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

H Tatsumoto¹, K Ohtsu¹ T Aso and Y. Kawakami¹
J-PARC Center, JAEA, Tokai, Ibaraki 319-1195, Japan.
E-mail: tatumoto@post.j-parc.jp

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.

1. Introduction
At the Japan Proton Accelerator Research Complex (J-PARC), a 1 MW beam of 3 GeV protons driven by an accelerator strikes a mercury target at a rate of 25 Hz and fast neutrons are produced via spallation. The high-energy neutrons are reduced to cold neutrons of a lower energy level, which is suitable for neutron scattering experiments, by passing them through three types of hydrogen moderators (coupled one with high intensity, poisoned one with sharp pulse shape and decoupled one with both intensity and sharp pulse shape). These moderators use supercritical hydrogen at 1.5 MPa and 18 K. Nuclear heating in the hydrogen moderators is estimated to be 3.8 kW for 1-MW proton beam operation. Figure 1 shows a schematic of the cryogenic hydrogen system for the J-PARC spallation neutron source. In this system, the hydrogen loop including the moderators is cooled by a helium refrigerator with a refrigerator power of 6.45 kW at 15.6 K [1]. An expansion turbine is located downstream of the H₂–He heat exchanger and the feed helium temperature, T16, is maintained at 16.5 K by a heater. The hydrogen loop circulates cryogenic hydrogen at the supercritical pressure of 1.5 MPa and the temperature of approximately 18 K, and flow rate of 0.185 kg/s using two hydrogen pumps with dynamic gas bearings. An ortho-para hydrogen converter with 32% porous hydrous ferric oxide (Fe(OH)₃) catalyst is installed to maintain a para-hydrogen concentration of more than 99%. The temperature rise in the moderators because of nucleate heating is estimated to be 2.3 K for the 1-MW proton beam operation. We were concerned that the slight temperature change would bring about a severe pressure fluctuation because supercritical hydrogen behaves as incompressible fluid. Therefore, we developed a pressure mitigation system, comprising an accumulator and a heater to mitigate the pressure fluctuation to below an allowable level of 0.1 MPa. The accumulator has bellows in the supercritical hydrogen loop, which can spontaneously expand and contract because of change in the
hydrogen pressure. The heater compensates for heat load corresponding to nuclear heating by means of feedback and feed-forward control schemes when the proton beam is off. This makes it possible not only to mitigate the pressure fluctuation but also to maintain the supply hydrogen temperature, T01. A parallel flow configuration is adopted for moderator cooling. Hydrogen with a temperature of less than 18 K would be provided through a 22-m long coaxial transfer line, which has a coaxial piping structure with five layers to attain good thermal shielding.

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. We confirmed in an off-beam commissioning that the cryogenic hydrogen system could be cooled to 18 K within 19 h, as expected.

The cryogenic hydrogen system had succeeded in producing the first cold neutron beams in May 2008 [1]. 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 by 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. This code is based on a previous cool-down simulation code used to study how to operate the cryogenic hydrogen system for 1-MW proton beam operation. The adequacy of the simulation code was confirmed by comparison of the measured data under the same conditions for 300-kW and 500-kW proton beam operations.

2. Development of a pressure and a temperature fluctuation simulation code

2.1. Analytical model

Figure 2 shows the analytical model, in which only the hydrogen loop is treated. The hydrogen loop has a design pressure of 2.1 MPa, and it is made of stainless steel (SS316L) except for the aluminum alloy moderator vessel. The three transfer lines arranged in parallel are combined and the hydrogen

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

Figure 2. Analytical model.
loop is considered as a single loop. Furthermore, the hydrogen pump are combined and treated as one pump. The combined hydrogen pump, ortho-para hydrogen convertor, He–H2 heat exchanger, combined transfer line and moderator, heater, accumulator, two orifice flow meters and five valves are arranged as shown in figure 2. The pipe between each component has an outer diameter of 42.7 mm and thickness of 2.0 mm. The entire hydrogen inventory is 195.6 L when the bellows, whose variable volume is 6.84 L, are located at the intermediate position [3]. The hydrogen inventory in the accumulator is 44 L. However, helium gas is enclosed in the bellows with a volume of 61 L and behaves as a compressible fluid at approximately 20 K. The 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. The ortho-para hydrogen convertor has a catalyst packed-bed volume of 35 L and is filled with 32% porous hydrous ferric oxide (Fe(OH)$_3$) catalyst. The hydrogen inventory of the catalyst bed is estimated to be 17 L. The $C_v$ value of the flow control valve for the moderator is 17.7, that at the inlet of the ortho-para hydrogen convertor is 27.4, and that for the rest of the control valves is 25.44. The beta values of the orifice flow meters located in the moderator transfer line and at the outlet of the pump are 0.624 and 0.502, respectively.

In this analysis, the hydrogen loop is modeled using a one-dimensional pipe with a cross-sectional area of $1.1 \times 10^{-3}$ m$^2$ and total length of 168.59 m.

2.2. Basic Equations

2.2.1. Enthalpy equation
Heat transport through the hydrogen loop is calculated using by the following enthalpy equation. The diffusion term in the enthalpy equation is ignored in the analysis and expressed as follows:

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

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

2.2.2. Hydrogen pump characteristics
A centrifugal pump with a dynamic gas bearing [4] was developed to circulate supercritical hydrogen at a large flow rate. This pump was based on the supercritical helium (SHe) pump for the International Thermonuclear Experimental Reactor (ITER) project [5]. Its closed impeller was made of aluminum alloy and had a diameter, $d$, of 26.0 mm. The allowable revolution rate ranged from 30,000 rpm to 63,000 rpm, and the allowable pump head, $\Delta P$, was 120 kPa. Figure 3 shows the dimensionless expression of the measured pump characteristics in terms of a discharge coefficient $\phi$, and head coefficient $\varphi$ for parallel operations as follows:

Figure 3. Measured pump characteristics for a single operation at a temperature of 20 K.
\[ \phi = \frac{V}{d^2 u_s} \]  

(2)

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

(3)

where \( V \) is the volumetric discharge flow rate, \( u_s \) is the peripheral velocity and \( \rho \) is the density.

The measured pump characteristics exist on the same curve. We estimated the pump properties using a least squares approximation polynomial on the basis of the experimental data in this analysis.

Furthermore, the heat load generated in the pump, \( Q_p \), is calculated using the following correlation.

\[ Q_p = \frac{V \Delta P}{\eta_p} \]  

(4)

where \( \eta_p \) is the pump efficiency, which is set to 0.5.

2.2.3. Correlations for pressure drop

The flow rate through the hydrogen loop is determined using the entire pressure drop and the pump characteristic shown in figure 3. Therefore, it is important to accurately estimate the pressure drops through intricately-shaped components such as the heat exchanger, accumulator, heater, and moderator vessel. Tatsumoto et al. [6] analyzed the pressure drop through the components using STAR-CD, a CFD code [7]. They clarified that the pressure drop through each component was proportional to the volumetric flow rate. The parameter, \( F \), depended on the component geometry and was determined on the basis of the analytical results.

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

(5)

where \( m \) denotes the mass flow rate.

A well-known correlation for pressure drop through a pipe in which a friction factor, \( f \), that depends on Reynolds number, \( Re \), is used [8]

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

(6)

\[ f = \begin{cases} 
64 \frac{L}{D_H} & \text{for } Re < 2300 \\
\frac{64}{Re} & \text{for } 3000 < Re < 50000
\end{cases} \]  

(7)

where \( L \) is the tube length and \( D_H \) is the equivalent diameter.

The hydrogen transfer lines have coaxial corrugated pipe structure with five layers (hydrogen supply piping, vacuum insulation layer, hydrogen return piping, vacuum insulation layer, and helium blanket layer), and they connect the cold box and the moderator vessel. The friction factor in the corrugated pipe is calculated according to the following correlation [8]. We have already confirmed that the simulation results obtained using STAR-CD agree with those obtained using the correlation within an error of 10% [6].

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

(9)

where \( s \) denotes the corrugation pitch.
The pressure drop through the ortho-para hydrogen converter is calculated using Darcy’s law [7]. The pressure drops through the valves are estimated on the basis of the flow coefficient of the valve, \( C_v \), and those through the orifice flow meters are calculated using a formulation specified in Japanese Industrial Standards (JIS).

### 2.2.4. Heat transfer and heat inleak.

Tatsumoto et al. [9] and Shiotsu et al. [10] developed an experimental system that can safely use “hydrogen” and have measured heat transfer characteristics in forced flows of saturated, subcooled and supercritical hydrogen. It was clarified that heat transfer for a wall temperature \( T_w \) lower than the critical temperature \( T_{cr} \) agrees well with that predicted by the Dittus-Boelter correlation [11] and tends to deteriorate for \( T_w > T_{cr} \). We have derived the following heat transfer correlation for supercritical hydrogen based on their experimental data. It was confirmed that the correlation was able to describe not only the experimental data of supercritical hydrogen but also those of supercritical helium as follows [12]:

\[
Nu = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} F_c
\]

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

where \( Nu \) is the Nusselt number, \( Pr \) is the Prandtl number, \( \mu \) is the viscosity. The symbols \( w \) and \( B \) represent heated wall and bulk fluid, respectively.

The pipe and the components are installed in the vacuum chamber and are wrapped in 20 layers of a multilayer insulation. The heat inleak is calculated according to the following correlation using an equivalent thermal conductivity \( \lambda_{\text{eff}} \) [13] as follows:

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

where \( n \) is the number of layers of multilayer insulation and the symbols of \( h \) and \( c \) indicates hot and cold, respectively.

### 2.2.5. PID control for heater.

We have developed a compact high power heater to reduce a temperature fluctuation because of the nuclear heating [14]. The heater power is adjusted by feedback control and feed-forward control schemes, and the temperature at the heater outlet is maintained at 20.95 K.

\[
MV = K_p \left( e + \frac{1}{T_i} \int e dt + T_D \frac{de}{dt} \right)
\]

where \( MV \) is manipulated variable, \( K_p \) is the controller gain, \( e \) is the error, \( T_i \) is the integral time, and \( T_D \) is the derivative time.

In this analysis, the 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 [15].

### 3. Numerical procedures

The entire hydrogen loop is modeled using a one-dimensional pipe with a cross-sectional area of \( 1.1 \times 10^{-3} \) m\(^2\), length of 168.59 m, and divided into 8443 grids. The volume of a grid is 0.0235 L. The enthalpy equation [equation (1)] is solved by the finite volume method. The convection term in equation (1) is discretized by applying a central differencing scheme. In this analysis, the diffusion term is ignored to simplify the calculation. Time integration is explicitly performed with a time step,
The properties of hydrogen are given as polynomial functions of temperature and pressure, which are obtained by least-square fitting of data calculated using GASPAK [16] within an error of 1.0%.

As initial conditions, the hydrogen and the helium pressures in the bellows are set to 1.5 MPa and 1.55 MPa, respectively, when the proton beam is switched off. These values apply to the actual rated operation condition as well. The hydrogen temperature at the heat exchanger exit, T₀₁, is set to 18.0 K. The pump speed is 40,000 rpm. The helium temperature in the bellows, buffer tank, and connecting pipe between them are 20.9 K, 300 K, and 160 K, respectively. The initial entire hydrogen inventory is set to 198 L.

The circulation flow rate is calculated using the entire pressure drop through the hydrogen loop and the pump property shown in figure 3. At the start, the tentative overall pressure drop is obtained from a tentative flow rate using equations (5)–(9). The three transfer lines are arranged in parallel and have the same flow rate. Therefore, the pressure drop through the transfer lines is estimated using one-third of the discharge flow rate. The pressure drop through each component is calculated using equation (5) and is equally distributed across the number of grids. 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 to below 10⁻³.

Heat transfer between the pipe and hydrogen and heat inleak caused by radiation are calculated using equation (10)–(12). Heater power is controlled using equation (13), and the hydrogen temperature at the heater exit, T₀₃, is maintained at 20.95 K, as with the actual heater control [14]. Nuclear heating at the moderator is proportional to the beam power and is estimated to be 3.8 kW for 1-MW proton beam operation. In this analysis, the quantity of 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. The enthalpy distribution is converted into temperature distribution, and a non-linear filter method [17] is applied to maintain numerical stability.

Finally, the volume change of the bellows at the accumulator and the pressure fluctuation are calculated on the basis of the temperature distribution at the given time step. At the outset, the helium pressure calculation is repeated by means of the Newton–Raphson method using a tentative volume change of the bellows until the mass of the helium in the present time step is consistent with that at the previous time step. Subsequently, the hydrogen pressure is calculated using the calculated temperature distribution to satisfy the law of conservation of mass. The expansion and contraction of the bellows is driven by a pressure difference between the hydrogen and the helium [3], which depends on the spring constant of the bellows, as shown in figure 4. 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, which depends on its.

4. Results and discussion
Figure 5 shows a comparison of the calculated pressure drop through the hydrogen loop with the measured drop. For comparison, the combined pump properties with a speed of 30,000 to 60,000 rpm for the parallel operation are also shown in the figure. The calculated pressure drop agrees well with the one. We confirmed that the pressure correlations can accurately calculate the pressure drop. Accordingly, the flow rate can definitely be given using the pump properties.

Figure 6 shows simulation results of dynamic behaviors in the hydrogen loop for 300 and 500-kW proton beam operations. Silicon diode temperature sensors are used and diaphram type pressure transmitters are used. When a temperature rise of 0.3 K appears, the heater power corresponding to nuclear heating is reduced sharply by its feed-forward controller. Although a slight temperature fluctuation exists at the heater exit, T₀₃, it was adjusted to 20.95 K by PI control within a relatively short time. After execution of the feedforward, the hydrogen pressure remains almost unchanged. The measured data under the same conditions as the simulations are also shown in the figure, for
comparison. The 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 fluctuations in the hydrogen loop by comparison with the experimental data.

Figure 4. Spring constant of bellows.

Figure 5. Calculated pressure drop through hydrogen loop

(a) 300-kW proton beam injection
(b) 500-kW proton beam injection

Figure 6. Dynamic simulation results for a 300-kW and a 500 kW proton beam injections.
5. 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.

References
[1] Tatsumoto H, Aso T, Ohtsu K, Uehara T, Sakurayama H, Kawakami Y, Kato T and Futakawa M 2010 in Advances in Cryogenic Engineering 55A pp 297-304
[2] Tatsumoto H, Aso T, Ohtsu K, Kato T, and Futakawa M 2010 in Advances in Cryogenic Engineering 55B pp 1154-1161
[3] Tatsumoto H, Aso T, Ohtsu K and Kawakami Y 2015 Development of a partitionable accumulator with pressure tolerance for the cryogenic hydrogen system at J-PARC Physics Procedia 10.1016/j.phpro.2015.06.022 (to be published)
[4] Tatsumoto H, Aso T, Ohtsu K, Uehara T, Sakurayama H, Kawakami Y, Kato T, Futakawa M and Yoshinaga S 2011 Proc. of 23th ICEC-ICMC 2010 pp 377-381
[5] Kato T, Kawano K, Hiyama T and Tsuji H 1992 Fusion Technology pp 887-891
[6] Tatsumoto H, Aso T, Ohtsu K, Kato T and Futakawa M 2010 in Advances in Cryogenic Engineering 55B pp 1162-1169
[7] User Guide Computational Fluid Dynamics Software STAR-CD Version 3.22 copyright 2004 (CD Adapco Group)
[8] Kanro Duct no Ryutaiteiko 1979 (The Japan Society of Mechanical Engineers) p.33. (in Japanese)
[9] Tatsumoto H, Shirai Y, Shiotsu M, Hata K, Kobayashi H, Naruo Y and Inatani Y 2010 J.Phys:Conf. Seri. 234, 032056
[10] Shiotsu M, Shirai Y, Tatsumoto H, Hata K, Kobayashi H, Naruo Y and Inatani H 2014 Advances in Cryogenic Engineering 59A 36
[11] Van Sciver S W 1986 Helium Cryogenics (New York: Plenum Press) p 251
[12] Shiotsu M, Okamura T, Shirai Y, Hata K, Hama K 2006 Advances in Cryogenic Engineering 51A 459-466
[13] Robert W V and Harold W 1969 Applications of Cryogenic Technology (Los Angeles: Timnon-Brown Inc.) p 70
[14] Tatsumoto H, Aso T, Kato T, Ohtsu K, Maekawa F and Futakawa M 2011 Cryogenics 51 315-320
[15] Tatsumoto H, Aso T, Ohtsu K and Kawakami Y 2015 C2PoH in CEC-ICMC 2015 Tucson, Arizona ,US
[16] GASPAK user’s guide 1998 (Cryodata)
[17] Shyy W, Chen MH, Mittal R, Udaykumar HS 1992 J Comput Phys 102 49