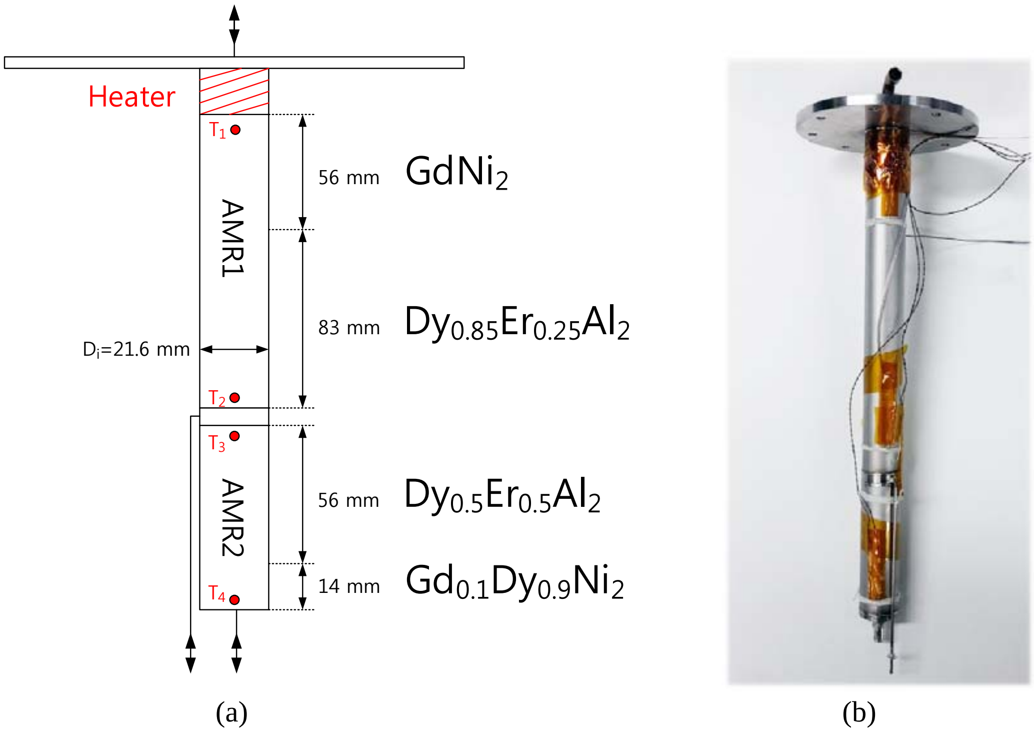


Figure 2. (a) Schematic diagram and (b) a photo of the AMR

conduction cooled hybrid current leads. The hybrid current lead consists of HTS and copper current leads. Since AC flows through the magnet, heat generation due to AC loss has to be effectively minimized and dumped to the environment. Maximum heat generation of the magnet in the experiment is 12 W with the operating frequency of 0.1 Hz and the magnet is conductively cooled to 20 K by a two-stage GM cryocooler (RDK-415D, Sumitomo). Thermally conductive components such as copper braided wires, a copper plate and copper supports enable the cryocooler to cool the magnet with negligible temperature difference. The magnet is composed of twelve double pancake coils which are connected to each other by superconducting joints. Each double pancake coil was wound by GdBCO conductor insulated with polyimide tape. The HTS coils are thermally connected to aluminum plates and aluminum wings by Stycast 2850FT in order to effectively remove heat generated from the coils. Maximum central magnetic field of 3 T is produced when the current of 150 A is provided for the magnet whose diameter is 26 mm.

Active magnetic regenerator

The two stage AMR is composed of four different kinds of rare-earth compounds and shown

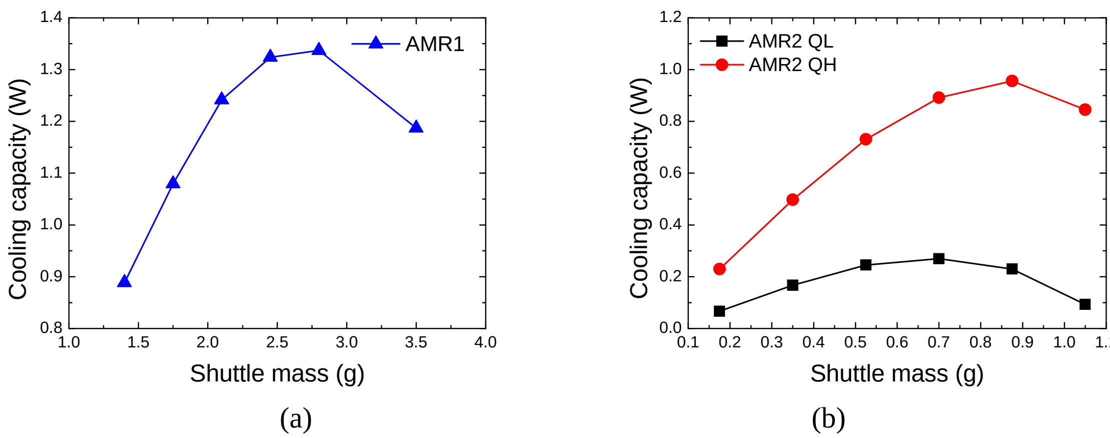


Figure 3. Cooling capacity of (a) first (AMR1) and (b) second stage (AMR2) of the AMR calculated by numerical simulation

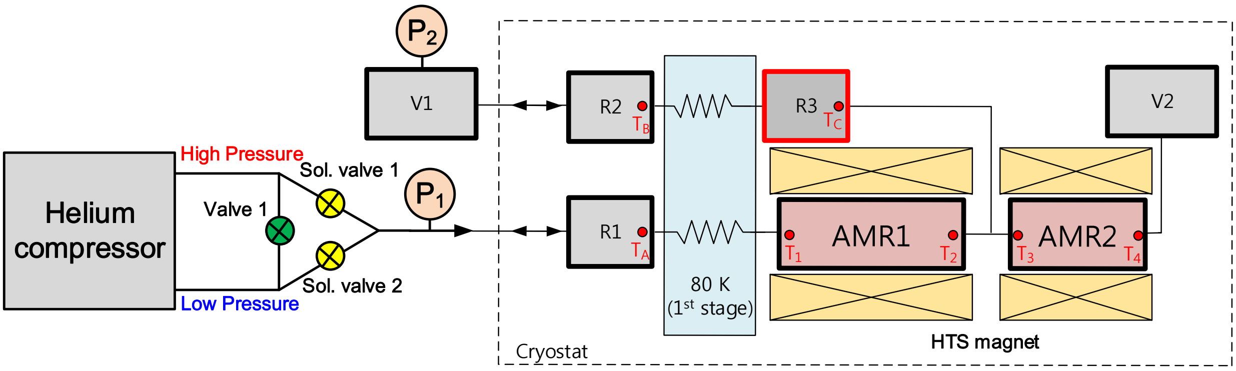
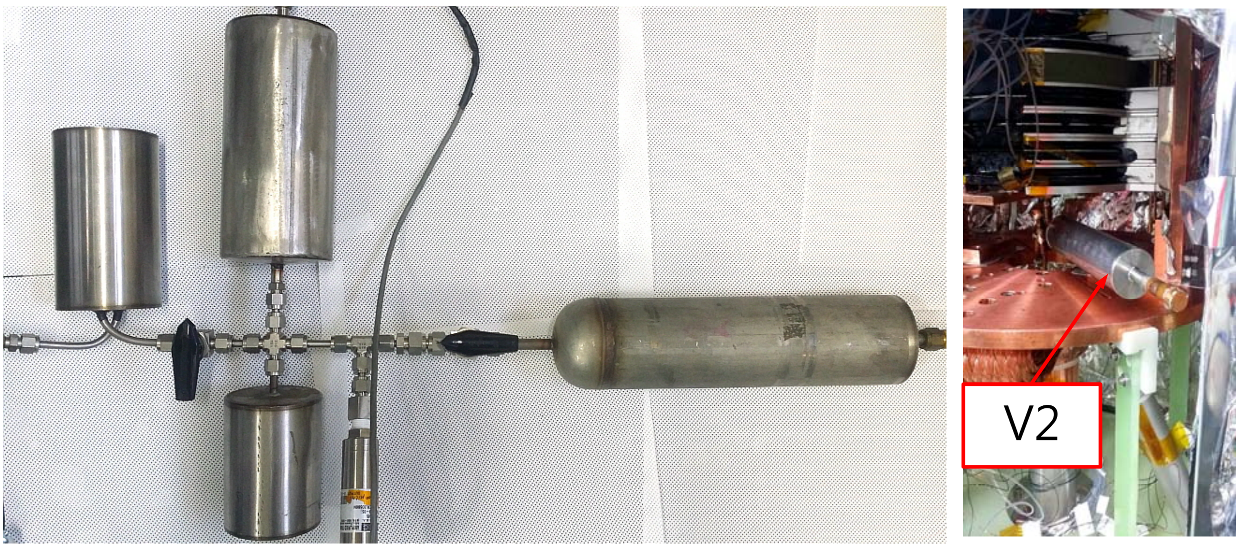


Figure 4. Helium gas oscillation flow system

in Fig. 2. The compounds are filled in the thin walled stainless steel tube with the inner diameter of 21.6 mm. The top end of the stainless steel tube is welded with stainless steel flange. The stainless steel flange is mechanically fixed to aluminum radiation shield by screws. Each compound is allocated in consideration of its primary transition temperature. $GdNi_2$ and $Dy_{0.85}Er_{0.25}Al_2$ which have relatively high transition temperatures are stacked in AMR1 while $Dy_{0.5}Er_{0.5}Al_2$ and $Gd_{0.1}Dy_{0.9}Ni_2$ are filled in AMR2 to cover low temperature region. A heater made by NiCr wire is installed in order to maintain 80 K at the warm end of the AMR1. Filling ratio of the AMR is determined by a one-dimensional time dependent numerical model and the numerical results are indicated in Fig. 3. Each operation temperature of AMR1 or AMR2 is set to 80 - 45 K or 45 - 20 K by numerical simulation. Precise numerical calculation method is well explained in previous study [14]. Because the heat capacity of AMR1 is much higher than that of AMR2, optimum amount of shuttle mass for AMR1 is larger than that of AMR2. Bypass line made of 1/16 inch stainless steel tube is installed between AMR1 and AMR2 to control the amount of the shuttle mass for each AMR. Four calibrated temperature sensors (Cernox, Lakeshore) are installed on the external surface of the AMR to measure the temperature variation. The experimental apparatus including the AMR and the HTS magnet in the cryostat is evacuated below 10^{-4} torr during the experiment.

Helium oscillation flow system

The helium gas oscillation flow system is illustrated in Fig. 4. The oscillating flow is



(a) (b)

Figure 5. Photo of the buffer volumes : (a) V1 composed of four stainless steel reservoirs and (b) V2 connected to the cold end of the AMR2

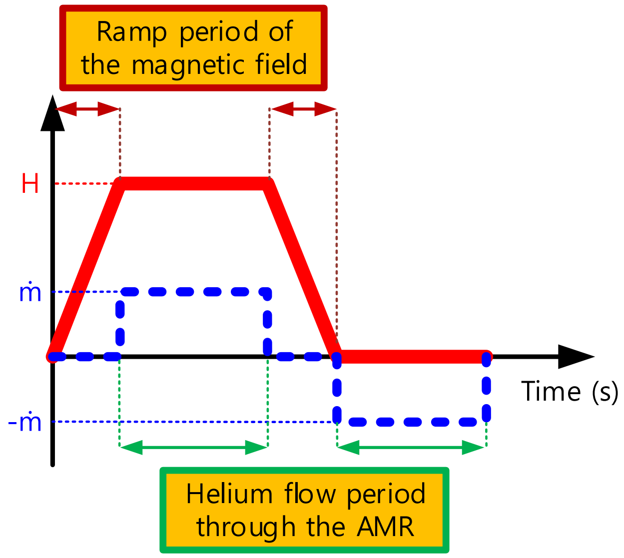


Figure 6. Magnetic field and mass flow rate variation during one cycle (the minus sign means down flow of the helium gas)

provided by a helium compressor (M125, Austin Scientific) and two solenoid valves. Helium compressor generates pressure difference and inlet pressure (P1) changes by opening two solenoid valves alternatively. When periodic inlet pressure variation occurs, helium gas flows through the AMR and its shuttle mass is determined by the size of the buffer volumes, V1 and V2. Figure 5 shows the fabricated buffer tanks to create the desirable amount of oscillating flow. Since the helium gas with ambient temperature enters into the cryostat, the gas is cooled by the first stage of GM cryocooler. Moreover, passive regenerators (R1, R2, R3) are added at the oscillating helium flow line to reduce the cooling load of the cryocooler and AMR1.

Table 1. Operating conditions of the AMR system

			Case 1	Case 2	Case 3
Cycle period (s)			20	30	40
Duration of mass flow during half cycle (s)			7	12	17
magnetization or demagnetization period (s)			3		
Buffer volume (m^3)		**V1**	2.79×10^{-3}		
		V2	4.83×10^{-5}		
Regenerator	**Length (m)**	**R1, R2**	0.2		
		R3	0.15		
	Diameter (m)	**R1, R2, R3**	0.248		
	Porosity (-)	**R1, R2, R3**	0.65		
P_1 (MPa)		**Max.**	1.3		
		Min.	0.3		
P_2 (MPa)		**Max.**	1.09	1.13	1.17
		Min.	0.76	0.67	0.58
Shuttle mass calculated by P_2 during half cycle (g)		**AMR1**	1.81	2.53	3.25
		AMR2	0.30	0.42	0.54

EXPERIMENTAL CONDITIONS AND RESULTS

Experimental process and operating conditions

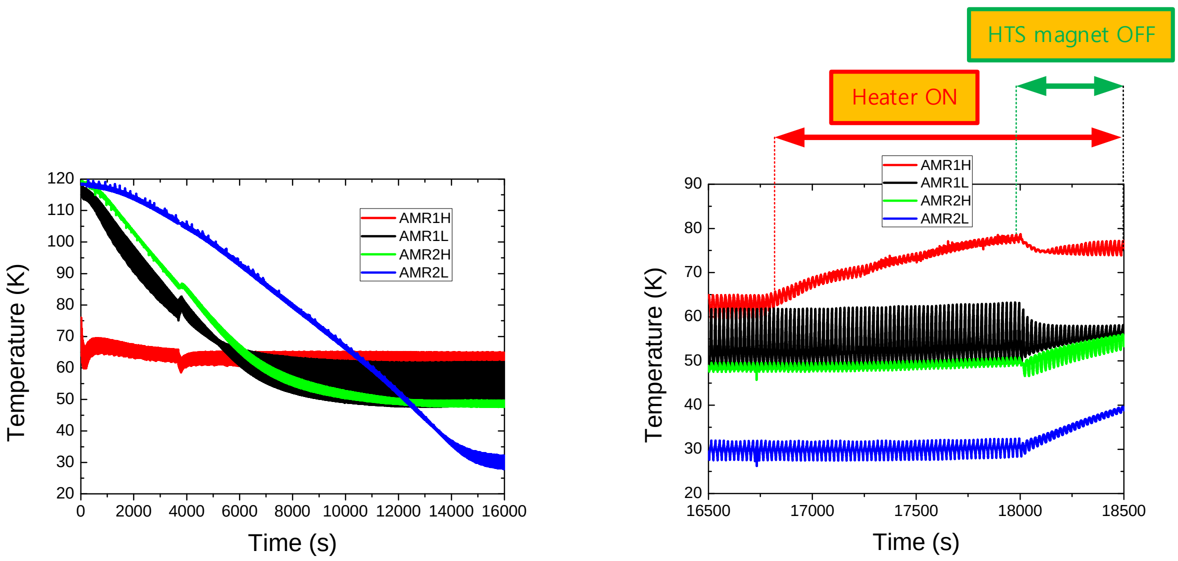
The experimental procedure is as follows:

1) Evacuate the AMR system for good thermal insulation
2) Cool down the AMR system including the HTS magnet and the AMR by a cryocooler
3) Proceed with HTS magnet test : continuous AC operation
4) Oscillate helium gas flow
5) Conduct the AMR experiment until the cyclic steady state is obtained
6) Change the operating conditions

The helium gas flow and the magnet field variation during one cycle are illustrated in Fig. 6. The AMR is pseudo-adiabatically magnetized without helium flow at first. When the magnetic field reaches its maximum value, the upflow is induced so that the heat generated during the magnetization process is rejected through the top of the AMR. Next, the AMR is demagnetized in a pseudo-adiabatic manner to create low temperature. The down flow after demagnetization produces a cooling effect at the bottom of the AMR. Three experimental cases are reported in this paper. Ramping up or down time of the magnetic field is set to 3 seconds in all cases while the constant magnetic field times or the flow period of the three cases are specified to 7, 12, 17 seconds, respectively. The oscillating helium flow is generated during the constant magnetic field period to simulate magnetic reverse Brayton cycle. The maximum amplitude of buffer volumes' pressure swing (P2) which is in proportion to the amount of the shuttle mass is controlled by helium flow time. The pressure swing amplitude increases as the gas flow time during half cycle lasts longer. The temperatures of the AMR, the pressures of the inlet and the buffer volume (V1) and the electric current supplied to the magnet are recorded by 10 samples per second using Labview program during the experiment. Summary of the operating conditions of three cases are presented in Table. 1.

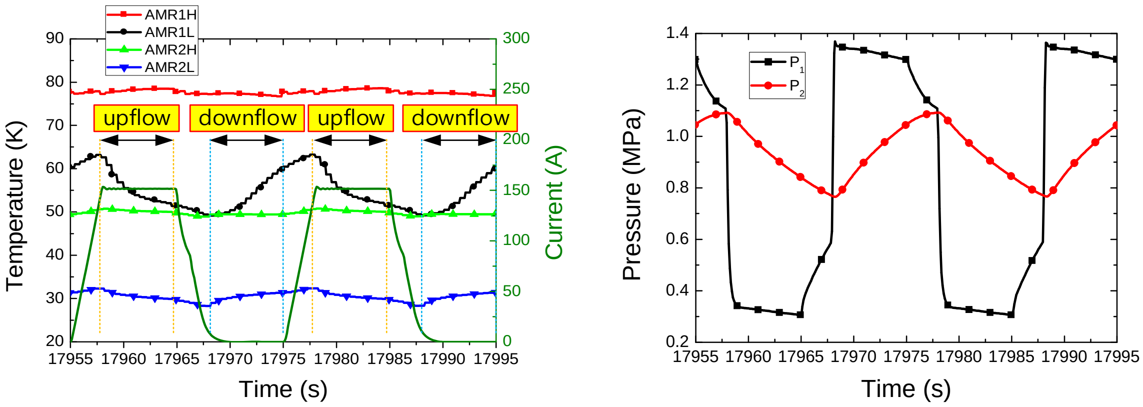
Experimental results and discussions

Figure 7 shows the temperature history of the AMR in case 1. The warm end of the AMR1 (AMR1H) is cooled to 60 K by the first stage of the GM cryocooler at the beginning of the operation. During of the AMR operation, we can observe that the temperature of the AMR



(a) (b)

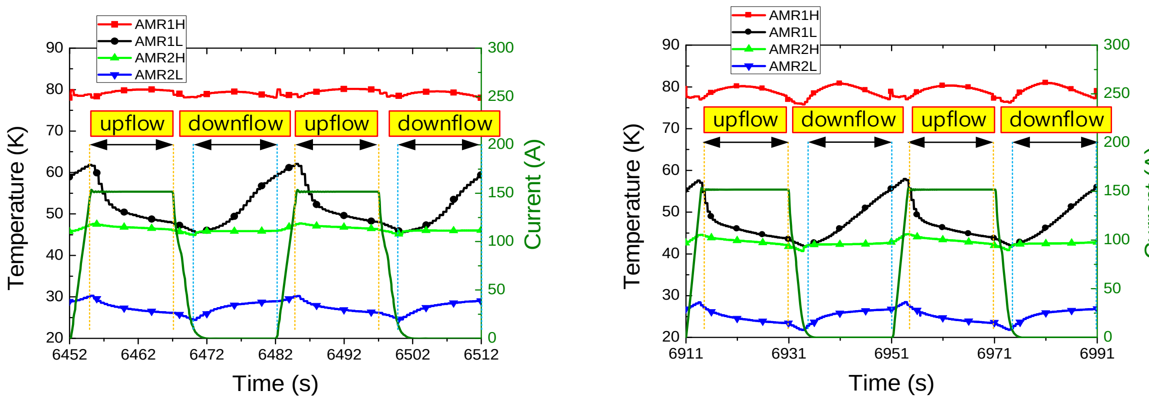
Figure 7. Temperature history of the AMR at case 1 (a) without (b) with heating of the AMR1H



(a) (b)

Figure 8. (a) Temperature variation of the AMR and (b) pressure variation of the P_1 and P_2 during two cycles at case 1

slowly decreases as shown in Fig. 7(a). A heater installed at the warm end of the AMR is turned on after the thermal cyclic steady state of the AMR is reached. The temperature of the AMR1H is held near 80 K by the heater as shown in Fig. 7(b). The no-load temperature spans and the lowest temperature of the AMR are 50.2 K and 28.3 K, respectively in case 1. If the AMR does not experience magnetic field variation, the overall temperature of the AMR slowly rises and it can be observed at Fig. 7(b) after 18000 seconds. The temperature variation during two cycles at the cyclic steady state is shown in Fig. 8(a). When the AMR is magnetized, the AMR temperature increases due to MCE. The cold ends of the AMR1(AMR1L) and AMR2(AMR2L) are cooled down by the upflow of the helium gas after magnetization. In contrast, the temperature of AMR1H slightly increases in upflow period. This means that the AMR dumps heat at the warm end by the upflow of helium gas which exchanges heat with the magnetic refrigerant. The AMR is demagnetized after the upflow of the helium gas and its temperature decreases. Finally, the temperature of the AMR increases in the downflow period because the heated helium gas from the warm end flows through the AMR and exchanges heat with the magnetic refrigerants. The pressure swing of the inlet of the AMR (P_1) and V1 (P_2) is shown in Fig. 8(b). The pressure variation of P_1 is identical in all cases. However, the amplitude of P_2 depends on the flow duration. It is interesting to note that the temperature span of the AMR increases in accordance with the amount of shuttle mass, even though the operating frequency of the AMR system decreases. The largest temperature span of 59 K is achieved in case 3 and the result is shown in Fig. 9(b). The shuttle mass of AMR1 in case 2 was estimated as the amount for optimal performance of the AMR1 in the numerical results as shown in Fig. 3. However, the largest temperature span of the AMR1 is achieved in the case 3. This discrepancy can stem from the inefficiency of R3. Since R3 is not an ideal regenerator, the cold end of R3 connected with



(a) (b)

Figure 9. Temperature variation of the AMR at (a) case 2 and (b) case 3

those of AMR1 deprives cooling capacity of AMR1 to maintain low temperature. The parasitic heat load by R3 is influenced by the operating frequency, the shuttle mass, and temperature span of R3. If V1 is installed in the cryostat by removing R2 and R3, we can directly compare the experimental results with the numerical results. The pressure swing of helium gas in V2 is not directly measured in this paper. If we assume the pressure swing in V2 is identical to that in V1, the shuttle mass of AMR2 can be estimated and the results are included in Table 1. Because the calculated shuttle masses in three cases are smaller than the optimal value (0.7 g) which is predicted by the numerical results of Fig. 3, the temperature span of AMR2 is expected to be further increased by transferring more shuttle mass of helium gas.

CONCLUSIONS

The multi-layered AMR operating between liquid nitrogen and hydrogen temperatures is designed, fabricated and tested. Four different kinds of magnetic refrigerants are arranged in the AMR bed. The cold end of the AMR reaches no-load temperature of 21.8 K and the maximum temperature span of 59 K is achieved. The performance of the AMR is investigated with various shuttle masses of helium gas. The temperature span of the AMR is increased with the increased the shuttle mass of helium. The numerical results predict that the performance of the AMR should decrease if the amount of the shuttle mass exceeds a certain value. In order to observe the performance tendency of the AMR, the buffer volumes (V1, V2) should be enlarged to increase the shuttle mass. Furthermore, the ineffectiveness of the auxiliary passive regenerator (R3) deteriorates the performance of the AMR1. Installation of the buffer volume, V1 in the cryostat will minimize heat leak at the cold end of the AMR1.

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