

Performance test of a helium refrigerator for the cryogenic hydrogen system in J-PARC

Tatsumoto H., Aso T., Kato T., Ohtsu K., Hasegawa S., Maekawa F., Futakawa M.

Japan Atomic Energy Agency, Toukai-mura, Naka-gun, Ibaraki, 319-1195, Japan

In J-PARC, a cryogenic hydrogen system, which plays a role in providing supercritical hydrogen with a pressure of 1.5 MPa and a temperature of 20 K to three moderators, has been designed. The performance test of the helium refrigeration system that is a part of the cryogenic hydrogen system was conducted independently. The helium refrigeration system was cooled down to 18 K within 4.5 hours, and the refrigerator power of 6.45 kW at 15.6 K was confirmed. The performance test results verified that the helium refrigerator satisfied the performance requirements.

INTRODUCTION

An intense spallation neutron source (JSNS) driven by a proton beam of 1 MW was constructed as one of main experimental facilities in J-PARC (the Japan Proton Accelerator Research Complex) [1]. In the JSNS, three kinds of hydrogen moderator are installed to provide pulsed low energy neutron beams with a higher neutronic performance. High-energy neutrons around MeV order generated in a mercury target are reduced to appropriate energy such as meV order through those moderators. The JSNS has selected supercritical hydrogen with a temperature of around 20 K and a pressure of 1.5 MPa as a moderator material [2].

A cryogenic hydrogen system [3] provides supercritical hydrogen to three moderators and absorbs nuclear heating produced in the moderators, which was estimated to be 3.8 kW for a proton-beam power of 1 MW and was proportional to a proton beam power. Figure 1 shows the cryogenic hydrogen system in JSNS, which involves a hydrogen circulation system and a helium refrigeration system. The hydrogen circulation system consists of two centrifugal pumps, a He-H₂ heat exchanger, an ortho-para hydrogen converter, an accumulator and a hydrogen heater. The total heat load of the hydrogen circulation system was estimated to be about 5 kW, composed of the nuclear heating in the moderators and heat loss of 1.2 kW in transfer lines, valves and other components. A helium refrigeration system with the refrigeration power of 6 kW at 17 K that has a margin of 20 % for the estimated total heat load has been designed to cool the hydrogen circulation system through the H₂-He heat exchanger.

In March 2007, the helium refrigeration system has been installed prior to the hydrogen circulation system. Commissioning of the helium refrigeration system without being connected to the hydrogen

circulation system was conducted using a bypass line in the cold box. This paper reports the helium refrigeration system performance test results.

HELIUM REFRIGERATOR SYSTEM

An oil lubricated screw compressor has a capacity to compress the helium gas with the mass flow rate of 290 g/s from 0.3 to 1.68 MPa as shown in Fig. 1. The compressor has the rated shaft power of 690 kW. The high pressure stream enters the cold box with the mass flow rate of 260 g/s and is cooled down to approximately 80 K through the plate-fin heat exchanger of HX1 and HX2 by liquid nitrogen and the counter flow of low pressure stream. In design, the liquid nitrogen consumption was estimated to be 22 g/s at rated condition. The feed gas passed through HX1 and HX2 is routed to the 80 K adsorber, in which nitrogen trace impurities in the feed gas are removed. The high pressure stream purified by the 80 K adsorber is cooled down to 15.5 K through the third heat exchanger, HX3, by the low pressure turbine outlet stream. And the high pressure cold stream is heated up to 17 K to be controlled by the helium heater with the capacity of 8 kW, and then it is provided to the hydrogen circulation system. The turbine is located after the H₂-He heat exchanger to keep the helium pressure higher than the hydrogen pressure such as 1.5 MPa, and to prevent hydrogen leak into the refrigeration system. The helium stream out of the H₂-He heat exchanger is expanded and cooled to 0.3 MPa and 12.7 K by the turbine. The low pressure stream is passed through HX3 and HX1 and is warmed up to ambient temperature, and finally comes

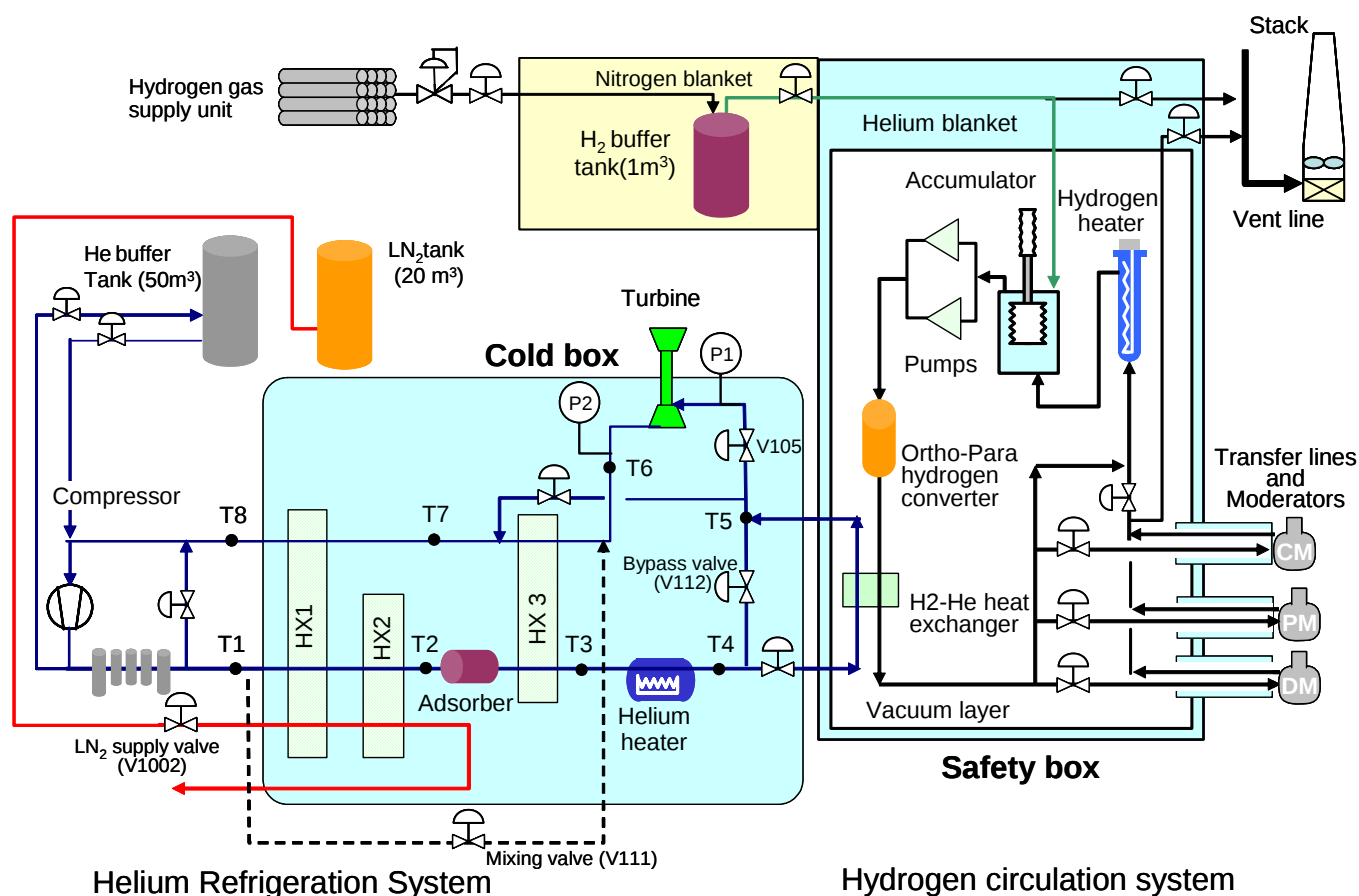


Figure 1 Overview of the cryogenic hydrogen system in JSNS

back to the compressor suction.

PERFORMANCE TEST RESULTS

Cool-down operation results of the helium refrigerator system are shown in Figure 2. The turbine with the revolution of 2470 rps was operated at an ambient temperature. The expansion ratio was controlled by a turbine inlet valve of V105, whose position was maintained to be 79 % in this performance test. The pressures in the inlet and the outlet of the turbine were maintained to be 1.54 MPa and 0.316 MPa, respectively. No sooner than starting cooling, the helium temperature, T6, at the outlet of the turbine rapidly decreased due to no heat load in the cold box. Downstream of HX3, the helium temperatures of T3 and T4 also decreased as well as T6. The temperatures reached 20 K within 1.5 hours. On the other hand, the helium temperatures between HX1 and HX3 gradually decrease as shown in Fig. 2. The helium temperatures at the entrance and the exit of the cold box, T1 and T8, were maintained almost constant. With decrease in the temperatures, the mass flow rate flowing into the cold box increases to 260 g/s. The supply temperature, T4, was maintained to be 19 K by controlling the helium heater. The liquid nitrogen precooling was started when the HX2 outlet temperature, T2, was below 190 K. The temperatures of T2 and T7 instantly decreased down to 100 K. After that, they slowly decreased to 80 K because the supply temperature was controlled by the helium heater. The helium refrigeration system could be cooled down to the rated condition within 4.5 hours.

Figure 3 shows the measured refrigeration power with liquid nitrogen precooling. In this measurement, the temperature at the inlet of the helium heater, T3, was measured by applying a constant heat load of 6.45 kW, which was slightly higher than the design value of 6 kW. The turbine revolution and the turbine expansion ratio were maintained 2470 rps and 4.95, respectively. The turbine inlet valve position was 79 %. For T3 = 15.6 K, the helium refrigeration system could be maintained in steady-state for four hours. The mass flow rate supplying the cold box was measured to be 260 g/s and the liquid nitrogen consumption as a pre-cooling was 18.63 g/s. A turbine expander efficiency was estimated to be 0.73. It was confirmed that the helium refrigeration system had the refrigerator power of 6.45 kW at 15.6 K that was enough to be satisfied with the design performance. The performance test results verified

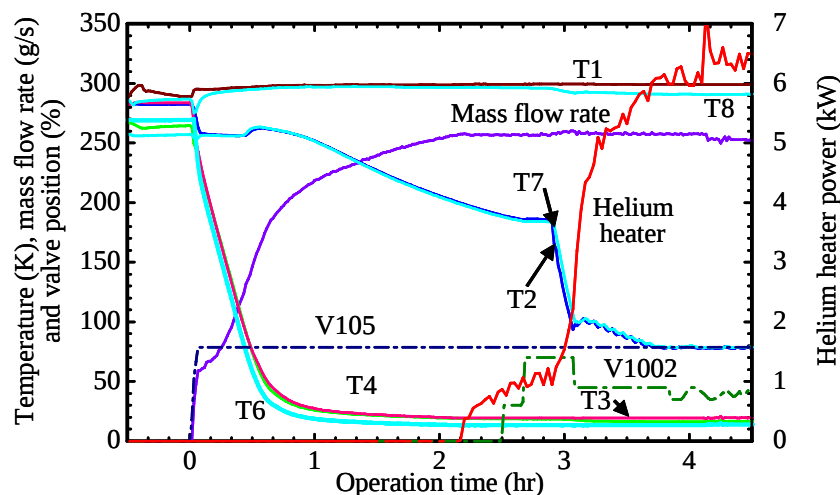
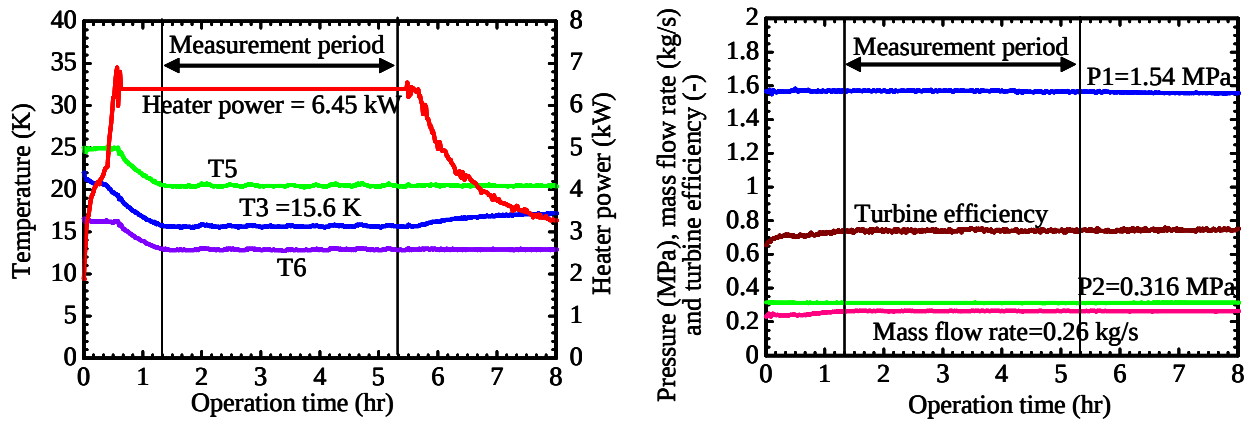


Figure 2 Cool-down operation results of the helium refrigeration system



(a) Temperature and heater power profiles.

(b) Pressure at the inlet and the outlet of the turbine, mass flow rate and turbine efficiency profiles

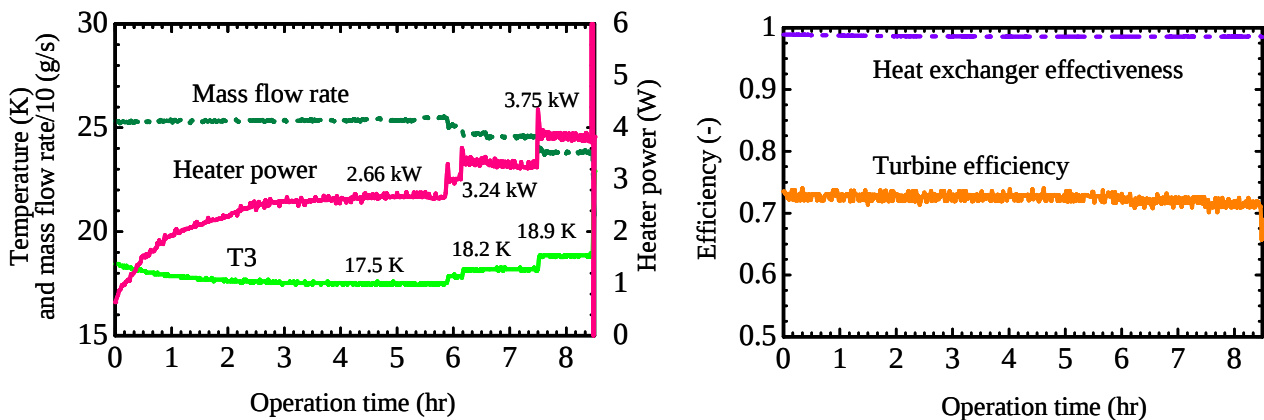
Figure 3 Measured refrigeration power of the helium refrigeration system with liquid nitrogen precooling

that the helium refrigeration system satisfied the performance requirements.

Figure 4 shows the measured the refrigeration powers without liquid nitrogen precooling for various inlet temperatures. With increase in the temperature, the refrigeration power increases under the same turbine revolution and turbine expansion ratio, although the circulation flow rate and the expansion efficiency of the turbine became lower. However, the reduction of the turbine efficiency was very small, being approximately 73 %. In the case of an operation without liquid nitrogen precooling, it can be considered that the heat exchangers in the cold box would be regarded as a combined heat exchanger. The efficiency of the combined heat exchanger also was estimated to be 0.985 as shown in Fig.4 (b). The refrigeration power of 3.75 kW at 18.9 K was confirmed for no liquid nitrogen precooling operation. A simulation model of the refrigeration power without liquid nitrogen precooling was derived in the next section.

ESTIMATION OF REFRIGERATION POWER WITHOUT LN₂ PRECOOLING

In order to predict the refrigeration power in the case of no liquid nitrogen precooling for each temperature, we derived a simulation model based on the experimental results. It is assumed that the heat



(a) Temperature, power and mass flow rate profiles

(b) Efficiencies

Figure 4 Measured refrigeration powers of the helium refrigeration system without liquid nitrogen precooling

exchangers in the cold box should be a combined heat exchanger. As shown in Fig.4, the heat exchanger effectiveness of it, ε_{hx} , was 0.985 around the temperature of 20 K. The expansion efficiency of the turbine, η_t , was 0.73. It is also assumed that the circulation flow through the turbine should be a critical flow, because the pressure difference through the turbine is lower than the critical pressure ratio of 0.46. In the simulation model, the circulation flow rate is expressed by using a flow coefficient of a valve,

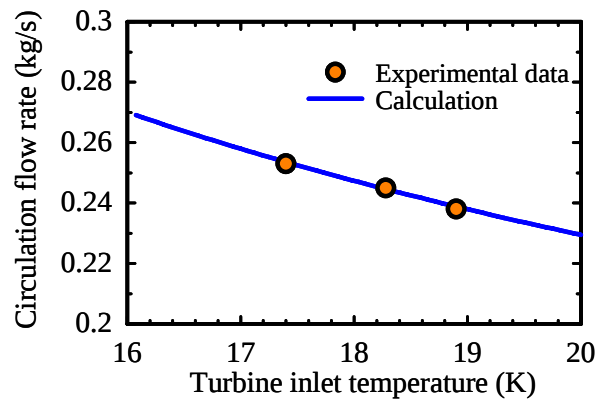


Figure 5 Circulation flow rate through the turbine

C_v , as functions of the inlet conditions of the turbine. The value of C_v was determined to be 2.53 based on the experimental data, and the circulation flow rate agreed well with the experimental data as shown in Fig.5. The refrigeration powers were calculated by using the combined heat exchanger effectiveness, the expansion efficiency of the turbine and the circulation flow rate, respectively. Figure 6 shows the simulation results compared with the experimental results. It was found that the refrigeration powers could be predicted by using the simulation model within 5 % errors. The refrigeration power at 15.6 K was calculated to be 1.18 kW. It is assumed that the helium refrigeration system operation with liquid nitrogen precooling would have 5.5 times higher refrigeration power than that without liquid nitrogen.

Design requirements of the cryogenic hydrogen system should be to provide hydrogen with the para-hydrogen concentration of more than 99 %, and maintain the average temperature through each moderator in less than 20 K. The nuclear heating through the moderator is proportional to a proton beam power. For example, for a 1MW proton beam operation, the nuclear heating was estimated to be 3.8 kW [3], and the predicted temperature rise through the moderator was 2.75 K at the rated circulation flow rate of 162 g/s. On the other hand, the heat loss in the hydrogen circulation system was estimated to be 1.2 kW [3]. The temperature difference at the cold end of the H_2 -He heat exchanger was determined to be within 1 K as the design condition. Therefore, the maximum allowable supply temperature is 19 K. The required supply temperatures from the helium refrigeration system for various heat loads were represented by a broken line in Fig.6. The figure indicates that the helium refrigeration operation without liquid nitrogen precooling should be available up to 550 kW proton beam operation.

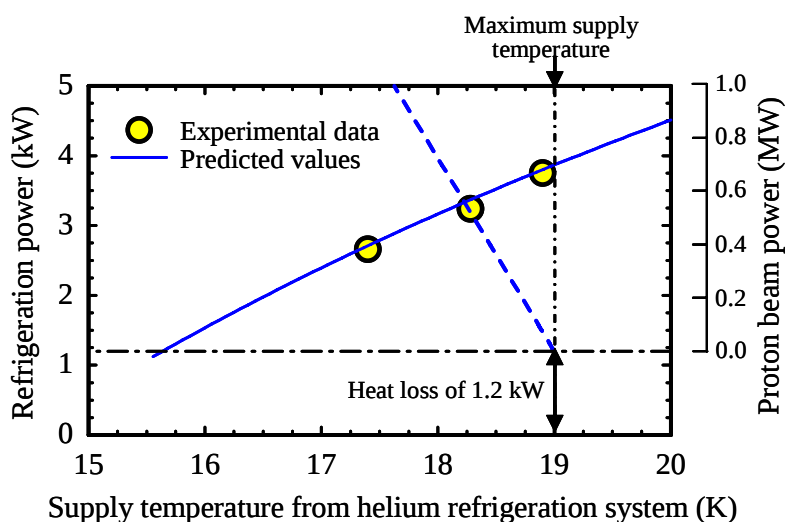


Figure 6 Comparison of the simulation results with the experimental data

CONCLUSIONS

The helium refrigerator performance test was performed before a commissioning of the cryogenic hydrogen system.

The helium refrigerator can cool down to the rated condition within 4.5 hours. The helium refrigeration was confirmed to have the refrigerator power of 6.45 kW at 15.6 K with the circulation flow rate of 260 g/s and with the liquid nitrogen consumption of 18.6 g/s. The performance test results verified that the helium refrigerator satisfied the performance requirements.

The refrigeration powers without liquid nitrogen precooling were also measured for various supply temperatures. With increase in the supply temperature, the refrigeration power increased under the same turbine revolution and turbine expansion ratio, although the circulation flow rate and the expansion efficiency of the turbine became lower. The refrigeration power of 3.75 kW at 18.9 K was confirmed without liquid nitrogen precooling operation. The turbine efficiency was approximately 73 %. The efficiency of a combined heat exchanger was estimated to be 98.5 %.

The refrigeration power without liquid nitrogen precooling operation was estimated. The simulation model derived here can describe the experimental data within 5 %. And then, the helium refrigeration system without liquid nitrogen precooling can be operated up to 550 kW proton beam operation.

REFERENCES

1. Oyama, Y., Present Status of J-PARC High Intensity Proton Accelerator Project in Japan, Proceedings of ICANS-XVI (2003), 7-11.
2. Kato, K., Aso, T., Furusaka, M., Takahashi, T., Ushijima, I., Watanabe, N., Hino, R., Ikeda, Y., Cryogenic System Design for Cryogenic Hydrogen Moderator of the Spallation Neutron Source in J-PARC, Proceedings of ICANS-XVI, (2003), 645-654.
3. Aso, T., Tatsumoto, H., Hasegawa, S., Ushijima, I., Kato, K., Ohtsu K., and Ikeda, Y., Design Result of the Cryogenic Hydrogen Circulation System for 1MW Pulse Spallation Neutron Source (JSNS) in J-PARC, Advances in Cryogenic Engineering, (2005), 51A 763-770.