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Design of a high power heater for the cryogenic hydrogen system at J-PARC

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ABSTRACT

The cryogenic hydrogen system, which provides the supercritical hydrogen with the pressure of 1.5 MPa and the temperature of around 20 K, adopts to moderate and convert high-energy neutrons into cold neutrons for neutron scattering experiments in the J-PARC. Large pressure fluctuation caused by the intense pulsed-proton-beam injection and trip should be mitigated by both an active heater control and a passive accumulator control. A compact high power heater should be required to compensate the heat load corresponding to the nuclear heating while the proton beam stopping. In this study, the high power heater used in the cryogenic hydrogen was designed and a numerical analysis was performed. Then the results confirmed that the heater could apply kW-order heat powers to supercritical hydrogen without any disturbance.

1. Introduction

Supercritical hydrogen with the temperature of around 20 K and the pressure of 1.5 MPa is selected as a moderator material [1] in an intense spallation neutron source (JSNS) driven by a 1-MW proton beam, which is as one of the main experimental facilities in the Japan Proton Accelerator Research Complex (J-PARC) [2]. Three kinds of hydrogen moderator (a coupled, a decoupled and a poisoned moderator) are installed to provide a pulsed neutron beam with the higher neutronic performance. Accordingly, those moderators can reduce high-energy MeV-order neutrons generated from the mercury target to the appropriate energy.

A schematic view of the cryogenic hydrogen system is shown in Fig. 1. The hydrogen circulation system, which consists of two centrifugal pumps, an ortho-para hydrogen converter, a helium–hydrogen heat exchanger, an accumulator and a heater, circulates the supercritical hydrogen through the moderators and removes the nuclear heating of 3.8 kW for a 1-MW proton beam power [2]. The total heat load is estimated to be around 4.51 kW, where the heat loss is 0.71 kW and the nuclear heating of 3.8 kW. Then a helium refrigerator should have a refrigeration power of 6 kW at 17 K at a maximum.

Because the supercritical hydrogen around 20 K behaves as an incompressible fluid, the cryogenic hydrogen system might have a severe pressure rise when the proton beam turns on. When a 1-MW proton beam, for example, is injected, the hydrogen temperature rise is estimated to be 2.5 K with the hydrogen flow rate of 0.162 kg/s but the pressure rise comes to be 3.4 MPa which is 2.3 times higher than the operation pressure of 1.5 MPa. The pressure control system is, therefore, indispensable. A pressure control system adopts both an accumulator system and a heater system to mitigate such a pressure rise. The accumulator system is composed of a bellows filled with helium gas that behaves as compressive fluid around 20 K. The bellows is surrounded by supercritical hydrogen. The bellows would be passively operated by the pressure fluctuation in the hydrogen loop. On the other hand, the heater system compensates the heat load corresponding to the nuclear heating generated at the moderators while the proton beam is stopped. Accordingly, the heat compensation is available to operate the helium refrigerator without thermal disturbance and the hydrogen supply temperature to the moderators can be also kept constant.

In this study, the high power heater that can maintain flow stability of supercritical hydrogen was designed, and the performance was evaluated using a CFD code, STAR-CD [3].

2. Pressure control system when the proton beam is injected and trips

Fig. 2 shows the pressure control approach of the cryogenic hydrogen system when the proton beam is suddenly turned on and off. The hydrogen temperature is 18 K at the cold end of the heat exchanger. While the proton beam is stopped, the heater compensates the heat load of around 4 kW, which is slightly higher than the nuclear heating of 3.8 kW. The hydrogen temperature rise through the heater is estimated to be 2.7 K with the flow rate of 0.162 kg/s. The heater power is always controlled to maintain the heater outlet temperature to be 21 K by a PID controller.

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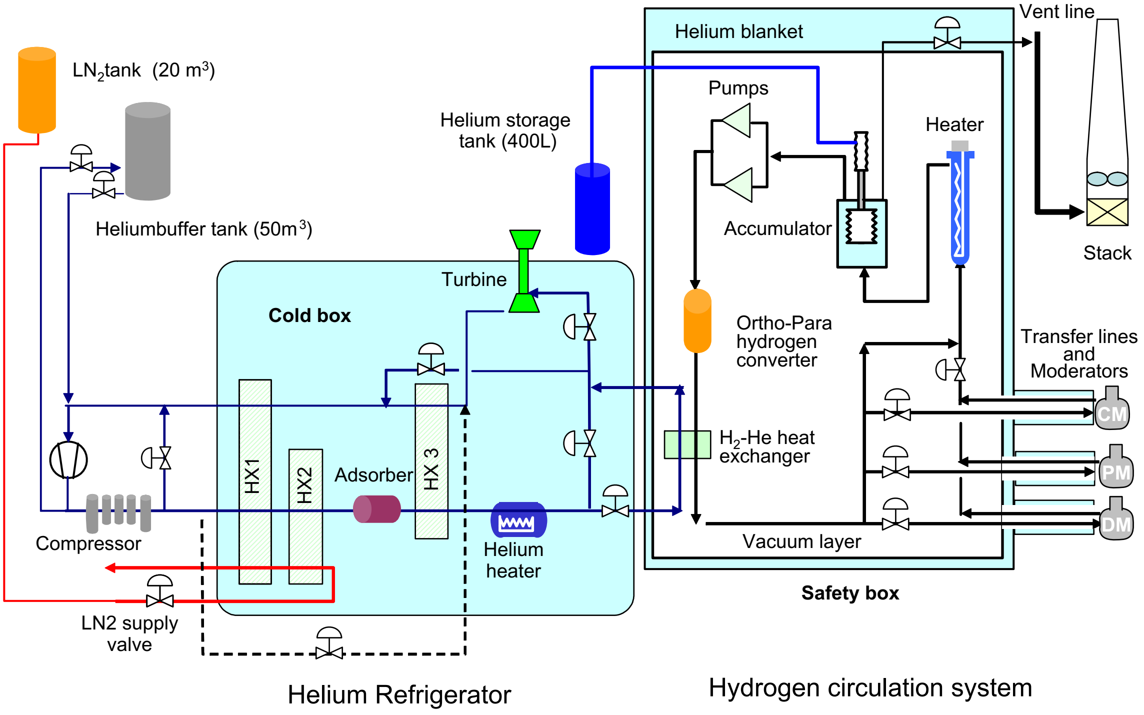
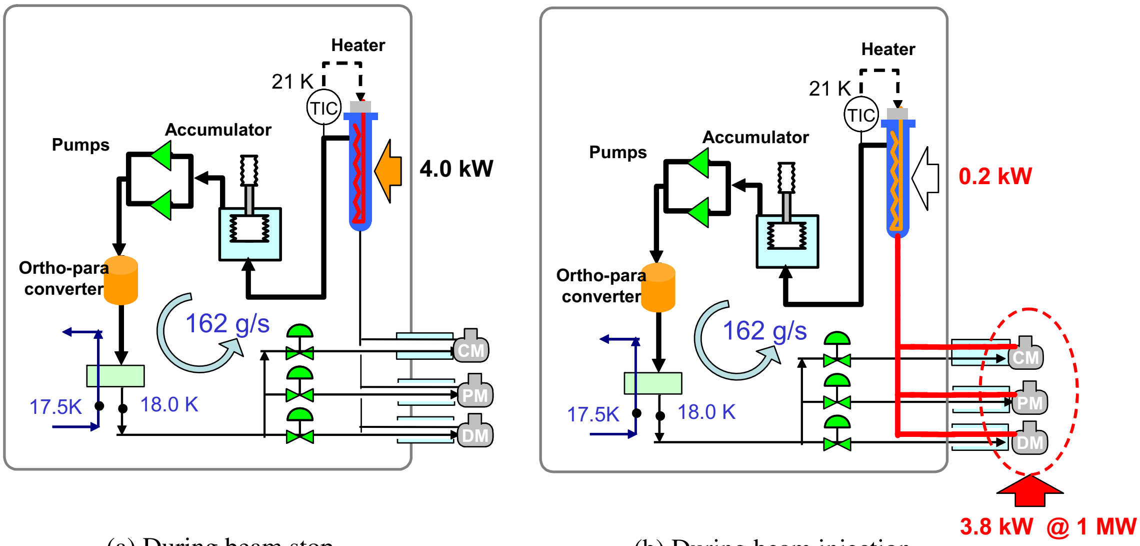


Fig. 1. Schematic view of the cryogenic hydrogen system.



(a) During beam stop

(b) During beam injection

Fig. 2. Pressure control approach of the cryogenic hydrogen system when the 1-MW proton beam is suddenly turned on and off.

When the 1-MW proton beam is injected, the hydrogen pressure and temperatures rapidly increase due to the nuclear heating. Then, the pressure control system starts to work to mitigate pressure rise by both of heater control and accumulator variation. When the temperature rise of 0.5 K appears at the heater inlet, the heat input power is suddenly reduced from 4 kW to 0.2 kW. And then the heat input is adjusted by the PID controller to maintain the heater outlet temperature to be 21 K. Such feed-forward control is adopted as an active heater control. The accumulator temperature, which is located downstream of the heater, can be also maintained to be a constant temperature such as 21 K. Therefore, the pressure fluctuation is not affected by moving the accumulator system. The system predicts that the pressure rise should be less than 40 kPa with the accumulator variation of 2.1 L.

3. Design of a high power heater

A compact high power heater, which can also maintain to stabilize a cryogenic hydrogen flow, was designed as shown in Fig. 3. The design conditions are as follows:

(1) The maximum heat load was determined to be 5 kW, which had a 25% margin of the required heat load of 4 kW for 1-MW proton beam operation.