Numerical Investigation of Two-phase Natural Circulation Containing Non-condensable Gas in a Loop

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1. Introduction

Natural circulation is caused by differences in fluid density in the loop. It plays an important role in passive core cooling systems that remove decay heat from the reactor core. Two-phase natural circulation has gained high attention in terms of passive cooling in Small modular reactor (SMR) in the event of loss-of-coolant accident (LOCA).

Various studies have predicted the behavior of two-phase natural circulation. Previously, several numerical studies have been performed to simulate two-phase natural circulation using CFD. Wang et al. performed numerical simulations of the water-steam two-phase natural circulation in a horizontal loop with ANSYS Fluent and compared them with experimental results [1]. Wu et al. investigated water-steam two-phase natural circulation in U-shaped loops using ANSYS Fluent [2].

In other hand, several experimental studies have been performed to investigate the effect of non-condensable gas in on natural circulation in loops [3, 4]. However, very few studies with CFD implementing two-phase natural circulation in loops in the presence of non-condensable gas have been found.

In this study, based on experiments, the two-phase natural circulation was simulated within a rectangular loop and the change in flow rate with the amount of non-condensable gas in the loop was. The natural circulation mass flow rate at the bottom of the loop was investigated and compared with experiments.

2. Numerical methods

2.1. Governing equations

The Euler model is adopted for simulation. The model is combination of equations of mass, momentum, and energy for each liquid and gas phase. Lee model is used to simulate mass transfer during evaporation and condensation [5]. ANSYS Fluent is used to simulate this study.

When the model calculates the equations for all phases, steam and non-condensable gas (NCG) consist one gas phase to improve the computation efficiency, and the phase interactions are separated by mass fraction. The mass transport equations are given as

$$\frac{\partial}{\partial t}\left(\alpha_l\rho_l\right)+\nabla\bullet\left(\alpha_l\rho_l\mathbf{u}_l\right)=-\Gamma_e-\Gamma_c \tag{1}$$

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g Y_v\right)+\nabla\bullet\left(\alpha_g\rho_g\mathbf{u}_g Y_v\right)=-\nabla\bullet\alpha_g\mathbf{J}_v+\Gamma_e+\Gamma_c \tag{2}$$

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g Y_{NCG}\right)+\nabla\bullet\left(\alpha_g\rho_g\mathbf{u}_g Y_{NCG}\right)=-\nabla\bullet\alpha_g\mathbf{J}_{NCG} \tag{3}$$

each α, ρ and $\mathbf{u}$ represents the volume fraction, density, and velocity respectively for each phase. l, g and v are liquid phase, gas phase and water vapor respectively. Y_v, Y_{NCG} represent mass fraction of water vapor and NCG in gas phase, and J_v, J_{NCG} represent mass dispersion of water vapor and NCG. The mass dispersion of water vapor and NCG follow Fick's law as:

$$\vec{J}_v=-(\rho_g D_{v,m}+\tfrac{\mu_t}{Sc_t})\nabla Y_v \tag{4}$$

$$\vec{J}_{NCG}=-(\rho_g D_{NCG,m}+\tfrac{\mu_t}{Sc_t})\nabla Y_{NCG} \tag{5}$$

Each $D_{v,m}$, $D_{\mathrm{NCG},m}$ are mass dispersion coefficient of water vapor. μ_t is turbulent viscosity, and Sc_t represents turbulent Schmidt number. The turbulent is computed with Realizable k-ε model.

Γ_e, Γ_c represent mass transfer rates of evaporation and condensation of water respectively, and adopted in the Lee model [5]. Γ_e, Γ_c are given as

$$\Gamma_e=\begin{cases}0 & T_l\le T_{sat}\\ \lambda_c\alpha_l\rho_l\dfrac{\left(T_l-T_{sat}\right)}{T_{sat}} & T_l>T_{sat}\end{cases} \tag{6}$$

$$\Gamma_c=\begin{cases}\lambda_c\alpha_g\rho_g Y_v\dfrac{\left(T_{sat}-T_g\right)}{T_{sat}} & T_g<T_{sat}\\ 0 & T_g\ge T_{sat}\end{cases} \tag{7}$$

where T_l, T_g represent temperature of liquid and gas, and T_{sat} is saturation temperature of water. λ_c is a mass transfer relaxation factor. As shown in the equation (6) and (7), the evaporation and condensation only occur when liquid temperature is higher than saturated temperature at heater and below the saturated temperature at cooler, respectively.

2.2. Simulation conditions for natural circulation loop

An experiment of natural circulation in a loop [4] was simulated. 2D loop model is built to simulate the natural circulation as Fig. 1. The rectangular shaped loop has 1660mm height and 1000mm width, and pipes have various diameters between 13.7mm to 16.57mm. The loop natural circulation system consists of a coil heater and a cooling jacket, which are simplified to areal heat source and wall boundary with negative heat flux. The area of heat source is 490mm in height and 50mm in width, and the cooling surface is 400mm long and the pipe where the cooling surface is has 15mm width. The working fluid of the simulation is water, and air is used as NCG in the loop. Half of the loop is filled with water and gas fills the other to simulate the initial condition.

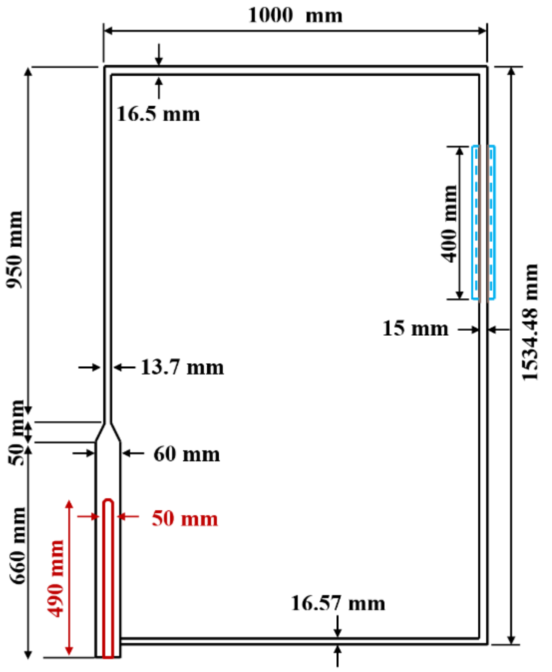

Fig. 1 Conceptional geometry of the loop system

Case ID	N-00-H-01	N-01-H-01	N-03-H-01	N-06-H-01
NCG (mg)	0	16.65	69.6	140.74
Pressure (bar)	1.005	1.012	1.073	1.260
Heat (kW)	3.78	3.78	3.78	3.36
Cooling (kW)	-2.63	-2.61	-2.65	-2.64

Table 1. Natural circulation simulation operating conditions

Set of experiment cases with similar conditions are selected to be simulated. The total mass of NCG in the loop is varied from 0mg to 140.74mg. An experiment case without NCG is also selected to test the grid and validate the numerical model. Table 1 shows the total mass of NCG, pressure, and power on the heater and cooler in the loop system for each experiment cases.

3. Results and discussion

3.1. Natural circulation without non-condensable gas

Grid test is conducted with N-00-H-01 case in Table. 1 that only including water in the loop without NCG. 5 different grids with various grid numbers from 96,712 to 354,654 are tested.

As same as the experiment, mass flow rate is measured at the right side of the horizontal path bottom of the loop for assessment. After natural circulation is established in the loop, the time-averaged mass flow rate was taken as the circulation mass flow rate. The circulation mass flow rates are measured for each grid numbers and compared for convergence.

The grid test results are compared in Table. 2 and Fig. 2 It is assumed to be converged enough at 133,991 grids, so it was chosen for further study. The circulation mass flow rate with 133,991 grids is measured 0.001182 kg/s, and it matches well to the experimental result 0.001269 kg/s, showing only 6.85% of error.

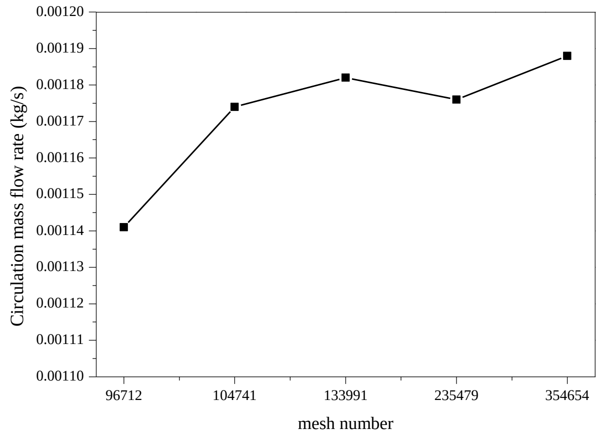

Fig. 2 Grid test results with a condition only contains water in the loop (N-00-H-01)

Grid numbers	Circulation mass flow rate (kg/s)
96,712	0.001141
104,741	0.001174
133,991	0.001182
235,479	0.001176
354,654	0.001188
Experiment	0.001269

Table 2. Grid test result without NCG in the loop

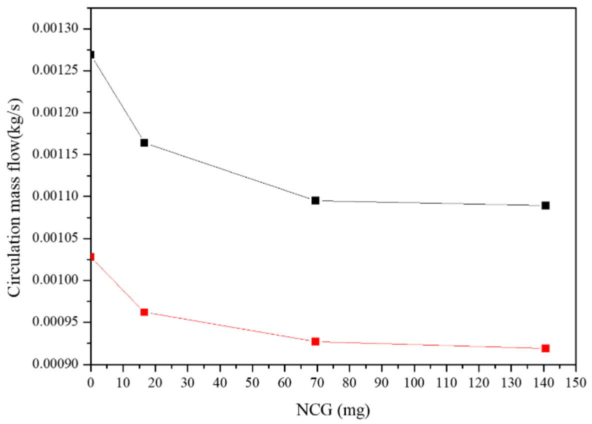

Fig. 3 Comparison of natural circulation mass flow rate by amount of NCG in numerical simulation and experiment

Mass flow rate (kg/s)	N-00-H-01	N-01-H-01	N-03-H-01	N-06H-01
NCG (mg)	0	16.65	69.6	140.74
Experiment	0.001269	0.001164	0.001095	0.001089
CFD result	0.001182	0.000962	0.000927	0.000919

Table 2 The mass flow rate of circulation for each case

3.2. Natural circulation with non-condensable gas

Set of simulations of natural circulation with NCG in the loop are conducted. The circulation mass flow rate measurement procedure is same as the case without NCG, it is measured after the natural circulation in the loop becomes stable. The mass flow rate is measured at the right-bottom side of the loop, and time-averaged to measure the circulation mass flow rate to reduce the effect of fluctuation.

As shown in Table 2, simulation and experimental results of circulation mass flow rates with different total mass of NCG in the loop are compared, and they are compared in Fig. 3. The comparison insists that the behavior of the natural circulation mass flow rate decrease along the increase of total mass of NCG in the loop in numerical simulation well matches to the experimental results.

5. Conclusions

Two-phase natural circulation using the Eulerian two-fluid model with Lee model in a loop with and without NCG were investigated. The effects of the total mass of NCG in the loop on the natural circulation mass flow rate was examined. The results can be summarized as follows:

• In the case of natural circulation without NCG, the circulation mass flow rate was measured to be 0.001182 kg/s, similar to the experimental values, 0.001269 kg/s. The comparison between simulation and experimental data confirmed the validity of the numerical model.

• Three cases of natural circulation conditions with different total mass of the NCG in the loop were simulated. The circulation mass flow rates were calculated to be between 0.001182 kg/s ~ 0.000919 kg/s. In the numerical simulation, the circulation mass flow rates tend to decrease as the total mass of NCG in the loop increases, and it matches the experimental results.

• The comparison between simulation results and experimental data shows the numerical model is sufficient to predict natural circulation with NCG in a loop.

This study focused on simulating the two-phase natural circulation in a loop with NCG using CFD. From a practical perspective, simplified 2D geometry can affect the deference between results of numerical prediction and experimental data. The effect of geometry will be investigated in the future.

6. Acknowledgment

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