Pressure and temperature fluctuation simulation of J-PARC cryogenic hydrogen system

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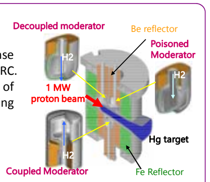
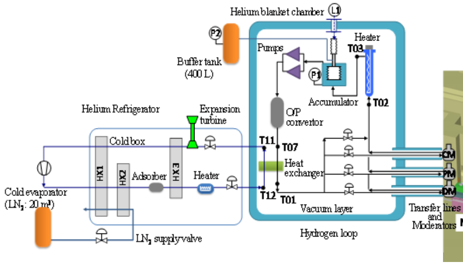
ABSTRACT

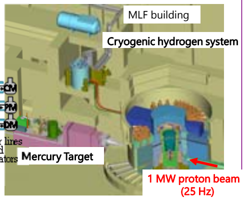
The J-PARC cryogenic hydrogen system provides supercritical cryogenic hydrogen to the moderators at a pressure of 1.5 MPa and temperature of 18 K and removes 3.8 kW of nuclear heat from the 1 MW proton beam operation. We prepared a heater for thermal compensation and an accumulator, with a bellows structure for volume control, to mitigate the pressure fluctuation caused by switching the proton beam on and off. In this study, a 1-D simulation code named DiSC-SH2 was developed to understand the propagation of pressure and temperature propagations through the hydrogen loop due to on and off switching of the proton beam. We confirmed that the simulated dynamic behaviors in the hydrogen loop for 300-kW and 500-kW proton beam operations agree well with the experimental data under the same conditions.

INTRODUCTION



Supercritical cryogenic hydrogen is selected as a moderator material in an intense spallation neutron source (JSNS), which is as one of main experimental facilities in J-PARC. A cryogenic hydrogen system provides supercritical hydrogen with a temperature of below20 K and a pressure of 1.5 MPa to three moderators and absorbs a nuclear heating of 3.75 kW for a 1-MW proton beam operation.





- Tatsumoto et al. [2] developed a simulation code to predict temperature behaviors in the hydrogen loop during the cool-down process and studied an operation method for the cool-down process.

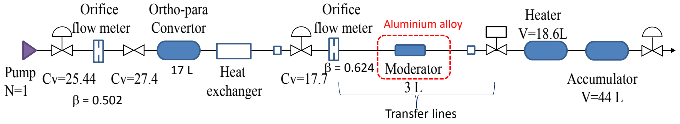
- The proton power was increased smoothly and a stable 500-kW proton beam operation was conducted in 2015. The plan is to increase the proton beam power to our goal of 1 MW until 2016.

In this study,
We developed a simulation code named DiSC-SH2 that can predict pressure and temperature fluctuation behaviors in the hydrogen loop because of the switching off and on of the proton beam.

SIMULATION CODE OF PRESSURE AND TEMPERATURE FLUCTUATION

Analytical Model

Hydrogen inventory = 195.6 L



- Hydrogen loop is considered as a single loop and is modeled using a one-dimensional pipe with a cross-sectional area of 1.1×10^{-3} m^2 and total length of 168.59 m.

- Pipe between each component has an outer diameter of 42.7 mm and thickness of 2.0 mm.

- Accumulator
  1)Helium gas is enclosed in the bellows with a volume of 61 L and behaves as a compressible fluid at approximately 20 K.
  2)Bellows are connected to a buffer tank with a volume of 400 L at room temperature through a 20-m long pipe with a volume of 9.5 L, which is installed in a vacuum chamber.

Basic Equations

Enthalpy equation

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

h: enthalpy
u : flow velocity
ρ :is the density
λ : thermal conductivity
S : energy source

Hydrogen pump characteristics

- Closed impeller: aluminium alloy and diameter, *d*, of 26.0 mm.
- Allowable revolution rate: 30,000 rpm to 63,000 rpm
- Allowable pump head ΔP: 120 kPa

$$\phi = \frac{V}{d^2 u_s}$$

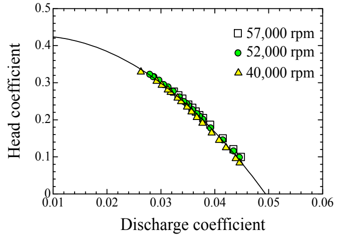
$$\mu = \frac{\Delta P}{\rho {u_s}^2}$$

V: volumetric discharge flow rate
u_s : peripheral velocity

Heat load generated in the pump, Q_p,

$$Q_p = \frac{V \Delta P}{\eta_p}$$

η_p : Pump efficiency (= 0.5)



Correlations for pressure drop

Components

$$\Delta P = F\frac{m^2}{\rho}$$

F: factor,
which depends on geometory.

Coaxial corrugated pipe (transfer line)

$$f = \frac{D_H}{s}\left\{1 - \left(\frac{D_H}{D_H - 0.4328s}\right)^2\right\}^2$$

s: Corrugation pitch.
D_H: Equivalent diameter.

Pipe

$$\Delta P = f\frac{L}{D_H}\frac{\rho}{2}u^2$$

(i) $f = \frac{64}{Re}$ for $Re < 2300$

(ii) $f = 0.316Re^{-0.25}$ for $3000 < Re < 50000$

Heat transfer

Tatsumoto et al. [10] and Shiotsu et al. [11] developed an experimental system that can safely use “hydrogen” and have measured heat transfer characteristics in forced flows of saturated, subcooled and supercritical hydrogen.

$$Nu = 0.023Re^{0.8}Pr^{0.4}F_c$$

$$F_c = \left[1 + 108.7\left(\frac{D_H}{L}\right)^2\right]^{0.25}\left[1 + 0.002\left(\frac{\Delta T}{T_{cr}}\right)\right]\left(\frac{\rho_w}{\rho_B}\right)^{0.34}\left(\frac{\mu_B}{\mu_w}\right)^{0.17}$$

Nu: Nusselt number
Pr: Prandtl number
μ: viscosity.
Symbols *w* and *B* represent heated wall and bulk fluid

Heat inleak

Heat inleak is calculated according to the following correlation using an equivalent thermal conductivity λ_{eff}

$$\lambda_{eff} = 3.65 \times 10^{-13} n^2 \left(\frac{T_h + T_c}{2}\right) + 1.1 \times 10^{-13}\frac{(T_h + T_c)\left({T_h}^2 + {T_c}^2\right)}{n}$$

PID control for heater

Hater power is adjusted by feedback control and feed-forward control schemes, and the temperature at the heater outlet is maintained at 20.95 K.

$$MV = K_p\left(e + \frac{1}{T_I}\int edt + T_D\frac{de}{dt}\right)$$

K_p: controller gain
e: error
T_I :integral time,
T_D : the derivative time

Value of T_D was set zero because the actual feedback control uses only PI control. Based on the experimental results, the values of K_p and T_I in the simulation code were determined to be 3 and 20, respectively.

NUMERICAL PROCEDURE

- Entire hydrogen loop is modelled using a one-dimensional pipe with a cross-sectional area of 1.1×10^{-3} m^2, length of 168.59 m, and divided into 8443 grids. The volume of a grid is 0.0235 L.

- Time integration is explicitly performed with a time step, Δt, of 0.01 s.

- Properties of hydrogen are given as polynomial functions of temperature and pressure, which are obtained by least-square fitting of data calculated using GASPAK [17] within an error of 1.0%.

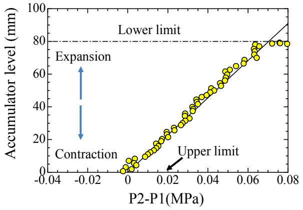
- Initial conditions
  i) Hydrogen pressure = 1.5 MPa and helium pressures = 1.55 MPa. (Actual rated operation condition as well.)
  ii) Hydrogen temperature at T01 = 18.0 K.
  iii) Pump speed is 40,000 rpm.
  iv) Helium temperature in the bellows, buffer tank, and connecting pipe between them are 20.9 K, 300 K, and 160 K, respectively.
  v) Initial entire hydrogen inventory is set to 198 L.

- Calculation of circulation flow rate
  - Using entire pressure drop through the hydrogen loop and the pump property.
  - This calculation is iteratively repeated using the Newton-Raphson method until the difference between the overall pressure drop through the hydrogen loop and the pump head given by the pump property converge.

- Heat loads
  - Heat removed by the heat exchanger is set to 5120 W, which is given by the temperature difference and the flow rate through the heat exchanger.
  - Heat loads are uniformly applied to each grid occupied by the heater, heat exchanger, and the moderators.

- Bellows behavior and Pressure change

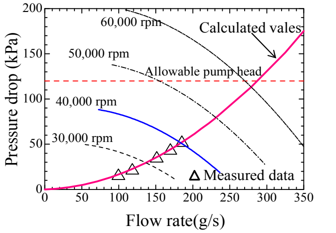
(1) At the outset, a tentative volume change of the bellows is set.
(2) Helium pressure calculation is repeated by means of the Newton-Raphson method.
(3) Subsequently, the hydrogen pressure is calculated using the calculated temperature
distribution to satisfy the law of conservation of mass.
(4) Expansion and contraction of the bellows is driven by a pressure difference between the hydrogen and the helium, which depends on the spring constant of the bellows.



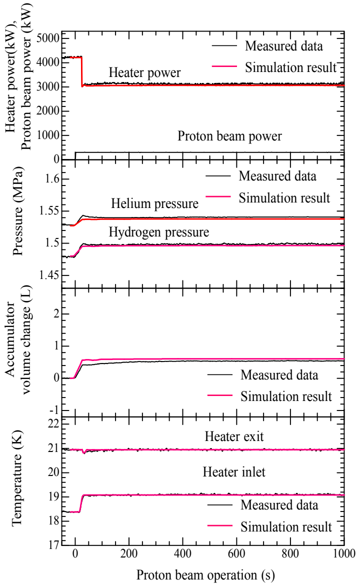
These calculations are repeated until the pressure difference between the hydrogen and the helium, P2-P1, becomes equal to the driving pressure difference of the bellows.

NUMERICAL RESULTS

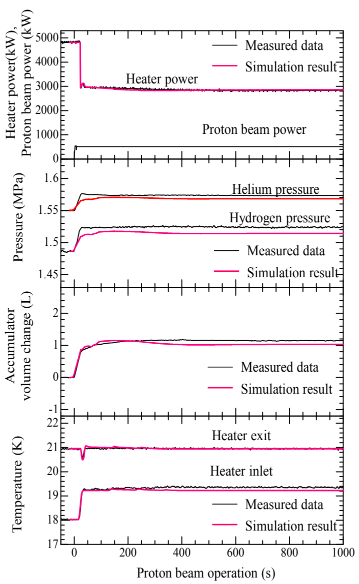
- Calculated pressure drop agrees well with the measured value.
  - We confirmed that the pressure correlations can accurately calculate the pressure drop. Accordingly, the flow rate can definitely be given using the pump properties.



300-kW proton beam operation



500-kW proton beam operation



- Simulation results agree well with the measured dynamic behaviors because of the proton beam being switched on.
- We confirmed that the developed simulation code can predict dynamic flucutuations in the hydrogen loop by comparison with the experimental data.

CONCLUSIONS

- A dynamic simulation code was developed to simulate the transient phenomenon in the cryogenic supercritical hydrogen loop because of switching the high-power proton beam on and off. The calculated pressure drop through the hydrogen loop agrees with the experimental data. We confirm that the pressure drops of the entire hydrogen loop can be accurately estimated using our correlation for each component and the conventional correlation for the pipe.

- The dynamic behaviors in the hydrogen loop for 300 and 500-kW proton beam operations are calculated using the developed simulation code. The simulation results are in good agreement with the experimental data under the same conditions. It is confirmed that the developed dynamic simulation code can be used for studying and optimizing the operation approach.