

# Performance evaluation of a developed orifice type heater for thermal compensation control at J-PARC cryogenic hydrogen system

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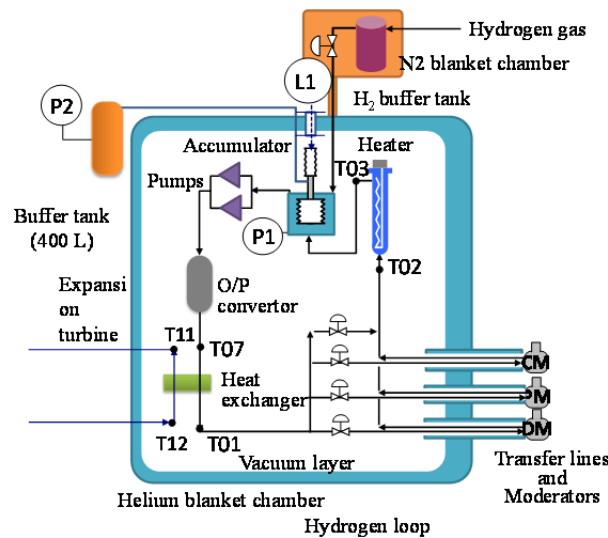
**Abstract.** Supercritical hydrogen with a temperature of less than 20 K and a pressure of 1.5 MPa is used as moderator material at J-PARC. Total nuclear heating of 3.75 kW is generated by three moderators for a 1-MW proton beam operation. We have developed an orifice-type high-power heater for thermal compensation to mitigate hydrogen pressure fluctuation caused by the abrupt huge heat load and to reduce the fluctuation in the temperature of the supply hydrogen to less than 0.25 K. Through a performance test, we confirmed that the developed orifice-type heater could be heated uniformly and showed fast response, as expected. Furthermore, a simulation model that can describe heater behaviors has been established on the basis of the experimental data. The heater control approach was studied using the aforementioned heater simulation model and a dynamic simulation code developed by the authors.

## 1. Introduction

A MW-class pulsed neutron source is installed in the Material and Life Sciences Experimental Facility (MLF), one of the main experimental facilities at the Japan Proton Accelerator Research Complex (J-PARC). High-energy neutrons (Mega electron volts) generated in the mercury target because of the injection of a 1-MW proton beam (3 GeV, 333  $\mu$ A, and 25 Hz) are slowed down to appropriate energy (milli electron volts) by three hydrogen moderators—a coupled, a decoupled and a poisoned moderator that use cryogenic hydrogen with a para-hydrogen concentration of more than 99% under a pressure of 1.5 MPa, which is supercritical pressure, and a temperature of approximately 18 K [1]. A sharp-edged pulsed cold neutron beam with a half bandwidth of approximately 100  $\mu$ s is efficiently acquired and is suitable for crystal and magnetic structural analyses.

We developed a cryogenic hydrogen system where para-hydrogen with a temperature of less than 20 K and a pressure of 1.5 MPa is circulated through a 22-m long moderator transfer line, as shown in figure 1. The nuclear heating is generated by the moderators and is estimated to be 3.8 kW for a 1-MW proton beam operation. The temperature rise at a net flow rate of approximately 190 g/s is 2.4 K, which is lower than the allowable temperature rise of 3 K. The heat load is removed through a H<sub>2</sub>-He heat exchanger by a helium refrigerator with a power of 6.45 kW at 15.6 K [2]. The hydrogen loop is filled with cryogenic hydrogen at the supercritical pressure, which behaves as an incompressible fluid. We were concerned that a slight temperature rise would lead to a large pressure fluctuation in the hydrogen loop. Therefore, we employed a heater for thermal compensation and an accumulator, with a





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

bellows structure, for volume control to mitigate the pressure fluctuation caused by the abrupt huge heat load below 0.1 MPa. The welded bellows of the accumulator have a diameter of 330 mm and a variable volume of 6.84 L in the hydrogen loop. The pressure of helium enclosed in the bellows is slightly higher than that of hydrogen. A high-power and fast response heater is required to compensate for the 3.8 kW of nuclear heating while the proton beam is turned off and to ensure that the heat load applied to the hydrogen loop is maintained constant. Tatsumoto et al. [3] developed a compact high power heater to satisfy the requirements.

In this study, we evaluated the performance evaluation of the developed high-power heater. A simulation model that can predict the transient behavior of the heater was developed.

## 2. Orifice-type high-power heater

The heater plays a role in compensating for the nuclear heating generated by the moderators when proton beam is off. The heat load applied to the hydrogen loop should be always maintained constant by switching rapidly between the compensated heat load and nuclear heating. By doing so, it is possible to reduce the fluctuation of the supply hydrogen temperature to within  $\pm 0.25$  K, which is required for providing a pulsed neutron beam with higher neutronic performance.

When the temperature fluctuation that propagates from the moderators arrives at the heater inlet, the heater power corresponding to nuclear heating is rapidly reduced by feed-forward control and is then adjusted to 20.95 K at the heater exit by a feedback control. Details of the pressure mitigation approach have already been described in [2]. We have developed a compact and high-power heater to satisfy the design requirements, and details of the heater are presented in another paper [3]. The developed heater vessel has an inner diameter of 133 mm, length of 1600 mm, and thickness of 3.4 mm. Ten U-shaped sheathed heaters with a diameter of 12 mm and length of 1358 mm, of which the average heat flux was determined to be  $5000 \text{ W/m}^2$  for a heat load of 5 kW, were arranged in parallel along the hydrogen flow. Baffle plates with a diameter of 130 mm and thickness of 3.0 mm were longitudinally arranged at 100-mm intervals. Each baffle plate had twenty holes, each having a diameter of 16 mm, which is slightly larger than the diameter of the sheathed heaters. The hydrogen inventory was 17.9 L in the heater region. Through the analytical results using a CFD code, STAR-CD [4], it has already been confirmed that the developed orifice type heater can apply a high heat load of 5 kW to the supercritical hydrogen uniformly without disturbance.

### 3. Performance test results

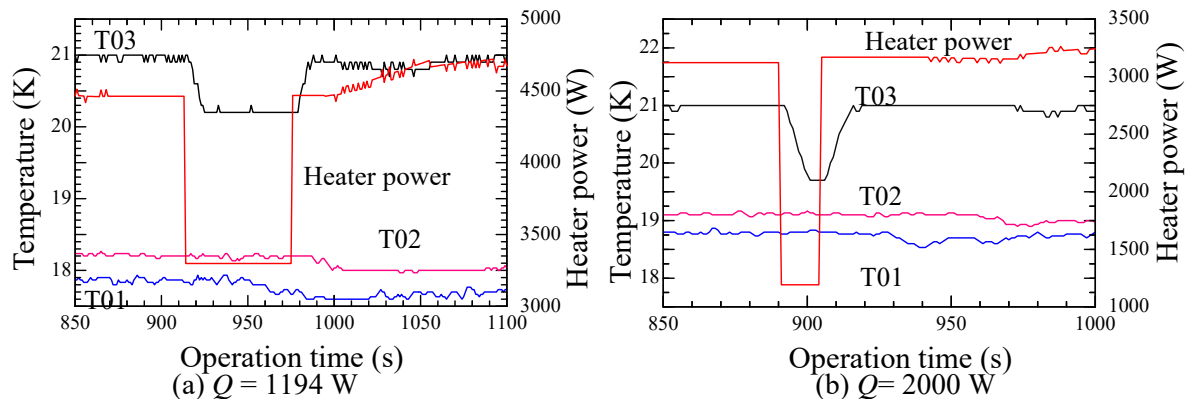
Figure 2 shows the temperature change at the heater exit, T03, when the stepwise heater power values,  $Q_s$ , of 398 W to 2429 W are rapidly changed from the initial heater power value of 4.8 kW for a certain duration,  $t_d$ . Silicon diode temperature sensors are used. Initially, the temperature at T03 is controlled to be 20.95 K. All measured data are acquired at a sampling interval of 1 s. The temperature at T03 begins to decrease 3 s after the stepwise heat load change. The temperature reduction continues over a period. Figure 3 shows the time before the temperature change at T03 for each abrupt stepwise heat load change. The travel time of hydrogen through the heater region is estimated to be 6.7 s at a flow rate of 0.185 kg/s. The durations required for the change in temperature at T03 are a few seconds longer than the travel times. For example, the durations for  $Q_s = 800$  W and 2429 W are approximately 9 s and 12 s, respectively. They seem to depend on the heat load change. The temperature at T03 can remain unchanged after the aforementioned durations. We confirmed that the developed orifice-type heater can apply such a stepwise heat load of kW-order to supercritical cryogenic hydrogen uniformly and rapidly without any disturbance, as planned.

### 4. Simulation model of heater control

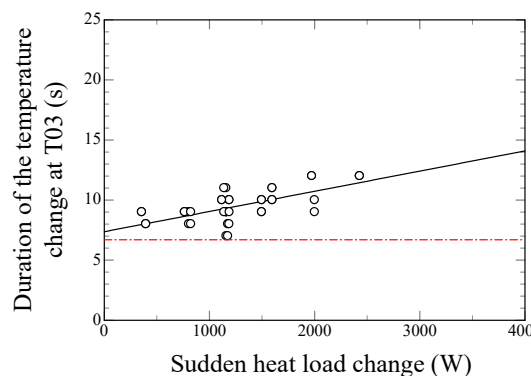
In recent times, in April of 2015 a stable 500-kW proton beam became operational. We plan to increase the proton beam power to our goal of 1 MW by the middle of 2016. It is necessary to develop an adequate and effective heater control approach for achieving a highly-reliable and matured operation to achieve the higher beam power. We developed a simulation code called DiSC-SH2 to study pressure and temperature fluctuations in the hydrogen loop when switching the proton beam on and off and details of DiSC-SH2 have already been described [5].

#### 4.1. DiSC-SH2

In this analytical model, the hydrogen loop is regarded as a single loop, although the moderators and



**Figure 2.** Temperature fluctuations caused by stepwise heater power changes.



**Figure 3.** Duration of temperature change at T03 due to a sudden change in heater power.

their transfer-lines are actually arranged in parallel. The hydrogen loop having an entire volume of 195.6 L, is modeled using a one-dimensional pipe comprising 8443 grid elements and having a cross-sectional area of  $1.1 \times 10^{-3} \text{ m}^2$  and length of 168.59 m. The relevant enthalpy equation was solved by the finite volume method as follows:

$$\frac{\partial(\rho h)}{\partial t} = -\frac{\partial(\rho u h)}{\partial x} + \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + S \quad (1)$$

where  $h$  denotes the enthalpy,  $u$  denotes the flow velocity,  $\rho$  denotes the density,  $\lambda$  denotes the thermal conductivity and  $S$  denotes the energy source

The circulation flow rate was determined using the pressure drop across the hydrogen loop and the measured pump properties by means of the Newton-Raphson method. We have already derived a pressure-drop correlation using intricately-shaped components based on the results of a CFD simulation performed using STAR-CD [4]. The enthalpy distribution was converted into a temperature distribution, and a non-linear filter method [6] was applied to maintain numerical stability. The effect of the expansion and contraction of the bellows, which are driven by a helium-hydrogen pressure differential, was considered as well. Time integration was explicitly performed with a time step of 0.01 s.

#### 4.2. Feedback control modelling

It is assumed that the developed heater could be expressed by a one-dimensional piping model because of its fast response and uniform heating. Heater power is adjusted by feedback control and feed-forward control. Proportional-integral (PI) control is adopted for feedback control, and the temperature at T03 is maintained at 20.95 K.

$$MV = K_p \left( (e_n - e_{n-1})e + \frac{\Delta t}{T_i} e_n \right) \quad (2)$$

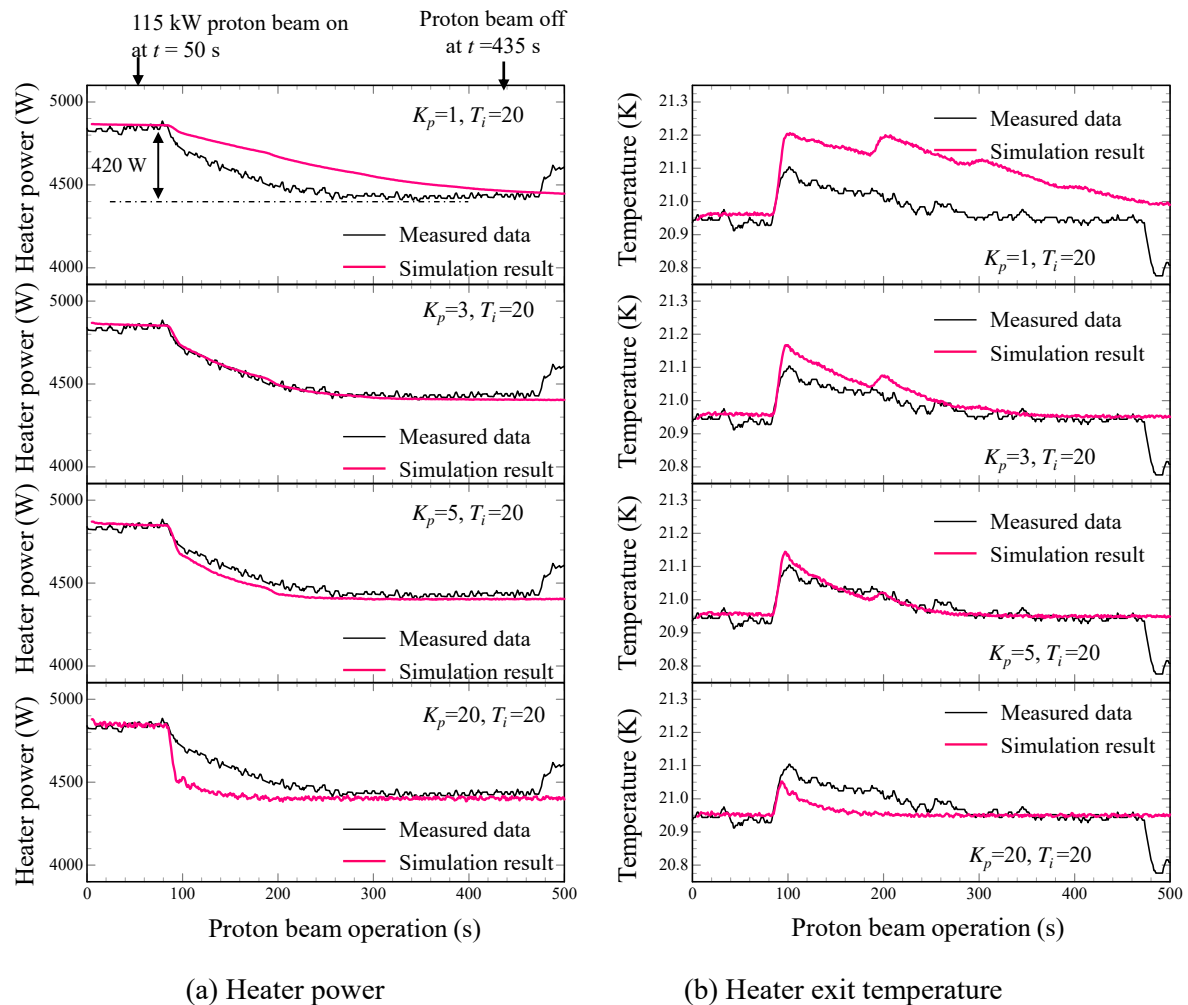
where  $MV$  is the manipulated variable,  $K_p$  is the controller gain,  $e$  is the error,  $T_i$  is the integral time, and  $\Delta t$  is the time step.

In this analysis, heater power adjustment by PI control is conducted at 1-s intervals, as is the case for the actual data acquisition system.

## 5. Simulation results

### 5.1. Determination of PI parameters

Figure 4 shows the simulation results of hydrogen temperature behavior at T03 and the controlled heater power without feed-forward control for a 120-kW proton beam operation. The values of  $K_p$  range from 1 to 20 at  $T_i = 20$ . The nuclear heating is estimated to be 420 W. For comparison, the measured values acquired under the same condition are also shown in the figure. Although the temperature at T03 increases temporarily because of the hydrogen flow being warmed by nuclear heating, the heater power is adjusted to maintain the temperature at T03 at 20.95 K. For larger  $K_p$ , the response time decreases. In contrast, the simulation results of the temperature at T03 and controlled heater power for a 120-kW proton beam operation at  $K_p = 3$  are shown in figure 5. The values of  $T_i$  are ranging from 0.5 to 40 at  $K_p = 3$ . For shorter  $T_i$ , the time required to come around seems to decrease and the tentative temperature rise becomes smaller. However, this brings about oscillatory instability of the heater output and the temperature at T03 oscillates as well. The adequate values of parameters  $K_p$  and  $T_i$  are determined to be 3 and 20, respectively, based on the experimental data, although those used in the actual control system are set to 14 and 20.

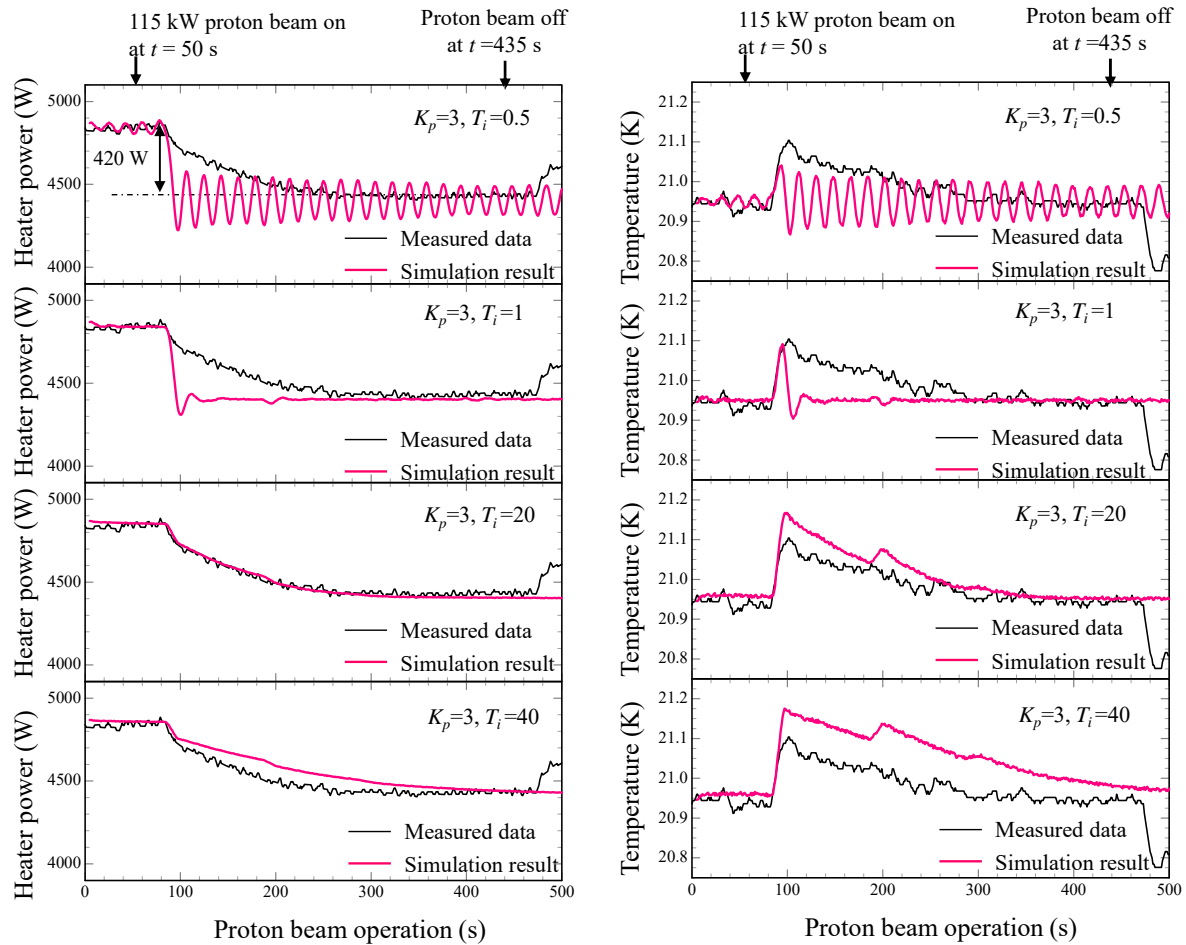


**Figure 4.** Effect of parameter of  $K_p$  on heater power control and temperature fluctuation at T03 for a 120-kW proton beam operation.

Figure 6 shows the simulation results of pressure fluctuation and bellows behavior for  $K_p = 3$  and  $T_i = 20$ . It was confirmed that the behaviors of the pressure fluctuations, which were measured by a diaphragm-type pressure transmitter, and the bellows can be predicted using the developed dynamic simulation code [5].

Figure 7 shows the simulation results of dynamic behaviors of the controlled heater power, pressures, accumulator bellows and temperatures caused by a stepwise heater power change of 1194 W for duration of 61 s. Initially, the heater power was maintained to be 3230 W. The temperature was decreased by 0.75 K and the effect propagated downstream of the heater. The pressure change was affected by the temperature distribution change in the hydrogen loop, and its effect could be mitigated by a spontaneous change in bellow volume. The tentative pressure fluctuations continue until the temperature distribution in the hydrogen loop came around. We confirmed that the simulation code and the modeled heater controller can accurately predict the behaviors of heater control, propagation of temperature and pressure fluctuations and bellow movement.

The 600-kW proton beam operation was trialed in April 2015 for the first time. The simulation results, where the feedback heater control approach is combined with the feed-forward one, under the same conditions for a 600-kW proton beam operation are shown in figure 8. The temperature of 0.3 K appears at T02 and the heater power of 2.28 kW rapidly decreases. The pressure increases by 34 kPa, and there are no tentative pressure fluctuations after the feed-forward heater control is executed. We

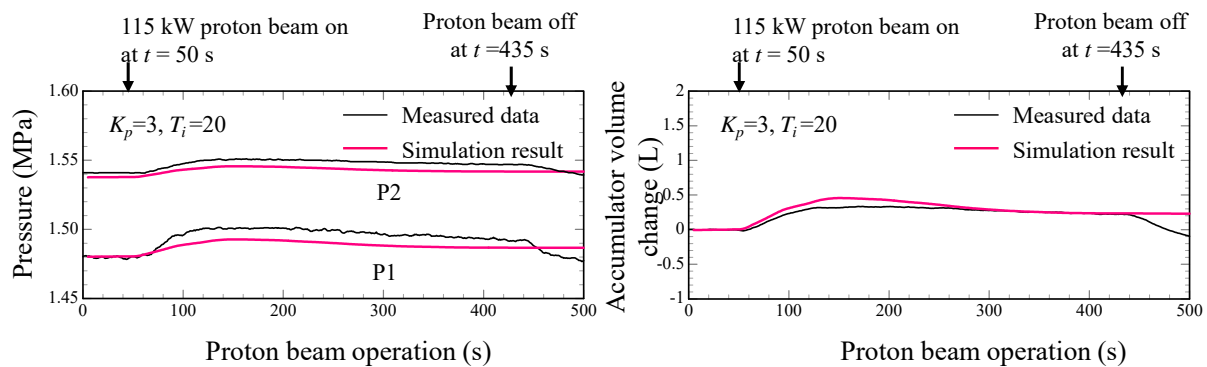


(a) Heater power

(b) Heater exit temperature

**Figure 5.** Effect of parameter of  $T_i$  on heater power control and temperature fluctuation at T03 for a 120-kW proton beam operation.

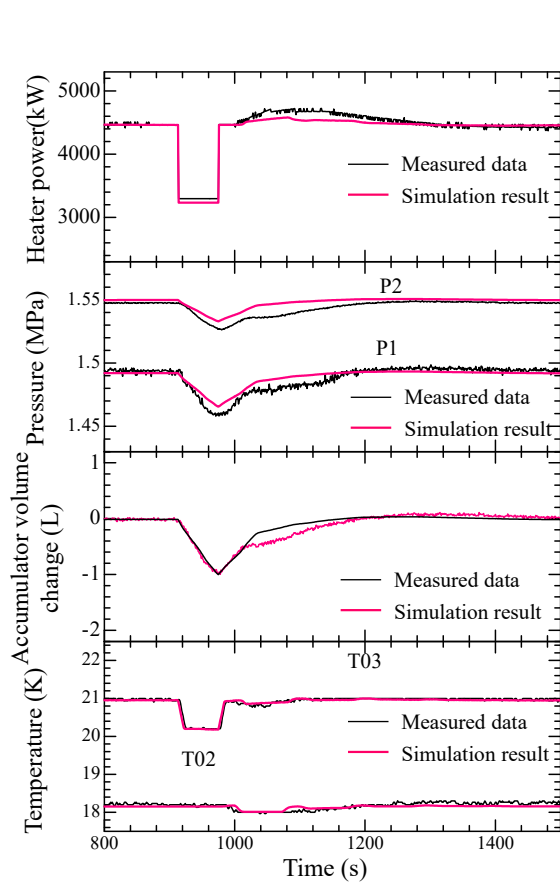
confirmed that the simulation code can also predict the dynamic behaviors of the hydrogen loop with feedforward and feedback control for the 600-kW proton beam operation.



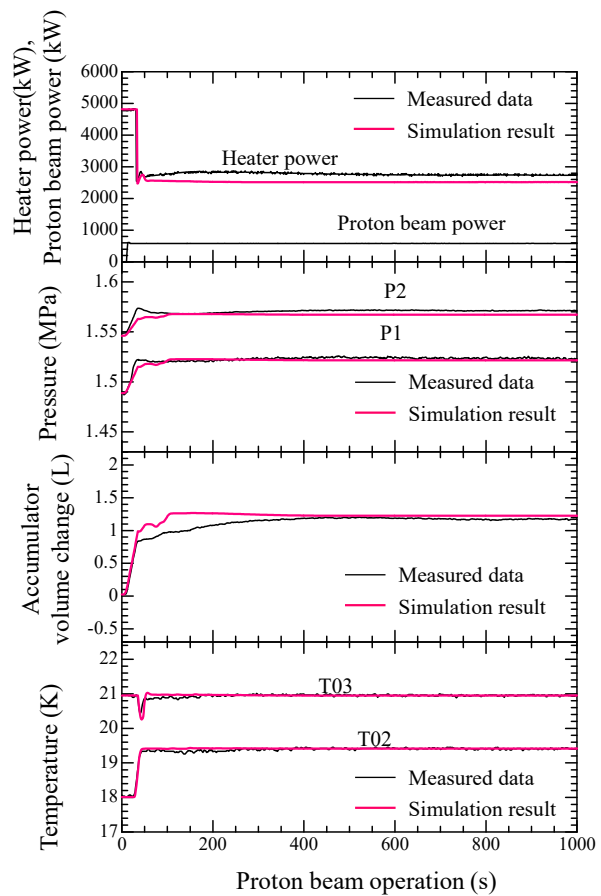
(a) Pressure fluctuation

(b) Accumulator bellows

**Figure 6.** Simulation results of a 120-kW proton beam operation for various  $T_i$ .

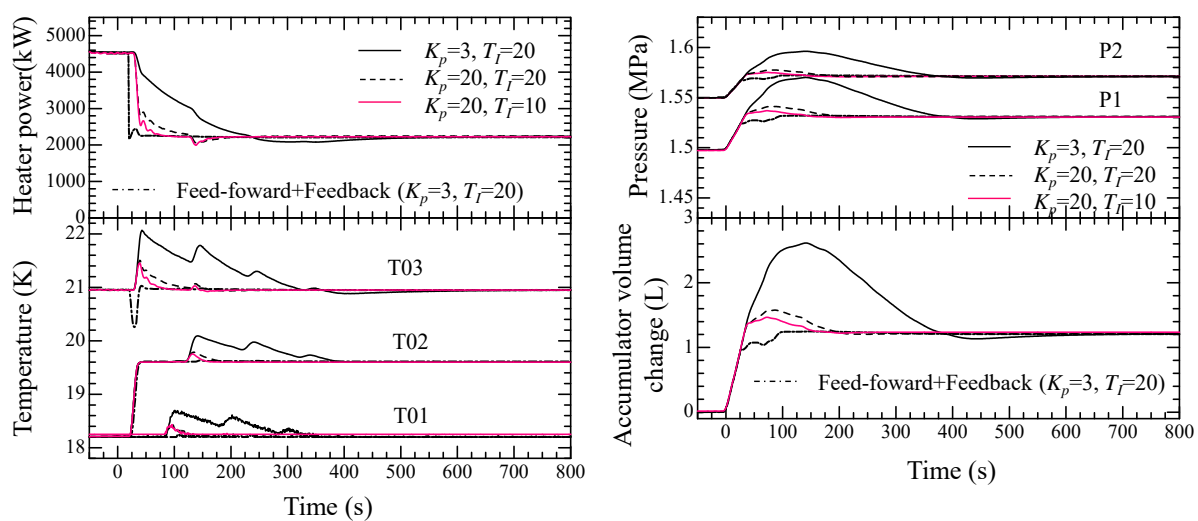


**Figure 7.** Simulation results for a sudden heater power change of 1194 W.



**Figure 8.** Simulation results for a 600-kW proton beam operation.

When the high-power proton beam was repeatedly switched on and off in a short period during a sequence of the feed-forward control program, we were concerned about the possibility of malfunction of the control program when the beam was switched off. Therefore, feedforward control was not



**Figure 9.** Simulation results for various  $K_p$  and  $T_i$  after 600-kW proton beam is switched on.

executed and the heater power was adjusted only by the feedback heater control. We studied the tentative changes in pressure using only the feedback heater control for the 600-kW proton beam operation. Furthermore, we optimized the PI parameters to reduce pressure fluctuation and the required volume change of the bellows using the simulation code. Figure 9 shows the simulation results of pressure and temperature fluctuations, controlled heater power, and bellows movement for various PI parameters of  $K_p$  and  $T_i$  for 600-kW proton beam operation. For  $K_p = 3$  and  $T_i = 20$ , the pressure temporarily increases by 72 kPa and the volume change of the bellows is up to 2.6 L, although these values are lower than the allowable pressure rise of 0.1 MPa and the maximum bellows stroke of  $\pm 3$  L. It takes approximately 600 s until the transient fluctuations disappear. For larger  $K_p$  and shorter  $T_i$ , the transient pressure fluctuation and volume change become smaller and approach those achieved with the use of the feedback and feed-forward control schemes. In such a case, the duration of the transient variation also becomes shorter. For  $K_p = 20$  and  $T_i = 10$ , the temporary pressure rise is reduced to 36 kPa, which is 20% higher than that with the use of feedback and feed-forward control and the temporary bellows change is 18% higher. The duration of the transient variation can be shortened by 450 s. It is found through the simulation results that the feedback heater control approach with  $K_p = 20$  and  $T_i = 10$  could be used without feed-forward control to mitigate the pressure fluctuation for the 600-kW proton beam operation.

## 6. Conclusions

A performance test of the compact orifice type high-power heater, which was developed to compensate for nuclear heating during proton beam off, was performed by varying the kW-order heat loads in a stepwise manner. We confirmed that the heater can apply a heat load of kW-order to supercritical cryogenic hydrogen rapidly and uniformly without any disturbance.

The heater characteristics were modeled to be introduced into the dynamic simulation code developed by the authors. The PI control parameters were determined on basis of the experimental data. We confirmed that the simulation code can predict the dynamic behaviors of the cryogenic hydrogen loop caused by thermal disturbances. The PI parameters were optimized using the simulation code. It was confirmed that feedback control for  $K_p = 20$  and  $T_i = 10$  was available without the feed-forward control to mitigate the pressure fluctuation to almost the same level as that with the use of feed-forward and feedback control.

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