Applicability of Non-condensable Gas Model for S-CO_2 Ingress to High Pressure Water

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1. Introduction

A Small Modular Reactor (SMR) is considered as a promising future reactor technology. For SMR development, many innovative power cycles have been proposed and among them, a Supercritical CO_2 (S-CO_2) power cycle is seriously being considered. A combination of mature water cooled reactor technology and an S-CO_2 power cycle is also one of the potential candidates for the future reactor technology.

Generally, the conventional operating pressure of S-CO_2 power cycle is higher than the operating pressure of water cooled reactor. For this reason, if the intermediate heat exchanger (IHX) fails, CO_2 would ingress to the waterside. This leads to an increase in system pressure, and it raises a question from a safety point of view. Thus, safety analysis code should have a capability to simulate the phenomenon. Researchers applied the non-condensable (NC) gas model to analyze the release of N_2 gas in safety injection tank with 1-D thermal hydraulic (TH) analysis codes such as CATHERE and APROS [1,2] previously. In a similar way, the authors tried to use the NC gas model to analyze the leakage of CO_2 in this paper. In short, the applicability of NC gas model in an 1-D thermal hydraulic (TH) analysis code is presented for the analysis of S-CO_2 ingress to high pressure water by comparing the experiment and the numerical simulation.

2. Non-condensable gas model

In this study, 1-D TH analysis in-house code written in MATLAB was use. In this section, major parts of NC gas model those are adopted in the in-house code are introduced. The basic assumptions of the code are as follows.

(1) The dissolved gas component is in mechanical equilibrium with the liquid phase
(2) Diffusion in the liquid is neglected.
(3) Wall heat transfer is not considered.
(4) Interfacial heat transfer between gas and liquid phase is neglected. Only the energy transfer accompanied by mass transfer is considered.

2.1 Continuity equation with non-condensable gas

The in-house code solves of 3 continuity, 2 momentum and 2 energy equations. Among the continuity equations, the first equation corresponds to the non-condensable gas, second to dissolved gas, and third to liquid. The dissolution and release of NC gas are modeled as a mass transfer term (Γ) which is a function of the NC gas mass fraction dissolved in the liquid.

$$\frac{\partial(\alpha_g\rho_g)}{\partial t}+\frac{1}{A}\frac{\partial(\alpha_g\rho_g V_g A)}{\partial x}=\Gamma_i \quad (1)$$

$$\frac{\partial((1-\alpha_g)\rho_l X_{n,l})}{\partial t}+\frac{1}{A}\frac{\partial((1-\alpha_g)\rho_l X_{n,l} V_l A)}{\partial x}=-\Gamma_i \quad (2)$$

$$\frac{\partial((1-\alpha_g)\rho_l(1-X_{n,l}))}{\partial t}+\frac{1}{A}\frac{\partial((1-\alpha_g)\rho_l(1-X_{n,l})V_l A)}{\partial x}=0 \quad (3)$$

$$where$$

$$\Gamma_i=\frac{(1-\alpha_g)\rho_l(X_{n,l}-X_{n,l,eq})}{\tau}$$

$$X_{n,l}=\frac{M_{Dissolved\ gas}}{M_{Dissolved\ gas}+M_{liquid}}$$

$$\rho_l=\frac{1}{v_l}=\frac{1}{v_{apparent}(X_{nl})+v_{liquid}(1-X_{nl})}$$

$$g: gas\ phase$$
$$l: liquid\ phase$$
$$n,l: dissolved\ gas\ in\ liquid$$
$$eq: equilibrium$$

For other equations and numerical techniques, MARS code is referred [3].

2.2 Constitutive equations for non-condensable gas

All physical properties of pure gas and liquid are calculated using REFPROP program [4]. To solve the governing equations, several constitutive equations are used. For calculating the liquid density and mass transfer term, apparent volume and solubility models are needed. In this study, apparent volume of CO_2 is calculated using the model proposed by Hu, Q et al [5]. Duan and Sun solubility prediction model is used [6].

For interfacial friction between the gas and liquid, drag coefficient method is adopted in the in-house code. Ishii and Zuber proposed bubble drag coefficient for various regions [7].

$$Undistorted\ particle\ regime \quad C_{D,1}=\frac{24}{Re_b}\left(1+0.1Re_b^{0.75}\right) \quad (4)$$

$$Distorted\ particle\ regime \quad C_{D,2}\cong\frac{2}{3}D_b\sqrt{\frac{g\Delta\rho}{\sigma}} \quad (5)$$

$$Churn\ turbulent\ flow\ regime \quad C_{D,3}=\frac{8}{3}\left(1-\alpha_g\right)^2 \quad (6)$$

The selection of drag coefficient is based on Eq. 7.

$$C_D=\max\left(C_{D,1},min\left(C_{D,2},C_{D,3}\right)\right) \quad (7)$$

3. Simulation of CO_2 injection into water

In this section, the experiment and simulation result using the in-house code are presented. The time constant (τ) related to release and dissolution is a key parameter determining the dissolution process. Thus, the sensitivity of the time constant to mass transfer term is presented.

3.1 Brief description of experiment and simulation

The experimental facility was described in detail in the reference [8]. Thus, the information used for boundary conditions of the simulation is briefly explained in this paper.

The nodalization and the experimental facility are shown in Fig. 1. As shown in the schematic, the left tank is filled with CO_2 and CO_2 flows into the right tank filled with water from below. In the simulation, only the right tank is modelled and CO_2 injection is dealt as the boundary condition. The mass flow rate of CO_2 was calculated using Eq. 8 with measured pressure and temperature data in the experiment. Fig. 2 shows the mass flow rate of CO_2 measured from the experiment.

$$\dot{m} = \frac{V_{tank}(\rho_{t+\Delta t}(P,T) - \rho_t(P,T))}{\Delta t} \quad (8)$$

$$\Delta t : \textit{measurement time interval}$$

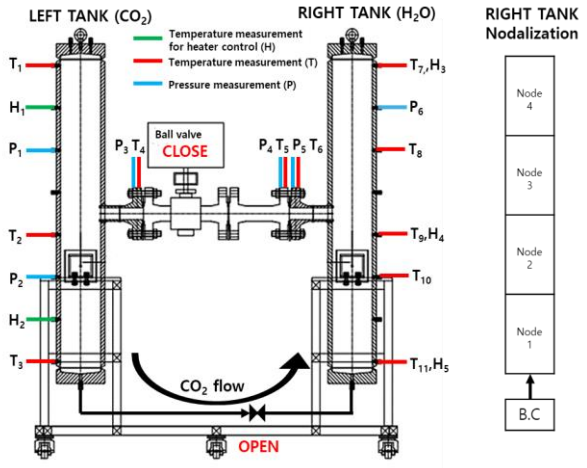

Fig. 1. Schematic of the experimental facility and nodalization for simulation.

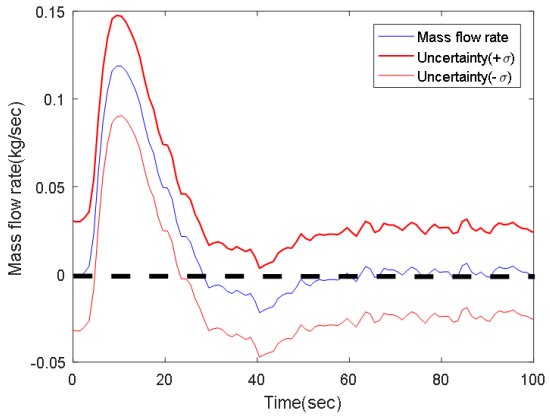

Fig. 2. Mass flow rate of CO_2

3.2 Simulation results

Fig. 3 and 4 show the behavior of pressure (P6) in the right tank and temperature (T7). To identify the effect of the time constant, simulation results with different time constant are also compared. A larger time constant means slower dissolution and release. Thus, the pressure of system becomes large if the small time constant is selected as shown in Fig. 3.

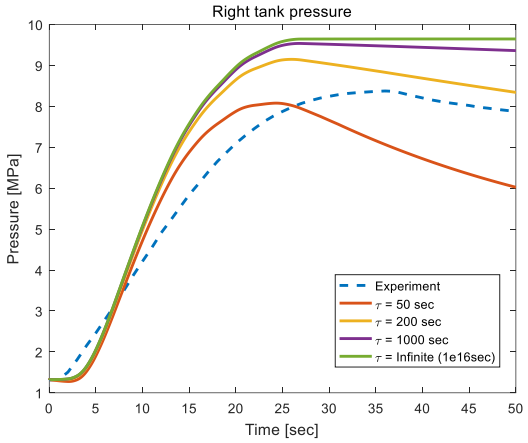

Fig. 3. Behavior of pressure at P6

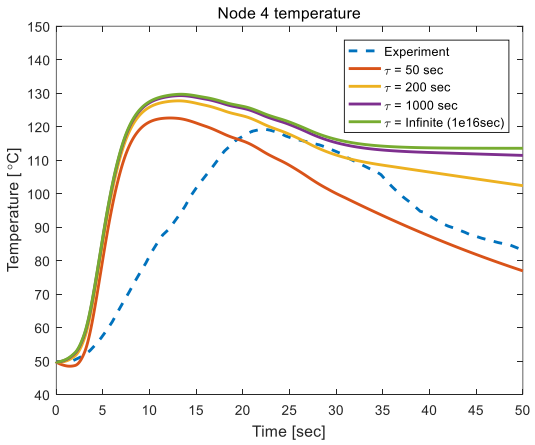

Fig. 4. Behavior of temperature at T6

The peak of the system pressure falls within the range between 50 sec to 200 sec but the slope of the change is less steep than all cases. Unlike the pressure, there is a large difference in the slope of the temperature change, which seems to be due to neglecting of heat transfer to the wall (heat loss) and interface.

4. Summary and Conclusions

The experiment that CO_2 flows into high pressure water was conducted and it was simulated using the in-house code. The in-house code using NC model simulated reasonably well. However, the slope of variation doesn't match exactly due to assumption such as zero heat loss. When the above results are considered, it can be concluded that the NC model can be applicable

to the phenomenon sufficiently with proper constitutive equations.

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