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

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ABSTRACT

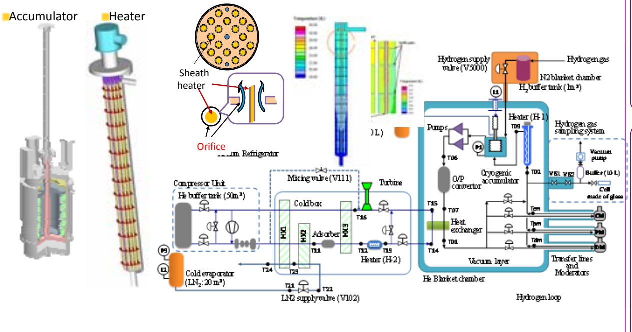
Supercritical hydrogen with a temperature of less than 20 K and a pressure of 1.5 MPa is used as moderator material at J-PARC. Total nuclear heating of 3.75 kW is generated by three moderators for a 1-MW proton beam operation. We have developed an orifice-type high-power heater for thermal compensation 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.

INTRODUCTION

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

Cryogenic Hydrogen System (Cryogenic Supercritical hydrogen at 1.5 MPa and 18 K)

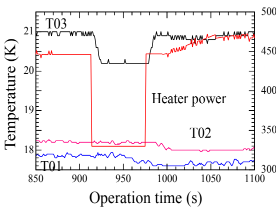
Accumulator Heater

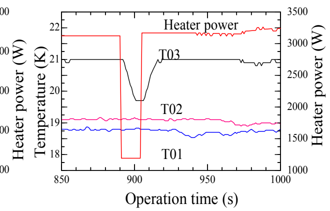


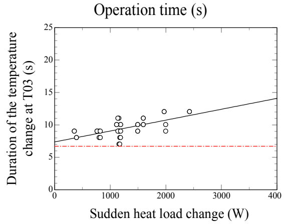
In this study,
we evaluated the performance evaluation of the developed high-power heater. A simulation model that can predict the transient behavior of the heater was developed.

PERFORMANCE TEST RESULTS

- Temperature fluctuations caused by stepwise heater power changes.
  - Initial temperature at T03= 20.95 K.
  - Sampling interval : 1 s.







- Travel time of hydrogen through the heater region is estimated to be 6.7 s at a flow rate of 0.185 kg/s.
- Durations required for the change in temperature at T03 are a few seconds longer than the travel times.
- They seem to depend on the heat load change.

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.

SIMULATION MODEL OF HEATER CONTROL

- In recent times, we conducted a stable 500-kW proton beam operation since April 2015. 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.

DiSC-SH2

- Hydrogen loop is regarded as a single loop, although the moderators and their transfer-lines are actually arranged in parallel.
- 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 1.1×10^{-3} m² and length of 168.59 m.
- Relevant enthalpy equation was solved by the finite volume method .

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

- Circulation flow rate was determined using the pressure drop and measured pump properties by means of the Newton-Raphson method.
- Pressure-drop correlation for intricately-shaped components, which was derived by authors, was used.
- Enthalpy distribution was converted into a temperature distribution, and a non-linear filter method was applied.
- Effect of the expansion and contraction of the bellows, which are driven by a helium-hydrogen pressure differential, was considered.
- Time integration was explicitly performed with a time step of 0.01 s.

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.

$$\Delta MV_n = K_p\left((e_n - e_{n-1}) + \frac{\Delta t}{T_I} e_n\right)$$

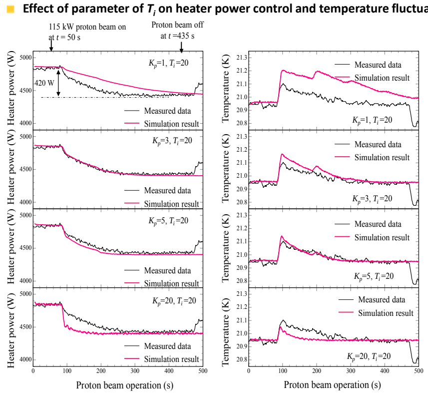
MV : manipulated variable
K_p : controller gain
e : error
T_I : integral time
Δ*t* :time step

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.

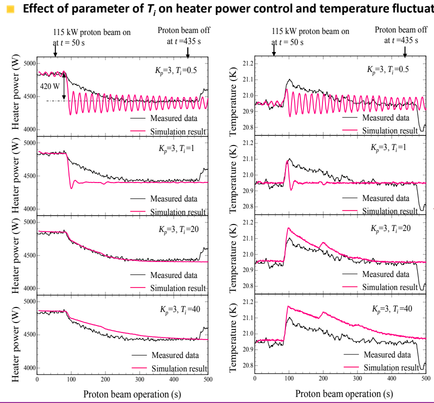
SIMULATION RESULTS

Determination of PI parameter

Effect of parameter of T_I on heater power control and temperature fluctuation at T03 for a 120-kW proton beam operation.

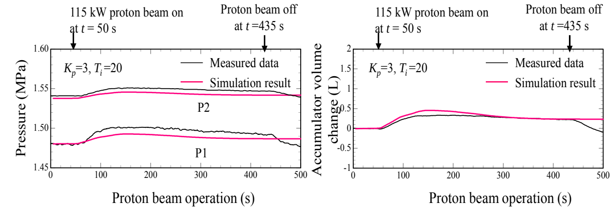


Effect of parameter of T_I on heater power control and temperature fluctuation at T03 for a 120-kW proton beam operation.



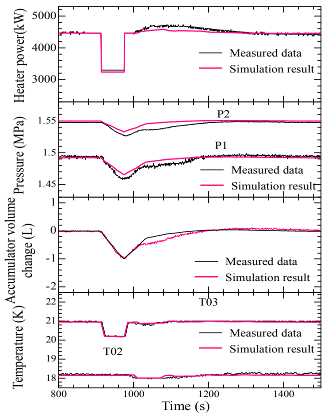
The adequate values of parameters K_p and T_I are determined to be 3 and 20, respectively, based on the experimental data, although those used in the actual control system are set to 14 and 20.

- Simulation results of a 120-kW proton beam operation for various T_I.



It was confirmed that the behaviors of the pressure fluctuations and the bellows can be predicted using the developed dynamic simulation code

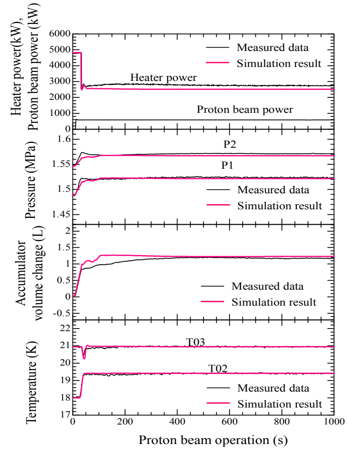
- Simulation results for a sudden heater power change of 1194 W.



- Pressure change was affected by the temperature distribution change in the hydrogen loop.
- 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.

- Simulation results for a 600-kW proton beam operation.



- 600-kW proton beam operation was trialed in April 2015 for the first time.
- Feedback heater control approach is combined with the feed-forward one, under the same conditions.
- There are no tentative pressure fluctuations after the feed-forward heater control is executed.

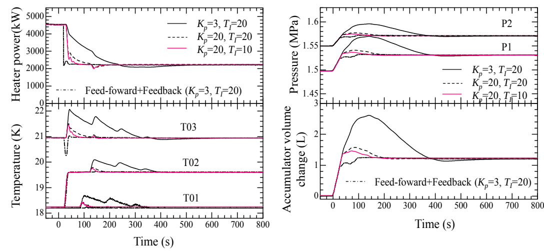
We confirmed that the simulation code can also predict the dynamic behaviors of the hydrogen loop with feedforward and feedback control.

- 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 executed and the heater power was adjusted only by only 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.

600-kW proton beam operation.



It is found through the simuation 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.

CONCLUSIONS

A performance test of the compact orifice type high-power heater, which was developed to compensating 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 modelled 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.