3.11.2

J-PARC cryogenic hydrogen system improvement for stable long-lasting operation

Hideki Tatsumoto[1], Kiichi Ohtsu[1], Tomokazu Aso[1], Yoshihiko Kawakami[1]

J-PARC Center, JAEA, Tokai, Ibaraki 319-1195, Japan.

E-mail: tatumoto@post.j-parc.jp

Abstract. The J-PARC cryogenic hydrogen system provides cryogenic hydrogen at a supercritical pressure of 1.5 MPa, whose temperature is less than 20 K, to three moderators so as to produce pulsed cold neutron beam with superior neutronic performance. The nuclear heating is estimated to be 3.75 kW at the moderators for a 1-MW proton beam operation. The heat load added to the hydrogen system is removed through a heat exchanger by a helium refrigerator with a refrigeration power of 6.45 kW at 16.5 K. Although the proton beam power has gradually increased up to 300 kW since April 2008, long-lasting stable operation of the helium refrigerator had never been conducted because of the performance degradation of the heat exchanger until 2010. It was clarified that the performance degradation was caused by impurities such as moisture and nitrogen adsorbed on an activated charcoal located downstream of the compressor. In 2011, we prepared a purification system, which consisted of a cryogenic adsorber, a dryer filled with zeolite and a heater for regeneration, and impurity detectors. As a result, long-lasting stable operation has been successfully achieved for 95 days.

1. Introduction

At the J-PARC spallation neutron source, high-energy MeV-order neutrons generated from a mercury target are reduced to an appropriate energy level (meV order) in three types of hydrogen moderators (i.e., coupled, decoupled, and poisoned). Fig. 1 shows a schematic of the J-PARC cryogenic hydrogen system, which provides supercritical cryogenic hydrogen to the moderators at a supercritical pressure of 1.5 MPa and temperature of 18 K and removes 3.8 kW of nuclear heating for the 1-MW proton beam operation [1]. The temperature rise is estimated to be 2.4 K at a circulation flow rate of 0.19 kg/s. It is cooled by a helium refrigerator with a refrigeration power of 6.45 kW at 15.6 K [2]. There was a concern that a slight temperature rise would lead to a large pressure increase in the hydrogen loop because the supercritical hydrogen behaves as an incompressible fluid. We prepared a heater for thermal compensation and an accumulator, with a bellows structure, for volume control so as to mitigate the pressure fluctuation (caused by turning the proton beam on and off) below the allowable pressure of 0.1 MPa [3]. An ortho–para hydrogen converter was prepared to provide para-hydrogen concentration of more than 99% to the moderators [4].

The cryogenic hydrogen system has been operated since May 2008 [1] when the proton beam power was 40 kW. The proton beam power gradually increased up to 120 kW until 2010. However, we had a problem of unstable helium refrigerator operation caused by impurities. Long-lasting stable operation of the helium refrigerator has never been conducted because of the performance degradation of the heat exchanger. We prepared a purification system, which consisted of a cryogenic adsorber, a

dryer filled with zeolite and a heater for regeneration, and impurity detectors, to effectively remove the impurities in the helium refrigerator.

In this paper, we describe the problem of the unstable helium refrigerator operation and the purification system introduced to mitigate the problem.

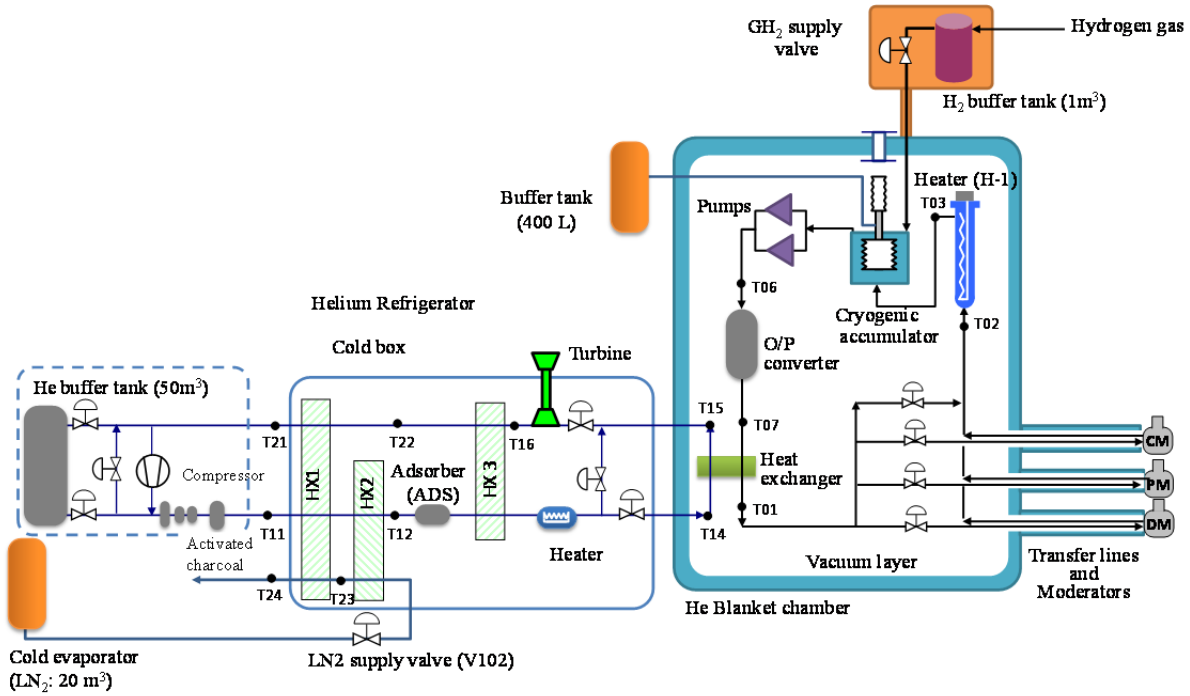


Figure 1. Schematic of the J-PARC cryogenic hydrogen system.

2. Helium refrigerator

An oil-lubricated screw compressor compresses helium with a mass flow rate of 290 g/s from 0.3 to 1.68 MPa. The rated shaft power is 690 kW. The high-pressure stream enters the cold box with a mass flow rate of 275 g/s and is cooled to approximately 80 K through the plate-fin heat exchangers (HXs) HX1 and HX2, where liquid nitrogen is used for precooling. The liquid nitrogen consumption is estimated to be 22 g/s. The feed gas passed through HX1 and HX2 is routed to an 80 K adsorber (ADS), filled with activated charcoals, where the trace amounts of nitrogen are mainly removed. The high-pressure helium temperature passing through HX3 is controlled at 17 K by an 8-kW heater. We had confirmed through a commissioning process, which was performed within a week, that the helium refrigerator met our requirements.

3. Unstable helium refrigerator operations

3.1. Helium refrigerator operation from 2008 to 2009

We tried to operate the cryogenic hydrogen system for more than two weeks for the first time in October 2009 (RUN #27), when the proton beam power was 40 kW. Fig. 2 shows the temperature behavior at the cold end of a heat exchanger in the high-pressure helium stream. The helium refrigerator was operated without liquid nitrogen precooling because the nuclear heating was only 150 W for the 40-kW proton beam power. Although the initial temperature was maintained at approximately 150 K, it gradually increased. After 18 operating days, the temperatures rapidly increased to 170 K.

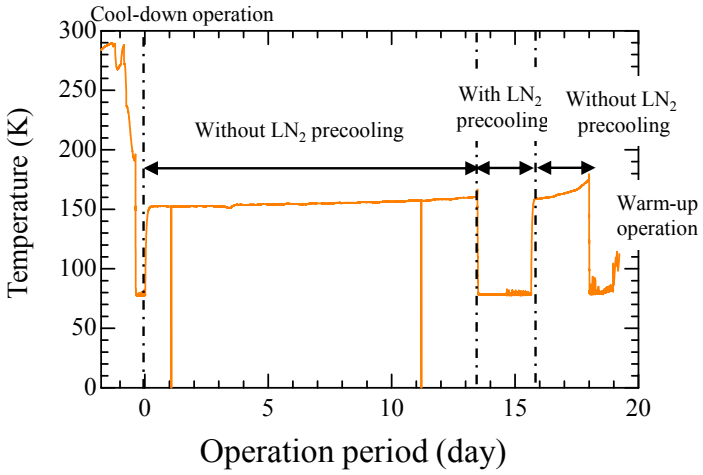


Figure 2. Temperature behavior at the cold end of a heat exchanger in the high-pressure stream.

Fig. 3 shows the pressure difference between the warm end of HX1 and the outlet of ADS. As the operation time increased, the pressure difference became higher. It was assumed that some impurities were accumulating on the surface of HX, and the heat exchange efficiency was deteriorating.

After warming up the helium refrigerator by supplying helium to the cold box, we measured dew points in the helium refrigerator. There was moisture with a dew point was –30 °C in HXs of the high-pressure helium stream, although the dew point before the operation was reduced to –70°C by a purification operation using ADS.

To conduct stable operation of the helium refrigerator, we tried to purge the moisture existing in HXs using a dry nitrogen gas with a dew point lower than –96 °C and reduced the dew point below –76 °C. Most of the nitrogen in HXs was evacuated, and the residual was reduced below 1.7 ppm using a cryogenic adsorber. Fig. 4 shows the temperature and pressure difference behaviors in RUN#28 after purification, when the proton beam power was 120 kW. The helium refrigerator was successfully operated for 43 days without any problem for the first time, although there was a temperature rise of a few Kelvin.

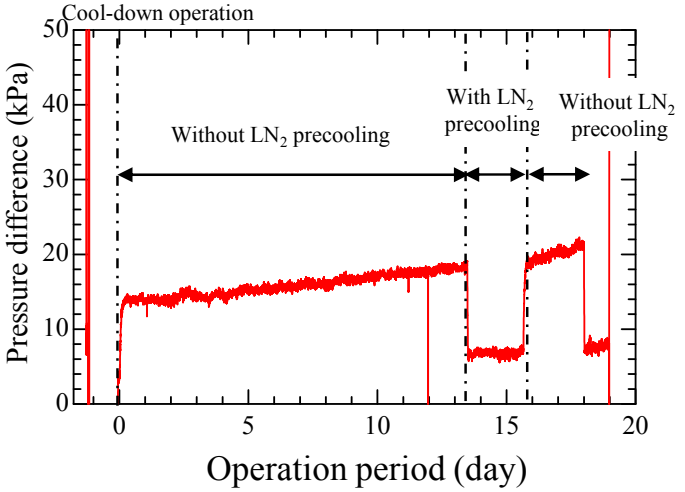


Figure 3. Pressure difference between HXs and ADS in the high-pressure stream.

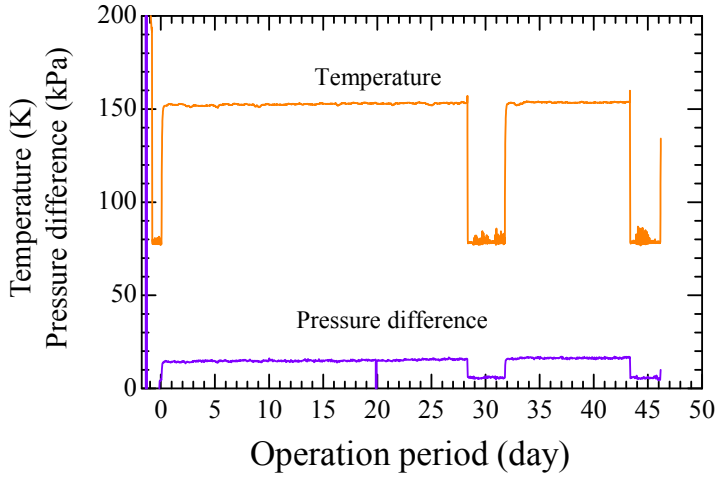


Figure 4. Temperature and pressure difference in RUN#28 after purification.

3.2. Helium refrigerator operation in 2010

For the first time, we exchanged the activated charcoal in the summer outage of 2010. The activated charcoal vessel is located downstream of the compressor and the packing weight is 350 kg. After the replacement, we evacuated the activated charcoal vessel below a few Pascal and performed a purification operation using the cryogenic adsorber for one week. We confirmed that the dew point in the helium stream was reduced to 1.8 ppm, which was lower than that for RUN#27.

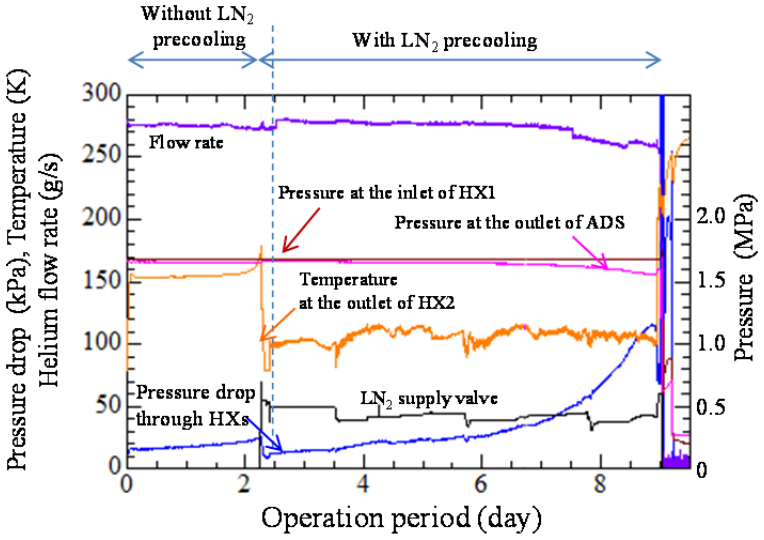
Fig. 5 shows the behaviors of the helium refrigerator operated in October 2010 when the proton beam power was 120 kW. After the cool-down operation, we stopped using the liquid nitrogen precooling. The pressure difference through HXs gradually increased, and a rapid temperature rise appeared at the cold end of HXs after three days. We tried to cool the helium stream at HXs by providing liquid nitrogen because the continued operation of our cryogenic system was required. Although the pressure drop and temperature were temporarily reduced, the pressure drop continued to increase; the temperature was 20 K higher than that for normal operation and remained unstable. After nine days, the pressure difference increased to 120 kPa. As shown in Fig. 5(b), the helium temperature of the high-pressure stream at the cold end of HX2 and the nitrogen temperature at the warm end of HX2 rapidly increased up to 220 K, while the temperatures of the nitrogen and the low-pressure helium stream were reduced below 0 °C at the warm end of HX1. We considered that the rapid deterioration of the heat exchange capability of HX1 could be caused by the extraordinary deposition of impurities such as moisture on the surface of HX. Eventually, the pressure difference exceeded 500 kPa. We stopped the helium refrigerator operation for its protection and warmed it up by supplying helium gas into the vacuum chamber up to 30 kPa.

After the temperature of HXs increased to room temperature, we measured the dew point of the high-pressure helium stream in HX1 and HX2. A dew point of –20 °C was detected, although it was reduced below –72 °C, which was lower than that for the operation in 2009, before the cool-down operation. On the other hand, a dew point of –40 °C was detected in ADS. There was no moisture that had an unfavorable impact on the helium refrigerator operation except in HXs and ADS. Accordingly, it is assumed that the moisture desorbed from the activated charcoal would generate unstable helium refrigerator operation. Moisture in the high-pressure helium stream would be adsorbed on the surface of HX, whose temperature is normally maintained below 0 °C, by passing through HXs during the cryogenic operation. The purified helium stream results in promoting the desorption of moisture from the activated charcoal. We considered that this phenomenon was continuously repeated because large amounts of moisture would be adsorbed on the activated charcoal.

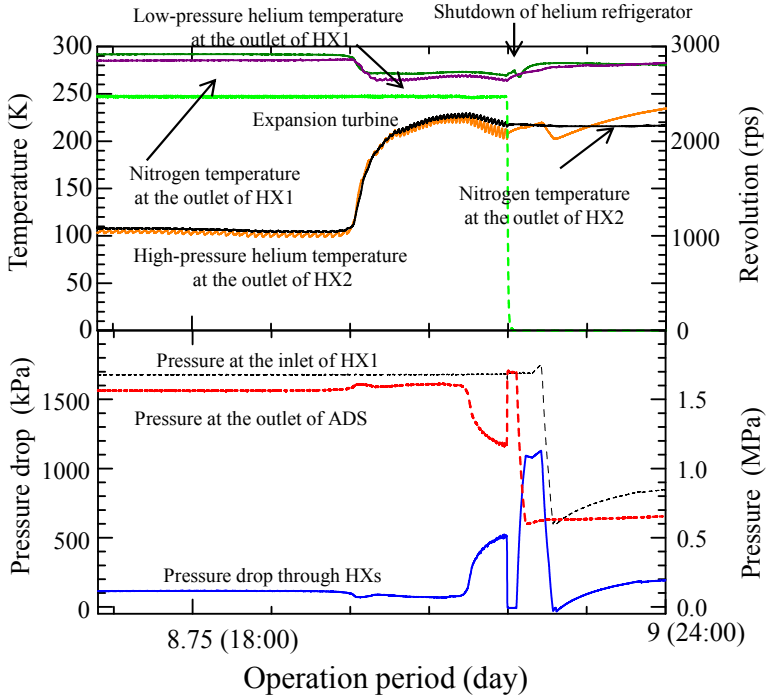
To resume the helium refrigerator operation, we needed to regenerate the activated charcoal using a hot dry nitrogen gas, which should be maintained below 100 °C because of the allowable temperatures

of the seal material and a filter in the activated charcoal vessel. We prepared a temporary heater to increase the temperature of the purge nitrogen gas.

Fig. 6 shows the regeneration operation of the activated charcoal, which was performed with a dry hot nitrogen gas with a supply temperature of approximately 90 °C and a dew point of –96 °C. The activated charcoal vessel was covered with a lagging material. The dew point was measured at the outlet of the activated charcoal. It took five days for the charcoal temperature to increase to 90 °C at a flow rate of 30 Nm^3/h, although the outlet temperature increased only to 72 °C. During the



(a) Behaviors of the helium refrigerator over an entire run period.



(b) Behaviors of temperature, pressure, and pressure difference at an anomalous occurrence.

Figure 5. Unstable operation of the helium refrigerator in October 2010.

regeneration, the purge nitrogen flowed upward with the effect of natural convection. With the increase in the activated charcoal temperature, the dew point temporarily increased from –68 °C to –50 °C during the early stage. Subsequently, it gradually decreased to –62 °C in 19 days. Furthermore, the dew point can be reduced to -74.5°C, with a decrease in the temperature from 90 °C to 10 °C. Most of the nitrogen in the activated charcoal vessel was removed by evacuating it three times, and the residual nitrogen was eventually removed using a cryogenic adsorber.

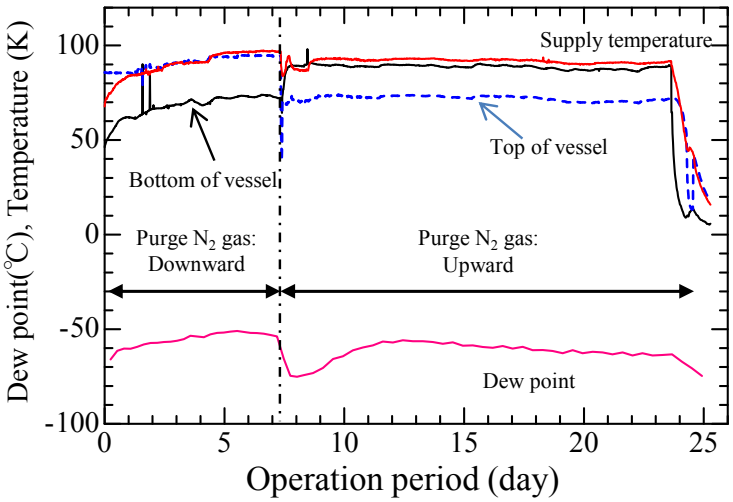


Figure 6. Regeneration operation of the activated charcoal in 2010.

On the other hand, ADS was also filled with activated charcoal and its packing weight was 26 kg. The moisture in ADS was removed by a dry nitrogen gas. The dew point can be reduced to –64 °C by purging ADS for one week.

Fig.7 shows the temperature at the cold end of HXs in the high-pressure helium stream and the pressure difference through HXs and ADS during cryogenic operation after the regeneration. Although it appears that the pressure drop through HXs increased slightly, the temperature at the cold end of HX was maintained nearly constant for one month. We could perform a stable one-month operation of the helium refrigerator.

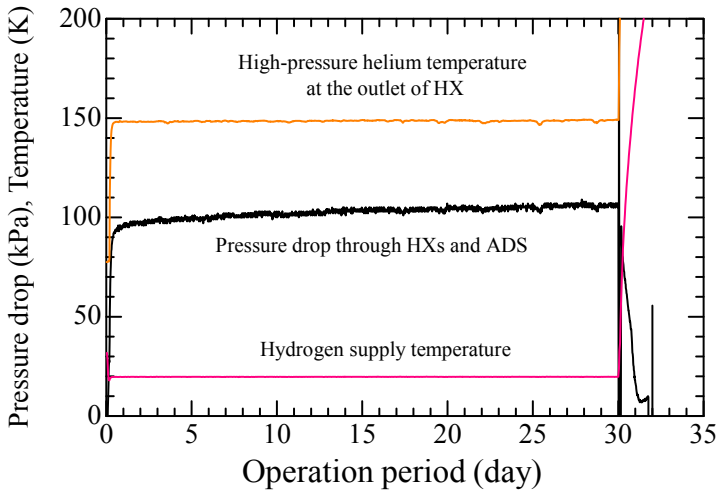
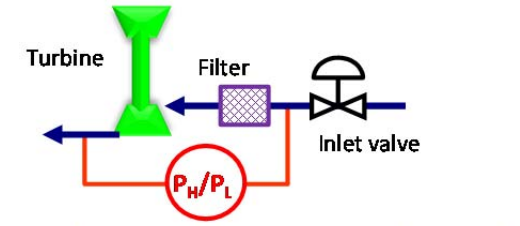


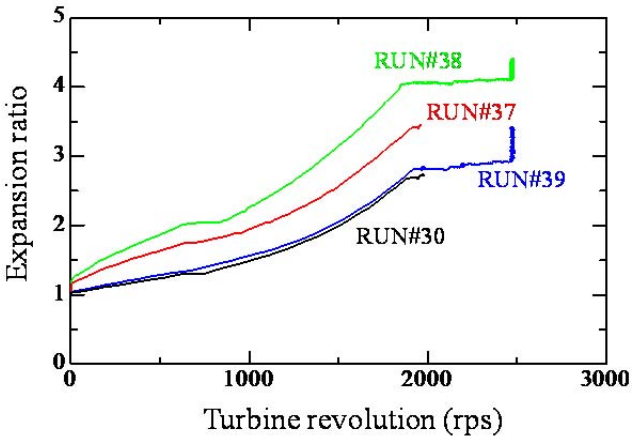
Figure 7. Temperature at HXs and pressure difference through HXs and ADS after the regeneration in 2010.

However, the pressure drop was considerably larger than the usual value, which was approximately 15 kPa. Before the cool-down operation, there was seat leakage through a turbine bypass valve (V103). Powders of the activated charcoal that came from ADS were found at the seat and the shaft of the valve. Furthermore, at the expansion turbine start-up, the expansion ratio became larger than the normal value, as shown in Fig.8. It was found in the summer of 2011 that the powders also existed at the filter at the inlet of the turbine. Therefore, we replaced damaged ADS with a new one. Fig. 9 shows the photograph of ADS that was removed from the cold box. It was found that the abnormal pressure difference, as shown in Fig. 8, was due to the powder of the activated charcoal that became trapped in the filter of ADS.



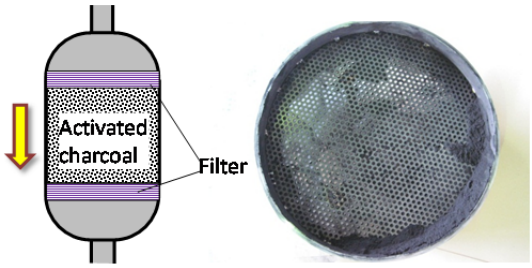
(a) Schematic of the expansion turbine unit.

(b) Photograph of the turbine inlet valve.

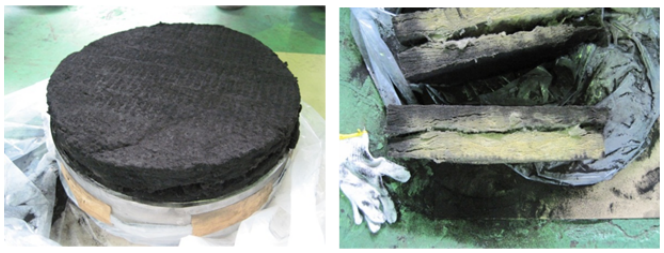


(c) Comparison of expansion ratio for each operation.

Figure 8. Expansion ratio of the turbine at the start-up.



(a) Schematic of ADS.



(b) Photographs of the powderized activated charcoal in ADS.

Figure 9. Damaged ADS of the helium refrigerator.

4. Improvement of the helium refrigerator

4.1. Purification system

Fig. 10 shows the purification system, which consists of a dryer, a cryogenic adsorber, a heater and gas analyzers. We prepared it to realize the stable operation of the helium refrigerator by removing impurities such as moisture and nitrogen. The dryer, which has a volume of 0.064 m^3 and is filled with zeolite, mainly removes moisture. The operating pressure is 1.58 MPa, which corresponds to the discharge pressure of the compressor. It was designed to be continuously operated at a flow rate of 100 Nm^3/h for 48 h under the following dew point conditions: –20 °C at the dryer inlet and below –70 °C at its outlet. After the purification operation, the dryer needs to be regenerated using a dry hot nitrogen

gas with a flow rate of 100 Nm^3/h and a temperature of 150 °C for a few hours. The dryer is evacuated below 10 Pa to reduce the nitrogen concentration below 20 ppm. Empirically, we confirmed that three cycles of evacuation reduced the nitrogen concentration in it below 20 ppm. It takes approximately 12 h to finish the regeneration process.

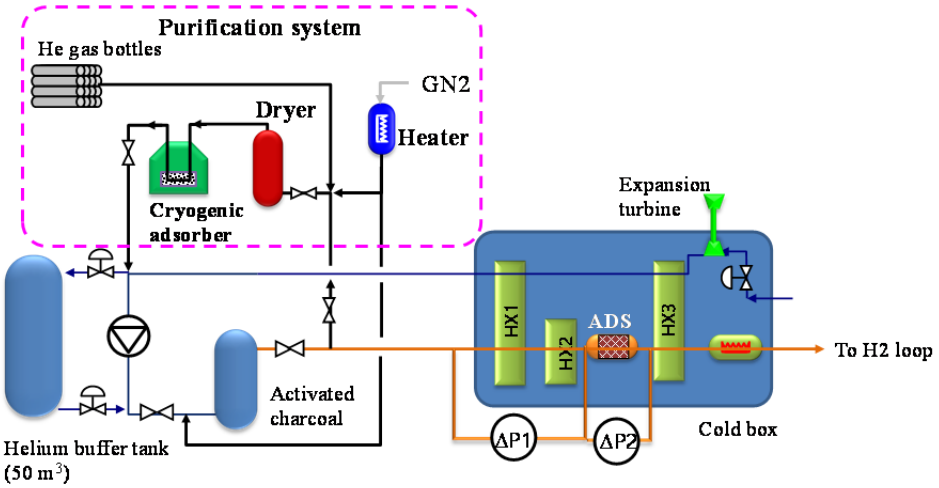


Figure 10. Schematic of the purification system.

A cryogenic adsorber, which is "MODEL HE" manufactured by Linde Cryogenics, was prepared to mainly remove the nitrogen component in the helium stream. Activated charcoal is used and cooled by liquid nitrogen. The allowable flow rate is 100 Nm^3/h. We always measure the nitrogen concentration at the outlet of the cryogenic adsorber using gas chromatography to confirm its performance degradation. We have empirically confirmed that the nitrogen concentration is always maintained below a measurable limit, even if the inlet nitrogen concentration is approximately 100 ppm after the regeneration of the dryer.

A 5-kW heater was prepared to effectively regenerate the dryer and the activated charcoal for the compressor using dry hot nitrogen gas from a cold evaporator with a volume of 20 m^3.

Furthermore, differential pressure transmitters are installed at HX1 and HX2 in the high-pressure helium stream and ADS to continuously monitor for an abnormal pressure difference increase through HXs and ADS.

4.2. Regeneration of the activated charcoal

We exchanged the activated charcoal in the summer maintenance of 2013 when the operating temperature limit of the filter and seal materials in the charcoal vessel was increased to 150 °C for the efficiency of the regeneration operation. Fig. 11 shows the behaviors of a dew point and temperature of the activated charcoal during the regeneration operation. Unlike that in 2010, the flow rate of the dry nitrogen gas passing through the charcoal vessel can increase to 100 Nm^3/h and the temperature required for the regeneration can also increase to more than 100 °C. The initial dew point was –83 °C at the outlet of the charcoal vessel. Although the dew point temporarily increased to –28 °C with the increase in the regeneration temperature, it gradually decreased to –61 °C within 17 days. Furthermore, with the decrease in the charcoal temperature down to 50 °C, the dew point decreased to –93 °C. We confirmed that the regeneration had been operated effectively and the period of the regeneration can be shortened by 30% compared with that in 2010.

4.3. Purification operation

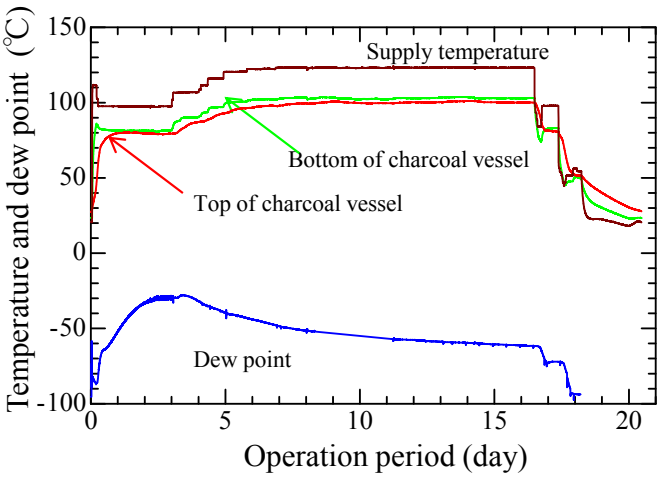
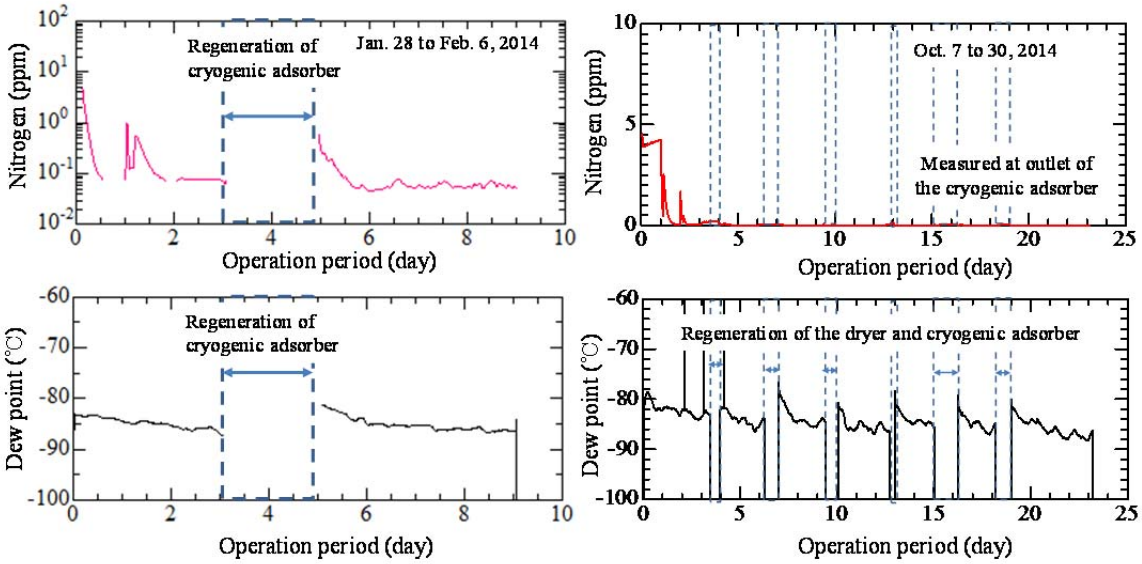


Figure 11. Behavior of a dew point and temperature of the activated charcoal during the regeneration operation.

The helium stream passes through the dryer and the cryogenic adsorber at a flow rate of 4.9 g/s (100 Nm^3/h), which corresponds to 5% of the main stream. Fig.12 provides one example of moisture and nitrogen in the helium stream during the purification operation. The dryer was regenerated using hot dry nitrogen gas every 48 h, even without performance deterioration. The cryogenic adsorber is regenerated when an increasing trend in the amount of nitrogen appears. The adsorber vessel is warmed to room temperature using warmed nitrogen gas and is evacuated below 10 Pa. We confirmed that the nitrogen and moisture can be reduced below 0.1 ppm and –85 °C within one week, although this depends on initial concentrations.

The complement of helium gas is supplied to the suction side of the compressor at 0.2 MPa, passing through the dryer and the cryogenic adsorber. We use helium gas bottles with a “four nines” grade. We confirmed that the nitrogen concentration is always maintained at the outlet of the cryogenic adsorber below measureable limits by gas chromatography.

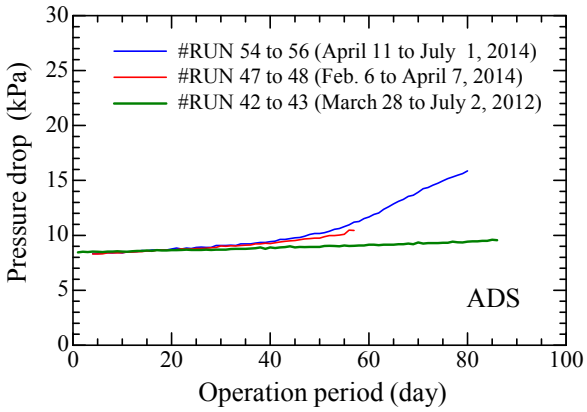


(a) January 28 to February 6, 2014. (b) October 7 to 30, 2014.

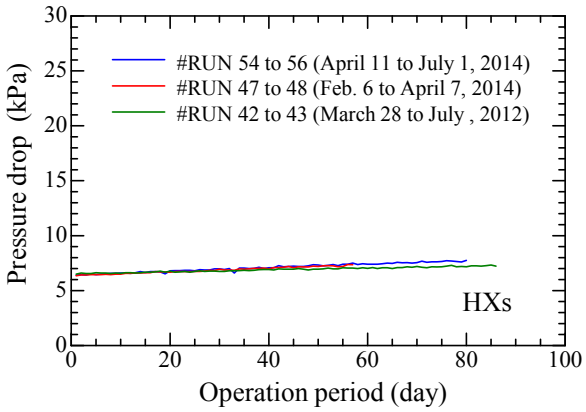
Figure 12. Purification operation.

4.4. Stable operation of the helium refrigerator

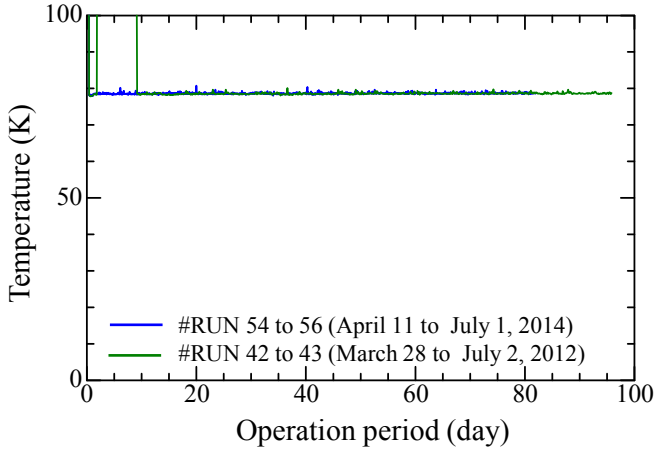
Fig. 13 shows the behaviors of temperature and pressure difference around HXs during cryogenic operation. The helium flow rate through the cold box is 273 g/s. The initial concentrations of moisture and nitrogen were reduced below 1.0 ppm, which corresponds to the dew point of –76 °C and 0.2 ppm,



(a) Pressure drop through ADS.



(b) Pressure drop through HXs.



(c) Temperature at the cold end of HX in the high-pressure helium stream.

Figure 13. Behaviors of temperature and pressure drops during cryogenic operation.

respectively, by the purification operation. Although the increase in the pressure drop through ADS becomes larger compared with that for HX, they are approximately 7.5 kPa at a maximum for 80 days of operation. Fig. 14 shows the desorbed impurities in ADS during the warm-up process of the helium refrigerator. We take a sample of the gas from ADS at 0.6 MPa at each temperature. A remarkable desorption of nitrogen appears in the vicinity of 120 K. The desorbed nitrogen increases to 626 ppm in ADS at room temperature. The increase in the pressure drop through ADS is assumed to be mainly due to nitrogen adsorbed on ADS. On the other hand, the increases in pressure difference of HXs are lower than 1.35 kPa for 80 days of operation, and they are considerably smaller than those for the operation until 2010. Fig. 15 shows the impurities desorbed from the surface of HX during the warm-up operation. It appears that nitrogen, oxygen, and hydrogen have relatively little impact on the increase in the pressure drop of HX. However, the dew point rapidly becomes lower above 280 K. We stopped the measurement of the dew point because it exceeded –20 °C. It was found that the moisture is mainly adsorbed on the surface of HXs. The temperature downstream of HX can be maintained at approximately 78 K. The slight fluctuation is affected by the behavior of the liquid nitrogen supply valve. The impurity can be reduced effectively by introducing the purification system and we can

conduct a stable three-month long-lasting operation of the helium refrigerator without any problem. In future, we will attempt a more long-lasting operation of the helium refrigerator toward the achievement of a stable 1-MW proton beam operation.

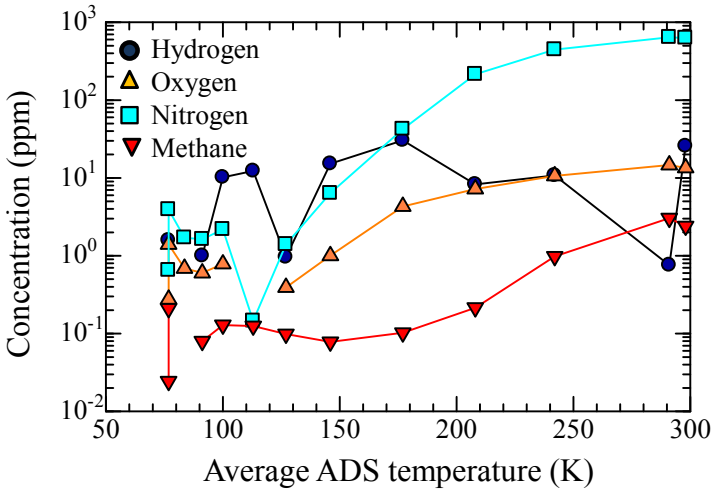


Figure 14. Desorbed impurities in ADS during the warm-up process.

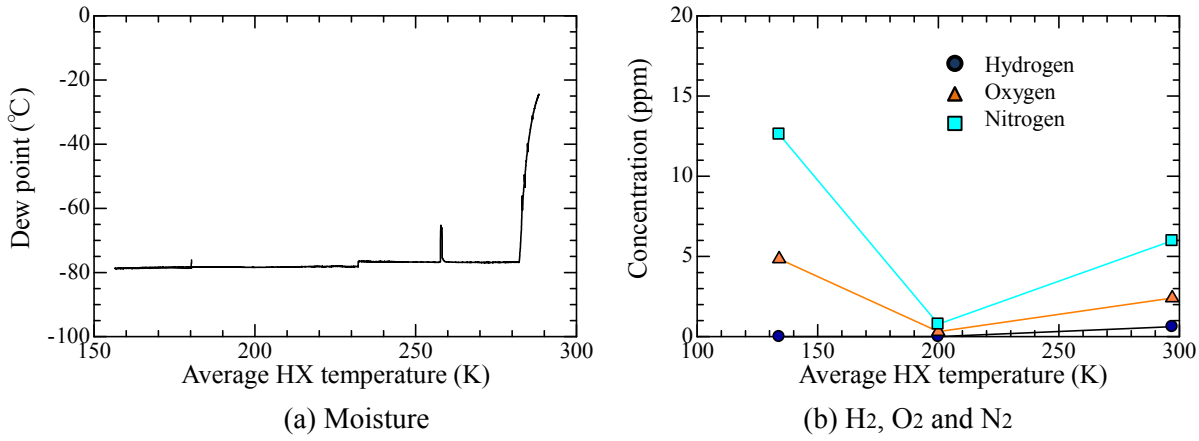


Figure 15. Impurities desorbed from the surface of HX during the warm-up operation.

5. Conclusions

It had been impossible to conduct stable long-lasting operation of the helium refrigerator until 2010. We found that the cause of instability was mainly due to moisture that adsorbed on the surface of the activated charcoal downstream of the compressor.

A purification system, which consisted of a dryer, a cryogenic adsorber and a heater for regeneration, was installed in 2011. We have established a method for purifying the helium refrigerator. We successfully performed a three-month long-lasting stable operation of the helium refrigerator without any problems.

Acknowledgments
The authors thank Mr. Uehara, Mr. Sakurayama, and the operator team for the J-PARC cryogenic hydrogen system for supporting the helium refrigerator operation.

References

[1] Tatsumoto H, Aso T, Ohtsu K, Uehara T, Sakurayama H, Kawakami Y, Kato T and Futakawa M, *Advances in Cryogenic Engineering* 55A, Melville, New York, 2010, pp.297-304.
[2] Tatsumoto H, Aso T, Kato T, Ohtsu K, Hasegawa S, Maekawa F and Futakawa M, *Procof ICEC 22 and ICMC 2008* Korea 2008 pp. 711-716.
[3] Tatsumoto H, Aso T, Ohtsu K, Uehara T, Sakurayama H, Kawakami Y, Kato T and Futakawa M *Adv. in Cryo. Eng.* 57A 2012 pp.368-375
[4] Tatsumoto H, Ohtsu K, Aso T, Kawakami Y and Teshigawara M *Adv. in Cryo. Eng.* 59A 2014