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Commissioning of the cryogenic hydrogen system in J-PARC: first cool-down operation with helium

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In J-PARC, an intense spallation neutron source (JSNS) driven by a 1-MW proton beam has been constructed. A cryogenic hydrogen system, which provides supercritical hydrogen at the temperature of around 20 K and the pressure of 1.5 MPa to the moderators and absorbs nuclear heating in the moderators, has been completed in November 2007 and the commissioning has been started. As the first step, the primary cryogenic operations were conducted by using helium, instead of hydrogen. We confirmed the soundness of the system at operation temperature, and established the operation method of the cool-down process. The cryogenic tests have been successfully completed without problems.

INTRODUCTION

An intense spallation neutron source (JSNS) driven by a 1-MW proton beam was constructed as one of main experimental facilities in J-PARC (the Japan Proton Accelerator Research Complex) [1]. Three kinds of hydrogen moderator (coupled, decoupled, and poisoned) are installed to provide a pulsed neutron beam with the higher neutronic performance. High-energy neutrons such as MeV orders generated from the target are reduced to the appropriate energy such as meV orders in those moderators.

A cryogenic hydrogen system provides supercritical hydrogen with a temperature of around 20 K and the pressure of 1.5 MPa to the moderators and absorbs nuclear heating in the moderators, which is estimated to be 3.8 kW for a proton beam power of 1 MW [2, 3]. Figure 1 shows a schematic of the cryogenic hydrogen system, which consists of a hydrogen circulation system to cool the high energy neutrons in the moderators and a helium refrigerator system to cool hydrogen in the hydrogen circulation system. The hydrogen circulation system consists of two centrifugal pumps, an ortho-para hydrogen converter, a helium-hydrogen heat transfer, an accumulator and a hydrogen heater. The total hydrogen inventory is 226 L. The hydrogen circulation system is cooled down to 18 K through the heat exchanger by the helium refrigerator. The total heat load is evaluated to be around 5.0 kW that is composed of the nuclear heating of 3.8 kW in the moderators and the heat loss of 1.2 kW in transfer lines, valves and other components. The refrigerator power of the helium refrigerator at 17 K was determined to be 6 kW that has a margin of 20 % for the total heat load. The hydrogen pump was designed to circulate the mass flow

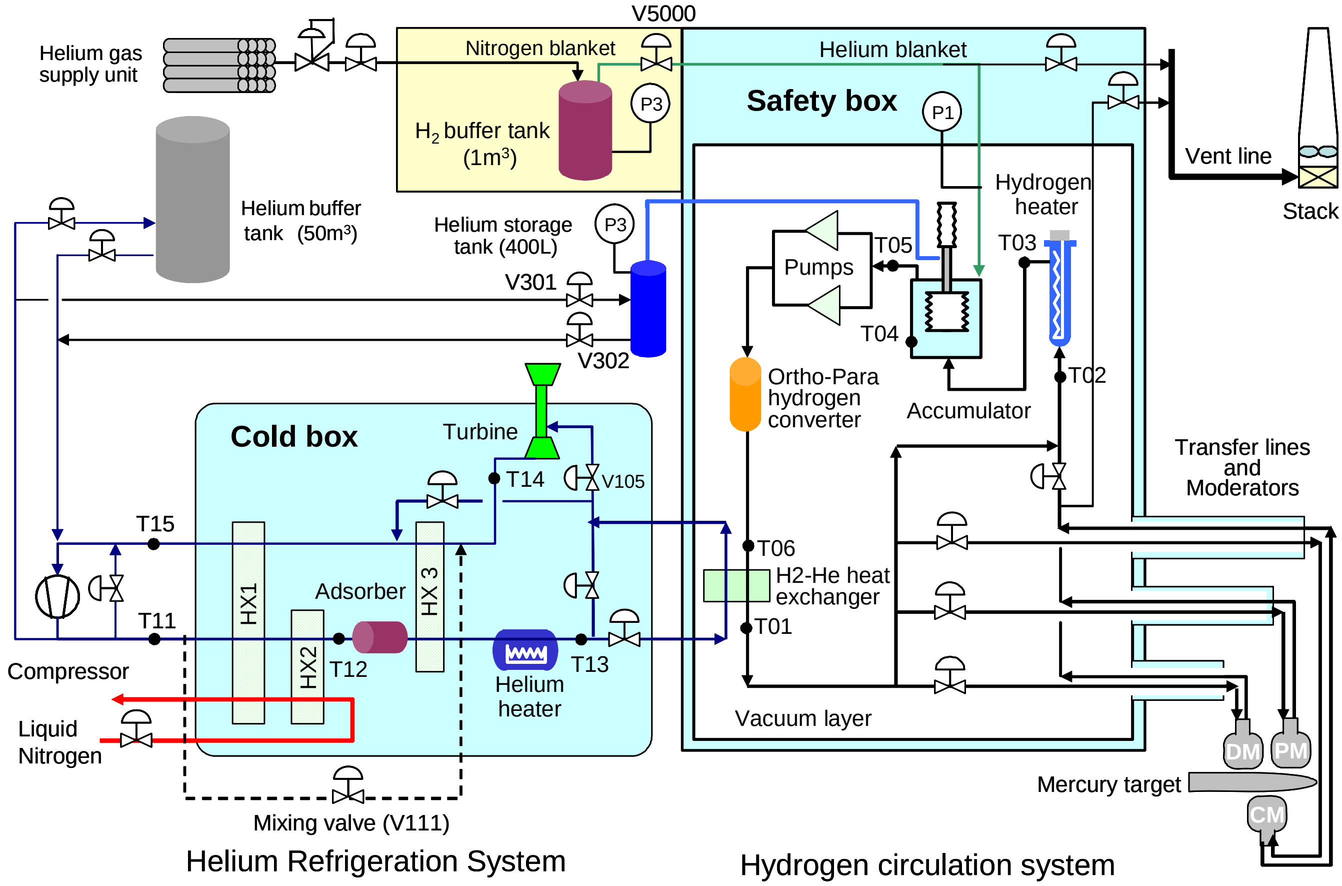


Figure 1 Overview of the cryogenic hydrogen system in JSNS

rate of 0.162 kg/s in order to maintain the temperature difference through each moderator within 3 K at the rated proton beam power of 1 MW.

Supercritical hydrogen around 20 K behaves as an incompressible fluid. It is considered that a slight change of the supercritical hydrogen temperature in the hydrogen loop should bring about a severe pressure change. Therefore, in order to mitigate such pressure change, a pressure control system is prepared, which is composed of an accumulator as a passive volume controller and a hydrogen heater as an active controller for thermal compensation [2]. The accumulator is composed of the bellows filled with helium gas in the hydrogen loop. The volume change of the bellows, in which the helium gas at around 20 K is still compressible, can absorb the pressure fluctuation in the hydrogen circulation system. The hydrogen heater plays a role in compensating the nuclear heating in the moderators, when the proton beam is turned off. In the system, we considered that the hydrogen temperature at the outlet of the heater should be maintained at 21 K by the hydrogen heater in order to avoid the heat load change in the helium refrigeration system. At the rated condition the hydrogen heater power to maintain at 21 K requires to around 4 kW that is slightly larger than the nuclear heating in the moderators for 1-MW proton beam operation.

In November 2007, the cryogenic hydrogen system has been completed, and the commissioning was started. As a first step, the cryogenic tests (TEST #1 and #2) were conducted from the end of November 2007 to December 2007 used helium, instead of hydrogen. The purpose of the first cryogenic test (TEST #1) was to study a control approach of the helium refrigeration system for the cool-down operation, and to determine controlled parameters. The hydrogen circulation system was cooled down to the operation temperature of 20 K by the helium refrigeration system, which was performed by manually operation. An automatic control sequence for the cool-down operation was established based on the results of TEST #1, and was confirmed in TEST #2. In TEST #1 and TEST #2, the hydrogen circulation system was cooled down to bypass the moderators without supplying cold helium to the moderators.

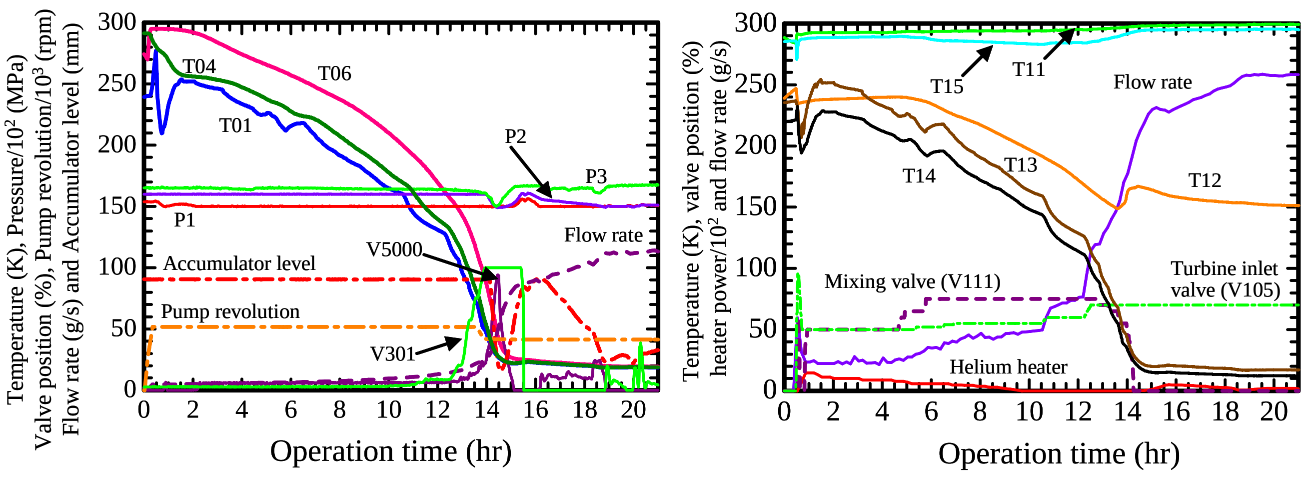
COMMISSIONING OF THE CRYOGENIC HYDROGEN SYSTEM

First cryogenic operation

Figure 2 shows a cool-down curve of the cryogenic hydrogen system in the first operation. An oil lubricated screw compressor generated the helium gas with the mass flow rate of 290 g/s from 0.3 to 1.68 MPa, having the rated shaft power of 690 kW. The turbine with the rated revolution of 2470 rps operated from ambient temperature. The turbine expansion ratio was controlled by operating the turbine inlet valve. It was necessary to avoid exceeding the allowable temperature difference such as 50 K through the warm to the cold end of the hydrogen-helium heat exchanger during the cool-down process. Therefore, the cooling rate of the refrigerator was controlled to maintain within the allowable heat exchanger temperature difference by the helium heater and the mixing valve that behaved to supply a warm high-pressure stream before entering the cold box to the turbine outlet stream. The liquid nitrogen as a precooling material had not been used in TEST #1.

The hydrogen pumps were operated at 52,000 rpm larger than a rated speed of 42,000 rpm, to generate a few-g/s helium flow despite very low density around ambient temperature. For helium, two hydrogen pumps could circulate the mass flow rate of 4.8 g/s at ambient temperature. The helium gas was supplied to the hydrogen circulation system through a hydrogen buffer tank with the volume of 1 m^3, in which the pressure was maintained to be 1.65MPa. The pressure in the hydrogen circulation system was maintained to be 1.5 MPa. On the other hand, the helium pressure in the bellows in the accumulator was maintained to be 1.6 MPa larger than that in the hydrogen circulation system, and the bellows was always fixed at fully extended location, which corresponded to the level of 90.5 mm. The hydrogen circulation system was cooled down through hydrogen-helium heat exchanger.

As temperature decreases such as less than 100 K, the mass flow rate both at the helium refrigeration



(a) Hydrogen circulation system (b) Helium refrigeration system

Figure 2 Cool down curve in the first cryogenic test system and the hydrogen circulation system increased and the cooling rate also speeded up as shown in Fig.2 (a) and (b), respectively. Below 70 K, the hydrogen pump revolution was reduced to the rated value of 42000 rpm. At around 40 K the pressure in the bellows of the accumulator was reduced to that in the hydrogen circulation system, although the supply valve to the bellows was fully open condition. Accordingly, the accumulator level was temporary contracted down to 16.5 mm, which corresponds to the volume increase of 12.8 L in the hydrogen circulation system. The feed rate from the hydrogen buffer tank to the hydrogen circulation system supply gas was increased because of the sudden volume increase. Although the pressure in the hydrogen circulation system could be maintained to be 1.5 MPa, the pressure in the hydrogen buffer tank was decreased down to 1.5 MPa. At the accumulator temperature of 25 K, the helium gas supply to the bellows was stopped. With decrease in the temperature, the accumulator was automatically contracted because of the condensation of the helium gas in the bellows. At the rated condition, there was little pressure difference between the inside, P1, and the outside of the bellows, P2.

At the rated condition, the feed helium gas, the mass flow rate of 258 g/s, from the cold box was controlled to be 17 K by the helium heater. The two pumps could circulate the mass flow rate of 114 g/s with the pump head of 43 kPa. For the helium gas operation, the cryogenic hydrogen system could be cooled down to around 20 K within 20 hours without problems when the helium gas was used instead of hydrogen.

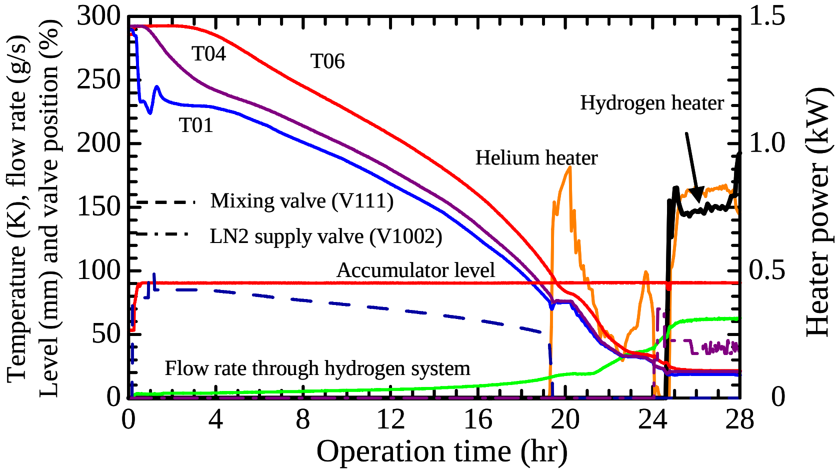
After that, the cryogenic hydrogen system was maintained at the rated condition for 24 hours without any problems, and then the cryogenic hydrogen system was warmed up to an ambient temperature within 24 hours. We have succeeded in the first cryogenic test (TEST #1) by using helium gas, and could have also confirmed a stability of the cryogenic hydrogen system at the operation temperature.

Second cool-down Operation Mode

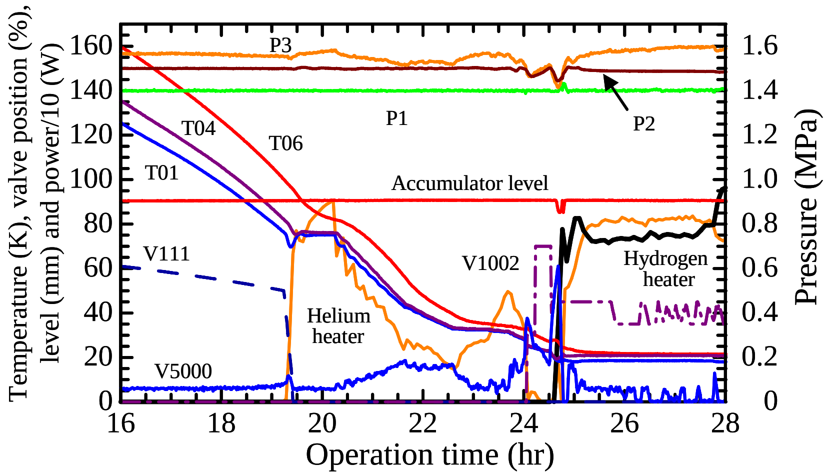
Figure 3 shows the cool down characteristic in the second cryogenic test (TEST #2), which was conducted by using an automatic sequence established based on the experimental data of TEST #1. In TEST #2, one hydrogen pump was used because the other was overhauled. The cooling rate was controlled from ambient temperature to around 70 K by using not the helium heater but the mixing valve based on the results of TEST #1. At around 70 K, the feed helium gas temperature from the cold box was kept constant for an hour by using the helium heater, and the temperature difference through the heat exchanger was reduced to consider characteristics of supercritical hydrogen. Then, the helium heater was used to control the feed helium temperature to bring about slow down the cool down of the operation temperature. Especially, the hydrogen circulation system was cooled more slowly during passing through around the critical temperature of 33 K. Therefore, the pressure fluctuation in the hydrogen buffer tank and the bellows became smaller unlike the case of TEST #1. Liquid nitrogen as pre-cooling was provided below 33 K.

On the other hand, the hydrogen pump revolution was changed from 52000 rpm to the rated revolution of 42000 rpm below 70 K as well as TEST #1. One hydrogen pump operation can obtain the mass flow rate of 63 g/s at the rated condition. Downstream of the hydrogen heater, the hydrogen heater power was controlled to keep a temperature of 21 K that was equal to that at the rated condition for the case of hydrogen, where the hydrogen heater power was around 4.0 kW and the hydrogen flow rate was 162 g/s.

The bellows of the accumulator was maintained at the fully extended location of 90.6 mm. The



(a) Overall cool down curve



(b) Cool down curve in low temperature region

Figure 3 Cool down curve in TEST #2

helium supply valve to maintain the pressure in the bellows constant was not closed automatically at the accumulator temperature of 23.6 K due to the sequence program error. Although the accumulator level would be supposed to autonomously contract to the rated level of around 40 mm with decrease in the temperature down to 21 K, it was maintained to be 90.5 mm throughout the cool down process.

It was confirmed that the cryogenic hydrogen system could be cooled down to the operation temperature within 27 hours according to the automatic sequential program, although there were some problems associated with sequence programs.

<u>Operation Test of the Accumulator</u>

The cryogenic hydrogen system was manually cooled down from 100 K to the operation temperature of around 20 K again during TEST #2 in order to conduct the operation test of the accumulator mentioned above. Figure 4 shows the result of the accumulator operation test during cool down process. At the accumulator temperature of 23.6 K, the helium supply valve worked. With decrease in the temperature down to 21 K, the bellows was automatically constricted to 33 mm as shown in Fig. 4, although the predicted level was 40 mm. The temperature distribution in the accumulator would exist during the cool down process. The thermo-sensor for the accumulator was located on the underside of it. Therefore, it was considered that, when the supply valve was closed, the average temperature through the accumulator would be higher than the temperature measured by the thermo-sensor. We confirmed that the accumulator level could be automatically adjusted by this means, although we should optimize the adjustment of the accumulator level in our future commissioning.

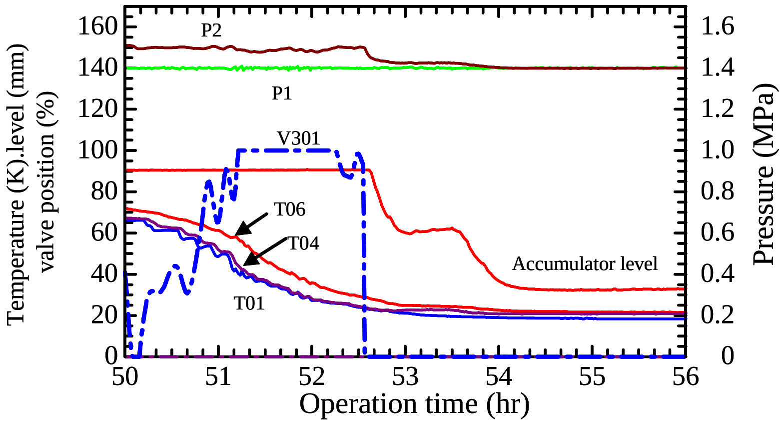


Figure 4 Accumulator operation test

CONCLUSIONS

As a first step of the cryogenic hydrogen system commissioning, we have conducted two cryogenic tests of the cryogenic hydrogen system in JSNS by using helium instead of hydrogen. The cryogenic test led to the following conclusions.

In TEST #1, the cryogenic hydrogen system can be cooled down to 20 K within 20 hours, and can be maintained for 24 hours without any problem. At the rated condition, the helium refrigeration system could circulate the mass flow rate of 258 g/s.The two pumps were able to circulate the mass flow rate of 114 g/s with the hump head of 43 kPa. We have succeeded in the first cryogenic test (TEST #1), and can have also confirmed a stability of the cryogenic hydrogen system. Based on the results of TEST #1, we have developed an automatic control sequence for the cool down operation.

In TEST #2, the cryogenic hydrogen system was cooled down according to the developed control sequence within 27 hours. We have succeeded in the cool down operation except for the accumulator control. We have confirmed that the accumulator level could be automatically adjusted by a retest of the accumulator operation conducted during TEST #2, although we should optimize the adjustment in our future commissioning.

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