Design of a hydrogen vent line for ESS cryogenic moderator system

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Abstract. The ESS cryogenic moderator system (CMS) circulates subcooled liquid hydrogen at 17 K and 1 MPa to remove nuclear heating at two hydrogen moderators. All the hydrogen will be safely released to the atmosphere on the roof top of the Target building through a hydrogen vent line (HVL) with a total length of 36 m. Two-phase hydrogen would flow through the HVL because the hydrogen expands by isenthalpic process. The HVL has been designed to avoid decreasing the wall penetration temperature below 253 K and to be sized big enough to limit the backpressure below the design pressure. One-dimensional transient thermohydraulic analysis code that can treat two-phase flow heat transport behavior has been developed. A natural convection heat transfer from air to the cold surface is considered. In this work, the wall temperature reductions and the pressure drop along the HVL during release of cryogenic hydrogen are analyzed. The size and thickness of the HVL have been verified based on the analysis results.

1. Introduction

The ESS cryogenic moderator system (CMS) has been designed to circulate subcooled liquid hydrogen of a temperature of 17 K and a pressure of 1 MPa in order to remove nuclear heating at two hydrogen moderators (four ones in the future), which is estimated to be 6.7 kW for a 5-MW proton beam operation, as shown in Figure 1 [1]. There are two hydrogen pumps, a pressure buffer tank (PCB), an ortho-parahydrogen convertor and heat exchangers in the CMS cold box (CB). The liquid hydrogen is supplied to a distribution box (DB) through a hydrogen transfer line (HTL). The HTL is subsequently split into distribution lines for each moderator. The liquid hydrogen inventory is 25.4 kg at the nominal operation condition. Spring loaded safety pressure relief valves, whose set pressure is 14.3 bar, are installed to protect the CMS process lines from an overpressure. There are two release control valves (CV-62001 and CV-82095) on the CMS CB and the DB that have a function as active pressure relief valves before the passive safety valves are getting activated. There are also vacuum safety relief devices for each vacuum space. All the hydrogen released from the safety devices and the control valves is released to the atmosphere through a hydrogen vent line (HVL).

The hydrogen released to the HVL partially liquefies by isenthalpic expansion process and two-phase hydrogen would flow in it. The HVL should be partially cooled down to cryogenic temperatures. The wall temperature at the roof penetration should be kept above 253 K. The backpressure should be limited below the design pressure, even if a severe failure event like a vacuum loss happens. In this paper, a one-dimensional transient thermohydraulic analysis code that can treat two-phase heat transport
behavior has been developed in order to estimate the HVL wall temperature reduction and the pressure drop.

2. Hydrogen vent line (HVL)
The hydrogen vent line (HVL) whose design pressure is 0.15MPa is routed from the A2T access room to the roof top through the hydrogen room, where the CMS cold box is placed. There is a merging point from the sub HVL for the CMS cold box in the hydrogen room. The HVL outlet is located at 3 m from the roof top and is guarded by a lightning rod. There is a check valve with Kv = 760 and a cracking pressure of 3.7 kPa on the roof top. The check valve maintains the HVL in a helium environment at a positive pressure, in order to avoid forming an explosive environment in it. The HVL has to be sized large enough to limit the backpressure below 0.15 MPa during the release of hydrogen. The released hydrogen flows for each postulated case are summarized in Table 1. Liquid hydrogen of 23.0 kg should be released until the process temperature is increased up to 45 K. During the normal warm-up operation, the warm-up speed is to be controlled by the helium refrigerator and hydrogen is to be always released via CV-62001, maintaining the pressure at 1 MPa. It would take an hour until the release of the liquid hydrogen is completed. The quick warm up mode is prepared in order to release the liquid hydrogen within 10 minutes by warm GH$_2$ purge. The two hydrogen pumps stop and the helium refrigerator is isolated. The average release flow rate is estimated to be 38 g/s. A vacuum loss around the moderators accompanied with air ingress is considered as one of the severe failure events. The moderator vessels and their pipes cannot be covered with MLI due to the high radiation environment. Lehmann et al. [2] reported that a maximum heat flux to equipment without MLI was 38 kW/m$^2$ due to air ingress. The heat load for the vacuum loss is estimated to be 148 kW and the maximum release flow rate is estimated to be 650 g/s appearing around its critical temperature.

| Operation mode                  | Flow rate (g/s) | Release time |
|---------------------------------|-----------------|--------------|
| Nominal case                    |                 |              |
| Normal warm-up                  | 6.4 (average)   | 60 minutes   |
| Quick warm-up                   | 38 (average)    | 10 minutes   |
| Failure case                    |                 |              |
| Pneumatic failure (CV-62001)    | 300 (maximum)   | 3 seconds    |
| Air leak into the moderator vacuum space | 650 (maximum) |              |

Table 1. Released hydrogen flow rate for each case.
implemented under the condition where 300 K-GH₂ is released at the maximum flow rate of 650 g/s and then the diameter of the HVL was determined to be 168.3 mm, while the pressure drop is calculated to be 25.4 kPa and is lower than the design pressure.

The released hydrogen expands in isenthalpic process and the HVL would be partially cooled down to cryogenic temperatures. The roof penetration temperature should be maintained above 253 K. A guide pipe with an inner diameter of 200 mm and a thickness of 9.5 mm has been already embedded. Rockwool will be stuffed into the gap between the guide pipe and the HVL. The allowable lowest HVL wall temperature is estimated by transient thermal analyses using a CFD code, ANSYS FLUENT. Figure 2 shows the analysis model. A LN₂ layer is added instead of air in order to consider the effect of the natural convection and the temperature on the outside of the air layer, $T_{air}$, is kept to 279 K, which is an average temperature between indoor and outdoor temperatures in winter. Pressure boundary conditions are applied to the top and bottom surfaces. The inner HVL temperatures, $T_w$, are changed from 50 K to 200 K. The properties of nitrogen given by GASPAK [3] are used. The Realizable $k$-$\varepsilon$ turbulent model with enhanced wall treatment is used. The time discretization for the transient analysis was 0.05 s and 10 iterations for each time step. It turns out from figure 3 that the HVL wall temperature, $T_w$, should be maintained higher than 175 K. However, even if the HVL wall temperature is decreased down to 50 K, the guide pipe temperature can be maintained above 253 K within 41 minutes.

![Figure 2](image1.png)  
**Figure 2.** Transient thermal analysis model at the penetration.

![Figure 3](image2.png)  
**Figure 3.** Allowable lowest wall temperature.

### 3. Development of one-dimensional thermohydraulic simulation code

The author [4] had developed a one-dimensional process simulation code to predict the temperature and pressure fluctuation behavior of the J-PARC CMS caused by a rapid heat load at the moderators. It was reported that the simulation results agreed well with the measured data under the same condition for 300 and 500-kW proton beam operations. In this paper, the one-dimensional thermo-hydraulic simulation code has been developed based on the J-PARC CMS simulation code in order to estimate the transient temperature and pressure distributions through the HTL during releasing liquid hydrogen.

#### 3.1. Analytical model

Figure 4 shows the analytical model where a one-dimensional horizontal straight pipe with an outer diameter of 168.3 mm is applied. The Main hydrogen vent line (MHVL) from the DB has a thickness of 3.0 mm and a total length of 36 m. The Sub hydrogen vent line (SHVL) from the CMS CB with a thickness of 7.0 mm and a length of 6.5 m is connected to the MHVL. Natural convection heat transfer between a cooled surface and the ambient air kept at 300 K is considered.
3.2. Enthalpy equation

Transient transport is calculated using the following enthalpy equation. The viscosity dissipation term and pressure-volume work term are ignored in the analysis.

\[
\frac{\partial (\rho h)}{\partial t} = -\frac{\partial (\rho u h)}{\partial x} + \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + Q
\]  

where \( h \) is the enthalpy, \( u \) is the flow velocity, \( \lambda \) is the thermal conductivity, \( Q \) is the energy source and \( T \) is the temperature.

3.3. Single phase forced convection heat transfer

Tatsumoto et al. [5] measured forced convection heat transfers of saturated and subcooled liquid hydrogen for tubes with diameters of 3, 4, 6 and 9 mm and reported that the non-boiling heat transfer in forced-flow can be expressed well by the Dittus-Boelter correlation [6].

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

where \( Nu \) is the Nusselt number, \( Re \) is the Reynolds number and \( Pr \) is the Prandtl number.

The correlation is generally valid for \( 10^4 < Re < 1.2 \times 10^5 \). As shown in Table 1, the maximum flow rate is 0.65 kg/s which corresponds to \( Re = 2.0 \times 10^6 \) at 50 K. Single-phase forced flow heat transfers of 100 K gaseous hydrogen at 0.12 MPa are calculated by a CFD code, ANSYS FLUENT, and estimate the applicability of equation (2) for high Reynolds number region. A quarter of the pipe with the inner pipe diameters of 6 and 160 mm is calculated, applying symmetric boundary conditions. The lengths correspond to a dimensionless distance, \( L/D \), of 16.7, is used as the same as the experiment [5]. The inlet temperature is set to 100 K and the inlet flow rates that correspond \( 10^4 < Re < 3 \times 10^6 \) are applied. A pressure condition is applied at the outlet of the pipe. The realizable \( k-\varepsilon \) turbulent model with enhanced wall treatment is used to treat the behavior of the turbulent flow. Steady-state turbulent heat transfer is calculated when an uniform heat flux is applied to the outer surface of the pipe. The parahydrogen properties are given by GASPAK. Figure 5 shows a comparison of the averaged heat fluxes by equation (2), \( q_{DB} \), with those by the CFD, \( q_{CFD} \). It turns out that, for \( Re < 10^5 \), the calculation results by the CFD agree well with those by equation (2). However, for \( Re > 10^5 \), the values of \( q_{DB} \) get higher than those by the CFD, \( q_{CFD} \). In this simulation code, the correction factor given by the figure is applied to equation (2) for \( Re > 10^5 \).
3.4. Two-phase forced convection heat transfer
The two-phase film boiling forced convection heat transfer is considered in this simulation code. A correlation developed by Giarratano and Smith [7] that utilizes the Martinelli parameter, $\chi_{tt}$, is applied.

$$ Nu_{FB} = \exp(0.22 + 0.16 - 0.008(\ln\chi_{tt})^2)Nu $$  

$$ Nu = 0.026Re^{0.6}Pr^{0.33}\left(\frac{\mu_v}{\mu_w}\right)^{0.14} $$  

$$ \chi_{tt} = \left(\frac{1 - X}{X}\right)^{0.9}\left(\frac{\rho_f}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_f}\right)^{0.1} $$

where $Nu_{FB}$ is the Nusselt number for two-phase flow, $\mu$ is the viscosity and $X$ is the quality. The subscripts of $w$, $l$ and $f$ denote the heated wall, liquid and gas, respectively.

3.5. Natural convection heat transfer from a cold surface to ambient air
The Nusselt number for natural convection from isothermal surface of a long horizontal cylinder is a function of the Grashof, $Gr$, and Prandtl numbers [8].

$$ Nu = C(GrPr)^a $$

where $C=0.53$ and $a=0.25$ for the laminar regime and $C=0.14$ and $a=0.33$ for the turbulent regime.

3.6. Pressure drop correlation
The Colebrook-White equation is used [9] to calculate the single-phase pressure drop.

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

$$ \frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) $$

where $f$ is the friction factor, $\varepsilon$ is the surface roughness, $L$ is the length and $D$ is the diameter.

For the two-phase flow pressure drop, the following homogeneous flow model [10] is applied where the pressure is defined in terms of the average mixture velocity.

$$ \frac{\Delta P}{\Delta x} = 2 \frac{f G^2}{D \rho_{TP}} $$

$$ f = 0.08Re^{-0.25} $$

$$ \rho_{TP} = (1 - \alpha)\rho_l + \alpha\rho_g $$

$$ \alpha = \left(1 + \frac{1 - X \rho_g}{X \rho_l}\right)^{-1} $$

where $G$ is the mass flow flux and $\alpha$ is the void fraction.
3.7. Numerical procedure

As shown in figure 4, two kinds of hydrogen vent paths are treated: (1) from the DB through the MHVL of 36 m and (2) from the CMS CB through the SHVL of 6.5 m and MHVL of 5 m. Each grid size is 0.1 m. The enthalpy equation is solved by the finite volume method. The convection term is discretized by applying a central differencing scheme. Time integration is explicitly performed with a time step of 0.05 ms. The parahydrogen properties calculated by GASPAK are given as polynomial functions of temperature at 1.2 bar within an error of 0.1%.

The pressure boundary condition is applied at the exit. The inlet temperature is set to 20.23 K, because the released hydrogen temperature decreases down to saturated temperature at 0.1 MPa due to isenthalpic expansion. The constant flow rates shown in Table 1 are applied to the inlet and the gas quality, \( X \), of 0.5 is used for the case where hydrogen at its critical temperature and 1.43 MPa expands.

Initially, the HVL is maintained at a temperature of 300 K. The representative temperature in the two-phase flow region is regarded as the saturated temperature. The two-phase forced convection heat transfer is calculated using equations (3) to (5), meanwhile the single-phase heat transfer is calculated using equation (2) and the correction factor shown in figure 5. The natural convection heat transfer from the cooled wall to the ambient air is calculated by equation (6). The pressure distribution is calculated by equations (7) to (12). The enthalpy distribution is converted into temperature distribution and a non-linear filter method [11] is applied to maintain numerical stability. This process is explicitly repeated with a time step of 0.05 ms until the hydrogen of 23 kg has been released as mentioned in section 2.

4. Results and discussion

First of all, a transient process was calculated for the case where 100 K-cold gaseous hydrogen was released at a flow rate of 0.49 kg/s through a 30-m long pipe and compared with the calculation results by FLUENT under the same conditions. The CFD calculation conditions are the same as those mentioned in 3.3. A constant heat transfer coefficient of 7 W/m-K was applied on the outside of the pipe. The time discretization of the CFD analysis was 0.01 s and 10 iterations for each time step. Figure 6 shows comparisons of the transient transport calculation results by the developed simulation code with those by FLUENT. It is proved that the average hydrogen and wall temperatures calculated by the developed code agree with those by FLUENT within 11%.

Figure 7 shows the transient HVL analysis results for the quick warm-up operation: (a) released liquid hydrogen from CV-62001 on the CMS cold box through the SHVL + MHVL and (b) that from CV-82095 on the DB through the MHVL. For the case (a) with thicker wall thickness, the two-phase

![Figure 6. Comparison of the one-dimensional transient calculation results with those by FLUENT.](image-url)
flow region where the hydrogen temperature of 20.23 K is shorter due to the effect of the heat capacity of the wall, compared with the case (b). After the merging point, the gradient of the temperature rise decreases. It turns out that the way to increase the wall thickness enables the release hydrogen to be warmed up effectively. For the case (a), there is a wall temperature drop at the merging point \(x = 6.5\) m because the wall thickness is changed from 7 mm to 3 mm. The wall temperature reduction is smaller than in case (b) at the same time step and the same location from the inlet. At the roof penetration, the wall temperatures for the case (a) becomes lower than the allowable value of 175 K after \(t = 5\) min and decreases down to 118 K at \(t = 10\) min, meanwhile those for the case (b) can be maintained above 175 K during the quick warm-up mode.

Figure 8 shows the transient HVL analysis results for the vacuum loss where liquid hydrogen is being continuously released at the maximum flow rate of 0.65 kg/s for 35 s from (a) SV-62009 on the CMS cold box and (b) SV-82093 on the DB. For higher flow rates, the two-phase flow region is observed over a wider range and the wall temperature reduction gets larger. For the case (a) the wall temperatures at the penetration decreases below 175 K for \(t > 20\) s and is 107 K at \(t = 35\) s, while those for the case (b) is slightly higher than 175 K at \(t = 35\) s. Figure 9 shows the wall temperature changes at the roof penetration for the case (b). After releasing liquid hydrogen of 23 kg, the wall temperatures gradually increase caused by the natural convection. The durations of the wall temperature being kept below 175 K are 13 and 9 minutes for the quick warm-up mode and the vacuum loss failure, respectively. It is
found from figure 3 that it takes 59 minutes until the guide pipe is cooled down below 253 K for \(T_w=100\) K. Even if the vacuum loss happens, the wall penetration temperature would be maintained above 253 K because the duration of the VHL wall temperature lower than 175 K is shorter than 59 minutes.

Figure 10 shows the pressure drop for various release flow rates, which includes that through the check valve. For the quick warm-up mode, the pressure drops are negligibly small. Even if the vacuum loss failure happens, the pressure drops can be always kept below the design pressure.

It is found from the analysis results that the CV-82095 on the DB should be used in the quick warm-up mode. If the vacuum loss failure occurs, a failure action mode of the CMS control logic will be activated and the moderators will be physically isolated from the CMS loop by closing the feed valve in the DB in order to avoid releasing extra liquid hydrogen at a time. The liquid hydrogen will be released by CV-82095, although the safety valve would work just after the vacuum loss happens.

5. Conclusions
It was confirmed from the analysis that the designed HVL can release liquid hydrogen without exceeding the design pressure. The increase in the pipe thickness was effective in warming the released hydrogen quickly. For the release of liquid hydrogen from the DB through the MHVL, the wall temperature reduction at the roof penetration can be always kept above 175 K, while for that from the CMS CB, the wall temperatures decrease below 175 K. However, the duration of it is relatively shorter and it turns out the guide pipe would be maintained above the allowable lowest temperature.

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