Liquid Level Estimation of Cold Neutron Source Loop

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1. Introduction

In Cold Neutron Source (CNS) module, thermal neutrons from the core are moderated by liquid hydrogen to become cold neutrons[1]. If there is not enough liquid hydrogen in the moderator cell (MC) of CNS, the upper of the MC is filled with gaseous hydrogen. Presence of the gaseous hydrogen in the MC will reduce the moderation performance due to much lower atom density of gas. Therefore, it is important to ensure that sufficient liquid hydrogen is maintained in the MC. In this paper, the calculation procedure to predict the liquid hydrogen level of the MC is described. By combining thermodynamic relation and related heat transfer correlations, the portion of the liquid and gaseous phases in the CNS loop is estimated. Utilizing developed methodology, the sensitivity analyses in terms of heat load, hydrogen inventory and operating pressure are also carried out.

2. Methods and Results

In this section, analysis geometry, calculation procedure and analysis results are presented.

2.1 CNS Loop

Figure 1 shows the schematic of the CNS loop being developed by KAERI which consists of a CNS module, transfer pipes, and a shell and tube heat exchanger. The entire loop is submerged in water pool. The MC as a part of CNS module contains the liquid hydrogen for cold neutron production. The MC is connected to the heat exchanger through H_2 transfer pipes. The vaporized hydrogen in the MC moves through the GH_2 transfer pipe to the heat exchanger. In the heat exchanger, the vaporized hydrogen is condensed by heat transfer to cryogenic helium. The condensed liquid hydrogen is first collected in the lower plenum of the heat exchanger and lower part of the phase separator. The condensed hydrogen in the MC moves through the LH_2 transfer pipe to the MC. The top of the heat exchanger is attached to a pipe extending to a H_2 buffer tank. During a normal operation, the connection between the CNS and buffer tank is maintained. Table I summarizes the volumes of each component.

Table I: Component volume data

Region	Volume [liter]
Moderator cell assembly	2.9
Heat exchanger tubes	3.1
Heat exchanger lower plenum	1.3
Phase separator	2.9E-1
H_2 buffer tank	1.6E3
H_2 connecting pipes	3.6E1

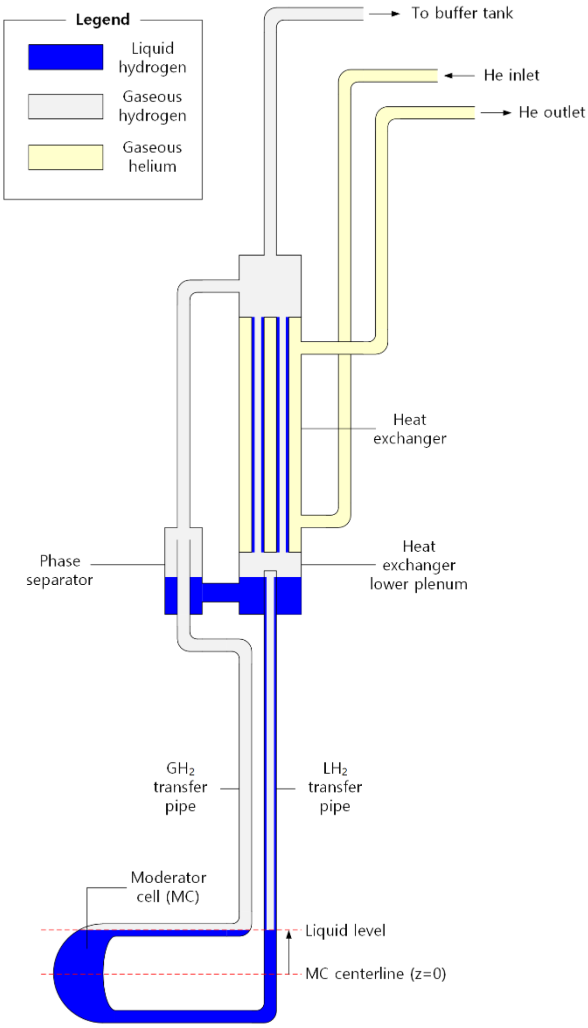

Fig. 1. CNS loop (not to scale).

2.2 Calculation assumption

The portion of each phase of hydrogen in the CNS can be estimated by thermodynamic relation which requires thermodynamic state properties such as temperature, pressure and total mass of hydrogen. In this study, the loop under consideration is assumed to be operated in a saturated state at a pressure of 2 bar. The buffer tank and the connecting pipe are presumed to be operating at high temperature condition (~310K). Table II summarizes the phase and flow assumptions.

Table II: Phase and flow assumptions

Region	Phase assumptions	Liquid flow assumption
MC	Liquid/gas	Stagnant
GH_2 transfer pipe	Liquid/gas	Stagnant
HX tubes (H_2 sides)	Liquid/gas	Downward film flow
HX lower plenum	Liquid/gas	Stagnant
Phase separator	Liquid/gas	Stagnant
LH_2 transfer pipe	Liquid/gas	Downward film flow
Connecting pipes to hydrogen system	Gas	-
H_2 buffer tank	Gas	-

2.3 Calculation procedure

During calculation, temperature dependent cryogenic properties of H_2 adopted from NIST database are used[2]. The partial masses of hydrogen in the buffer tank and connecting pipe is estimated by Eq. (1). The cryogenic hydrogen mass in CNS loop is obtained by subtracting the partial masses from the total mass. The amount of liquid in the interesting volume is estimated by solving mass conservation as shown in Eq. (2) to obtain liquid volume fraction ('α')[3]. The condensed liquid film thickness in the heat exchanger tubes is estimated by Nusselt (1916) correlation as shown in Eq. (3)[4]. The liquid film thickness in LH_2 transfer pipe is estimated using Karapantsios et al. (1995) correlation as expressed in Eq. (4)[5]. The Reynolds number in the region is estimated by H_2 vaporization (=condensation for steady state) rate. The liquid volume of film flow is obtained by integrating its thickness over the wetted perimeter and the flow length. The relationship between the liquid volume and the level is also required which is obtained from CAD data as shown in Fig. 2. The abrupt increase of liquid level ('MC top') occurs when the moderator cell overflows with liquid into the small diameter pipes. With non-flow boiling assumption, the H_2 vaporization rate is updated using equilibrium quality definition as shown in Eq. (5), and compared with the old one. The heat load which combines the moderation heat of the hydrogen and the heat transferred from the surroundings, is used to estimate the enthalpy change. If two values are not same, the liquid mass in LH_2 transfer pipe is updated by new value, and the subsequent procedures are repeated until the two values become equal.

$$\mathrm{m} = \frac{PV}{RT} \tag{1}$$

$$\mathrm{m}_T = \left[\rho_f \alpha + \rho_g (1-\alpha)\right] V_T \tag{2}$$

$$\delta = \left[\frac{4\mu_f k_f z (T_f - T_w)}{g h_{fg} \rho_f (\rho_f - \rho_g)}\right]^{0.25} \tag{3}$$

$$\delta = 0.451 \left(\frac{v^2}{g}\right)^{1/3} Re^{0.538} \tag{4}$$

$$\frac{m_g}{m_T} = \chi_e = \frac{h_m - h_f}{h_g - h_f} \tag{5}$$

where, m is mass [kg], P is pressure [kPa], V is volume [m^3], R is gas constant [kJ/kg-K], T is temperature [K], m_T is total mass [kg], ρ_f is liquid density [kg/m^3], ρ_g is gas density [kg/m^3], α is volume fraction [-], V_T is total volume [m^3], δ is film thickness [m], μ_f is liquid viscosity [Pa-s], k_f is liquid thermal conductivity [W/m-K], z is distance from tube top [m], T_f is film surface temperature [K], T_w is wall temperature [K], g is constant of gravitational acceleration [m/s^2], h_{fg} is latent heat [kJ/kg], v is kinematic viscosity [m^2/s], $Re$is Reynolds number, m_g is gas mass [kg], χ_e is equilibrium quality [-], $h_m$is mixture enthalpy [kJ/kg], $h_f$is liquid enthalpy [kJ/kg], h_g is gas enthalpy [kJ/kg], respectively.

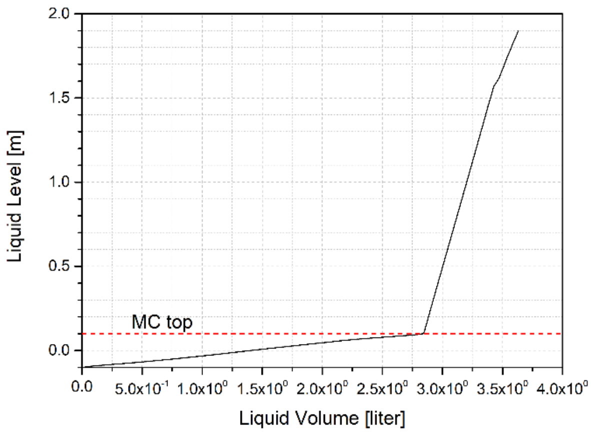

Fig. 2. Relationship between liquid volume and level

2.4 Calculation Results

In this study, the estimation of liquid level is carried out for various operating conditions. First, the effect of moderator cell heat load on the liquid level is analyzed. Figure 3 shows the variation of liquid level with heat load for different total hydrogen mass in the system. As the vaporization rate increases with the heat load, the liquid film in LH_2 pipe becomes thicker. For steady state, this reduces the amount of liquid that accumulates in the MC region when the total hydrogen mass is held constant, thus reducing the liquid level. In the same figure, it can be also concluded that at least 520g of total hydrogen mass need to be maintained in order for the MC to be filled with the liquid. Next, the effect of the operating pressure on the liquid level is studied.

Figure 4 depicts the change of liquid level with operating pressure for different hydrogen mass. The heat load is assumed be held at 800W. Since the system is operated at saturated state, its operating temperature is directly related with the pressure. Since the relative change of the pressure with respect to the reference value is much larger than that of the temperature, the gaseous hydrogen mass in the high temperature (~310K) region increases with the pressure according to Eq. (1). For constant total hydrogen mass, the mass increase in the high temperature region leads to the reduced liquid mass in the cryogenic region, so the liquid level decreases according to Eq. (2). In addition, the ruggedness of the lines near the water level of 0.1m seems to be due to the rapid change of the liquid volume-level relationship near the region.

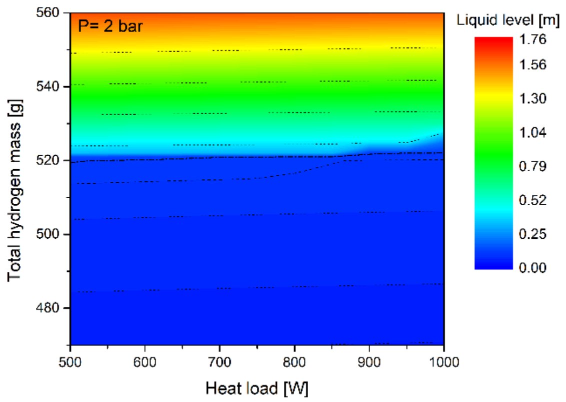

Fig. 3. Relationship between heat load/mass and liquid level

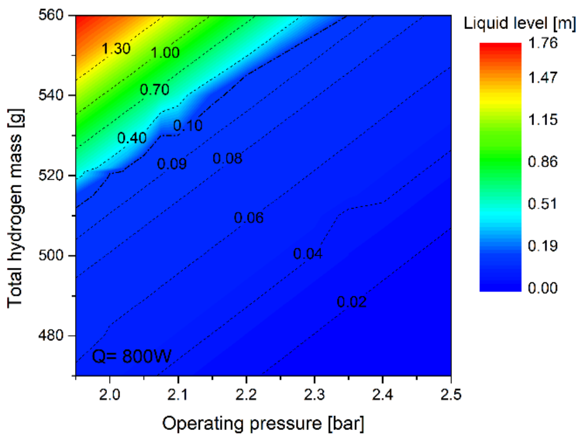

Fig. 4. Relationship between pressure/mass and liquid level

3. Conclusions

In this study, a simplified method to estimate liquid level of CNS loop is developed by utilizing thermodynamic relations, mass conservation and relevant correlations. Sensitivity analyses showed how heat load, operating pressure, and hydrogen mass affect water level. The analyses showed that at least 520g of hydrogen mass need to be maintained for 2 bar operating condition. The results also revealed the inverse proportional relationship between the operating pressure and the liquid level, which could be explained by law of thermodynamics. The developed evaluation method can be applied to the initial design stage of other similar cryogenic systems to estimate the required inventory and to quickly grasp the influence of the varying operating conditions.

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