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Development of Commissioning and operation of CSNS Cryogenic System

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ABSTRACT: China Spallation Neutron Source (CSNS) cryogenic system provides supercritical cryogenic hydrogen for two moderators of the target station. The commissioning work of the cryogenic system is mainly divided into four steps: (1) the acceptance test of the helium refrigerator, using the refrigerator internal heater as thermal load, and verify whether the helium refrigerator refrigerating capacity meet the requirements of the contract or not; (2) Helium commissioning, using dummy load to simulate the dynamic heat load of the moderator, and system cool down to 20K with He instead of H₂. (3) Hydrogen commissioning based on the step 2, while system is cooled down to 20K with hydrogen as working medium. (4) Joint Commissioning with two moderators. So far, the CSNS cryogenic system has completed all commissioning work and finished four rounds of stable operation for the commissioning of the target station and spectrometer.

1. Introduction

The cryogenic system of China Spallation Neutron Source (CSNS) provides neutron moderators with supercritical cryogenic hydrogen, which the concentration of para-hydrogen is 99%, working pressure and temperature is 15 bara and 18~22 K.^[1] The CSNS cryogenic system mainly include helium refrigerator system, hydrogen circulation system and the hydrogen safety system. The helium refrigerator is provided by Linde company with cooling capacity of 2200 W at 20 K. Hydrogen circulation system mainly include hydrogen cold-box, accumulator cold-box and cryogenic hydrogen pipes. Hydrogen pump, ortho-para hydrogen convertor, helium-hydrogen heat-exchanger, hydrogen heater and accumulator are integrated in the hydrogen cold-box and accumulator cold-box^[2]. The OP convertor can accelerate conversion of ortho hydrogen to para-hydrogen. The hydrogen heater is used to adjust the heat load of hydrogen loop. Cryogenic hydrogen transfer lines connect hydrogen cold-box with moderators^[3]. Dummy loads are used to simulate heat load of neutron moderators. Accumulator can change the hydrogen loop volume by bellows expansion or shrink, which will reduce the pressure fluctuations when the hydrogen loop temperature change^[4]. Figure 1 shows the Cryogenic system flow diagram.



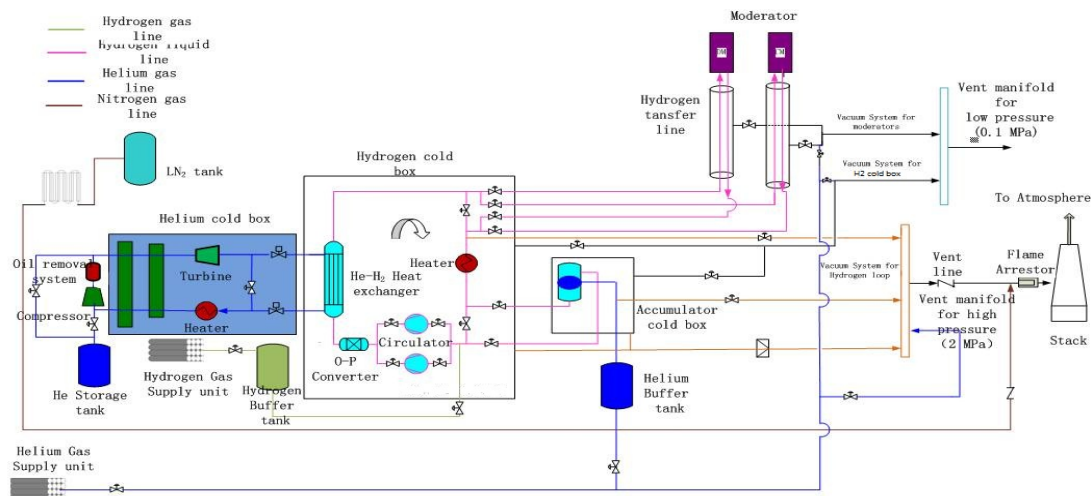


Figure 1. Flow Diagram of CSNS Cryogenic System

The commissioning work of the cryogenic system is mainly divided into four steps: (1) the acceptance test of the helium refrigerator, using the refrigerator's internal heater as thermal load, and verify whether the helium refrigerator refrigerating capacity meets the requirements of the contract or not; (2) Helium commissioning, using a dummy load to simulate the dynamic heat load of the moderator, and system cool down to 20K with He instead of H₂. (3) Hydrogen commissioning based on the step 2, while system is cooled down to 20K with hydrogen as working medium. (4) Joint Commissioning with two moderators. So far, the CSNS cryogenic system has completed all commissioning work and finished four rounds of stable operation for the commissioning of the target station and spectrometer.

2. Acceptance test of the helium refrigerator

In July 2016, the installation of the helium refrigerator is completed, which mainly includes compressor, oil separator, helium cold-box and so on. In order to ensure the purity of the helium in pipes, active carbon must be regenerate by high temperature and helium replacement for pipes must be done for three times. When commissioning starts, the test mode of the helium refrigerator is turned on, and the heater R3175 is used as the heat load. Through a week-long effort, the acceptance test of the helium refrigerator is completed successfully with three cooling powers: 700W, 1400W, and 2200W, respectively. Each power reaches the required flow rate and temperature, and the stable operation is more than 48h^[5]. Test results showed that the helium refrigerator can run stable, and refrigerating capacity meets the contract requirements. State point of helium refrigerator at 700W, 1400W, 2300W is shown in Table1, while the screenshot of helium refrigerator running at 2300W refrigerating capacity is shown in Figure 2.

Table 1. State point of helium refrigerator at 700W, 1400W, 2300W

Refrigerating capacity /W	Discharge pressure /bara	Suction pressure /bara	Post-expansion temperature /K	Post-expansion temperature / bara	Flow /g/s
700	8.64	1.541	14.5	1.76	83.8
1400	10.11	1.798	14.9	2.01	96
2300	11.86	1.97	15.8	2.25	104

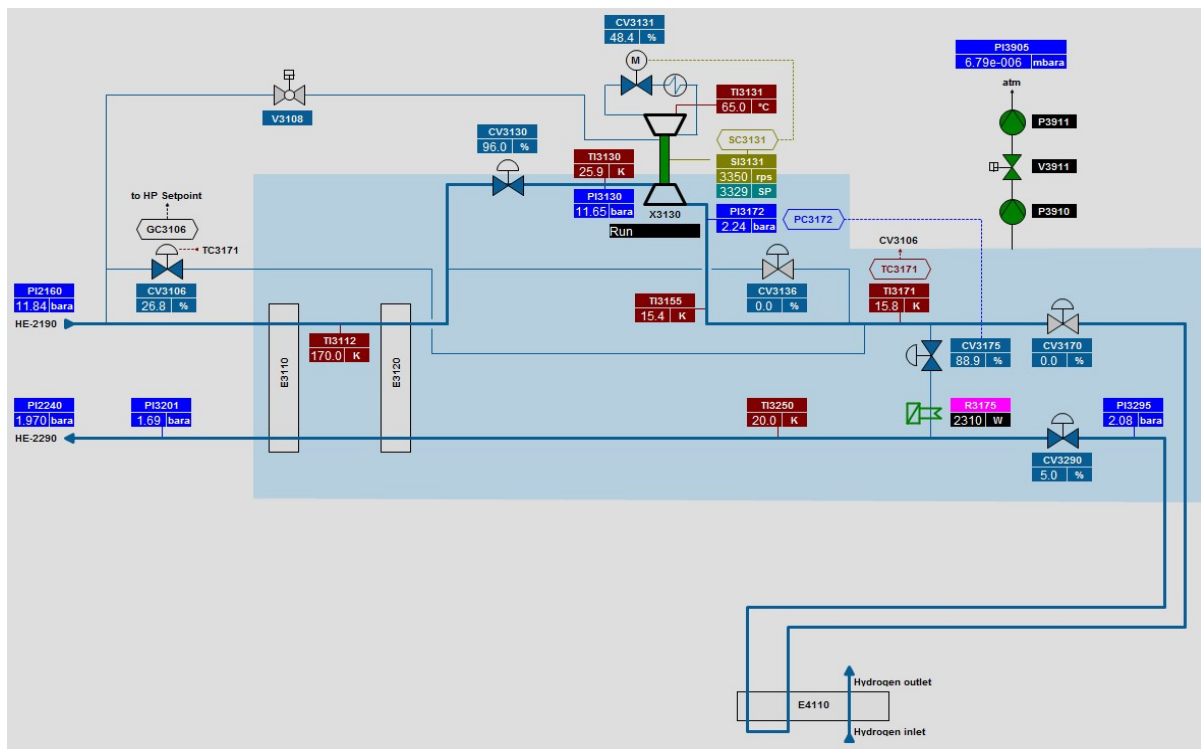


Figure 2. Screenshot of the Refrigerator Running State at 2300W

3. Helium commissioning with dummy loads

In January 2017, cryogenic system installation have been finished, while two dummy loads were used instead of two real moderators. From January to the end of April, five rounds of cool down commissioning is finished with He, which failed twice and succeeded three times^[6]. The process of helium commissioning is divided into 4 steps, including pressure-up mode, cool-down mode, stand-by mode, and warm up mode. In order to ensure the bellows not be destroyed, the differential pressure between two sides of the accumulator must be less than 1.5 bar. If the differential pressure is higher than 1.5 bar, interlock protection will be triggered. Helium pressure of accumulator is fixed at 14.5 bar and hydrogen pressure of accumulator must be strictly controlled during the process of commissioning. The first step is pressure-up mode, in which the pressure of helium side and hydrogen side rise alternately, and it must be confirmed that the differential pressure is within 0.5 bara all the time. The second step is cool-down mode, to start the helium refrigerator and set the outlet temperature at 16 K. After 18 hours cooling-down, hydrogen

circulation loop was cooled down to 20 K. The third step, stand-by mode, using dummy loads which set at 320 W and 240 W respectively to simulate the dynamic heat load of moderators. The fourth step is warm up mode, in which the hydrogen circulation loop is warmed up slowly by helium refrigerator system with the pressure controlled stable at 14 bara. When the temperature is warmed up to 300 K, the warm up mode is finished and He commissioning is completed. Cooling curves of helium commissioning is shown in Figure 3. TI4101 is the outlet temperature of the heat exchanger. TI4105 is the inlet temperature of the heat exchanger. PI4145 is the inlet pressure of the heat exchanger. FI4121 is the flow of hydrogen loop. P4104 is the frequency of the hydrogen circulation pump.

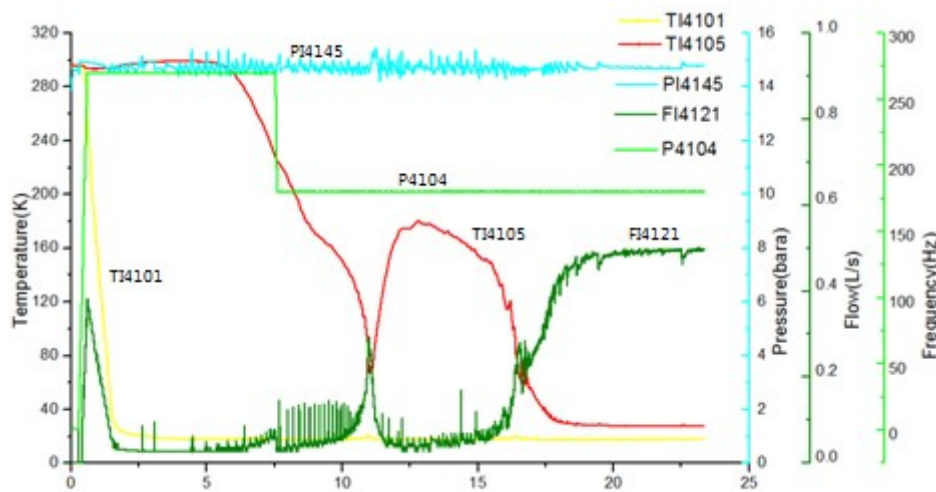


Figure 3. Cooling curves of helium commissioning

4. Hydrogen commissioning with dummy loads

From April to May, three times of hydrogen commissioning is finished, which also used the dummy loads instead of real moderators. The third hydrogen commissioning is completed successfully on May 5th 2017, while the first and second ones failed. Similar to helium commissioning, the cooling process is divided into 4 steps, include pressure-up mode, cool-down mode, stand-by mode, and warm up mode. In order to protect the bellows not be destroyed, the differential pressure between two sides of the accumulator must be less than 1.5 bar. If the differential pressure is higher than 1.5 bar, interlock protection will be triggered in order to protect the bellows not be destroyed. First, pressure of hydrogen side was set to 14.0 bara while helium side was to 15.0 bara. Second, the two hydrogen pumps are started and set the frequency to 283Hz, then opened the helium refrigerator and set the outlet temperature at 50 K. When hydrogen temperature was dropped totally to 50 K, change set value of outlet temperature to 16 K slowly, step by step. The temperature of hydrogen loop are all below 20 K after about 30 hours cooling down. Third, stand-by mode, we turned on hydrogen heater and set it to 700 W. In order to simulate the dynamic heat load of the moderators, dummy loads were set 320 W and 240 W while at the same time the heater turned off. During this operation, the cryogenic hydrogen circulation loop run stably without venting or filling gas. After 48 hours running, stand-by mode is stopped and changed to warm up mode, in which the hydrogen circulation loop is warmed

up slowly until 300 K by helium refrigerator with pressure stable at 14 bara. The cool down curves of hydrogen commissioning is shown in figure 4. TI4101 is the outlet temperature of the heat exchanger, TI4105 is the inlet temperature of the heat exchanger. PI4145 is the inlet pressure of the heat exchanger, FI4121 is the flow of hydrogen cycle. P4104 is the frequency of the hydrogen pump.

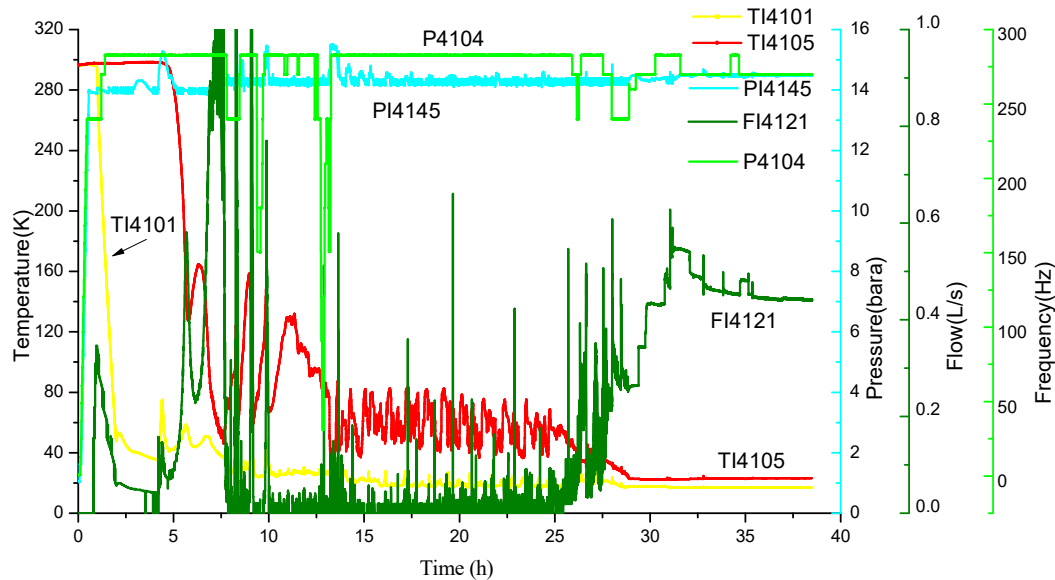


Figure 4. Cooling curves of hydrogen commissioning

5. Joint commissioning with moderators

After success of the hydrogen commissioning, the cryogenic system was disconnected from the dummy loads of the moderators and completed the connection with the real moderators in May. On 20th, June, 2017, the joint commissioning with moderators was conducted successfully. The Cooling curves of joint commissioning with moderators is shown in figure 5.

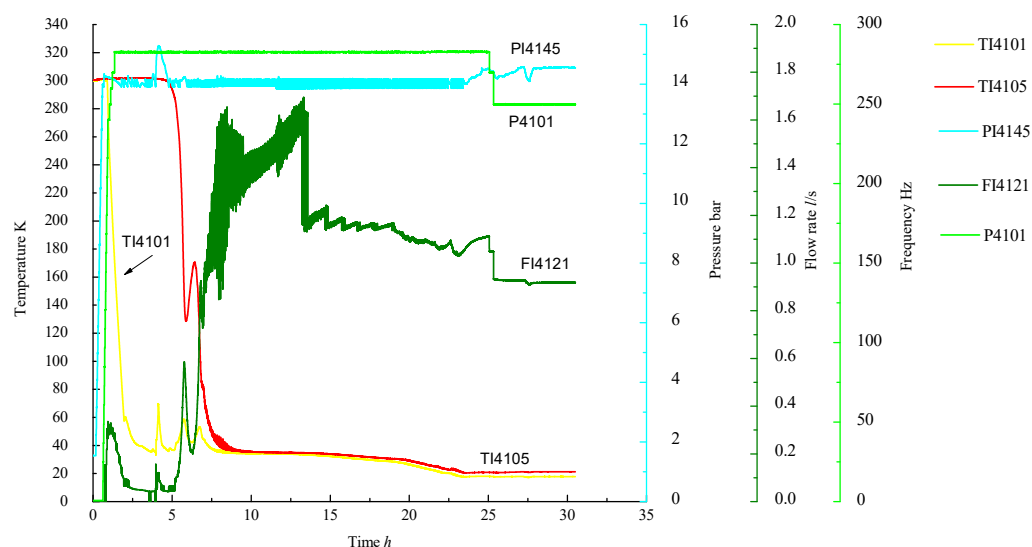


Figure 5. Cooling curves of hydrogen joint commissioning with moderators

6. Stable operations

Four rounds of operation of cryogenic system were finished in order to conduct the commissioning of target stations and spectrometers. The first operation was started on 16th of Aug, which obtained the first neutron beam. The flow rate of hydrogen circulation loop reached the maximum of 82.9 g/s, which is far exceeding the design value. On 25th, Sep., we started the second operation, during which the cryogenic system was first operated stably for more than a month, and the beam power of the accelerator reached 10 KW. On 11th, Dec., the third operation was started and continued stable operation for more than half a year. Then, on 22th of Jun. 2018, the fourth operation was started and lasted for about one month, during which the proton beam power reached 25 kW.

7. Conclusion

After four stages of commissioning, the CSNS cryogenic system continuously optimizes the control logic. Finally the joint commissioning with moderators was completed successfully, which can satisfy the requirement of moderators under the working condition of 200kW proton beams. CSNS cryogenic system finished four rounds of stable operation, which in total over 7000 hours without malfunction. However, the cryogenic system control logic will be further optimized, and we need a long-time running to verify the reliability of the cryogenic system.

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