CFD of Two-Phase Natural Circulation in the Presence of Non-Condensable Gas

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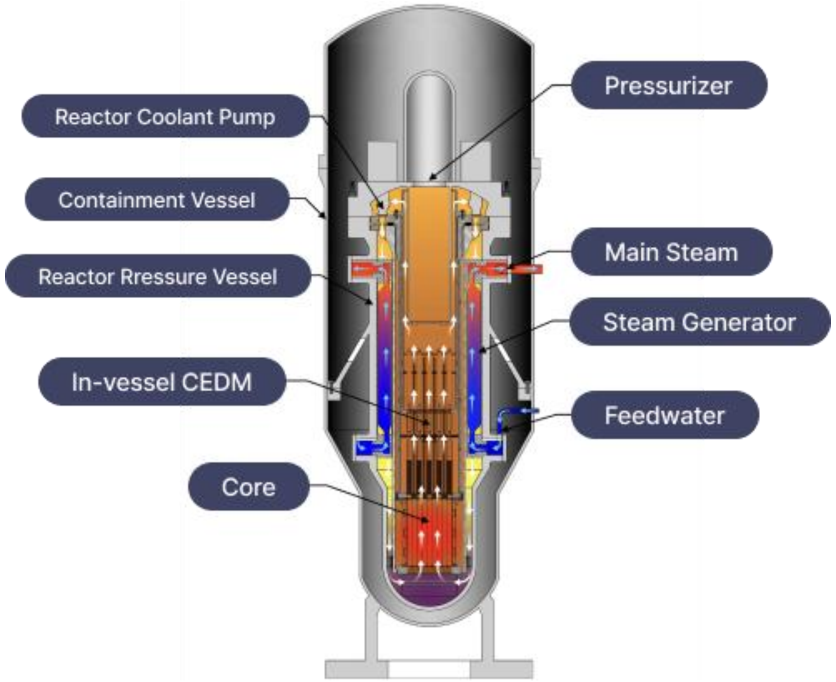
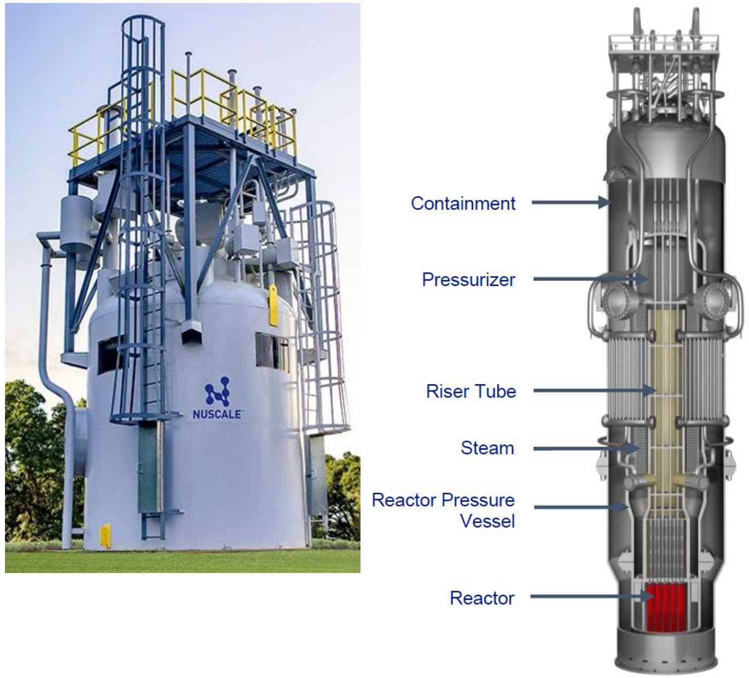
● Small Modular Reactor (SMR) overview



[Key concept of I-SMR]



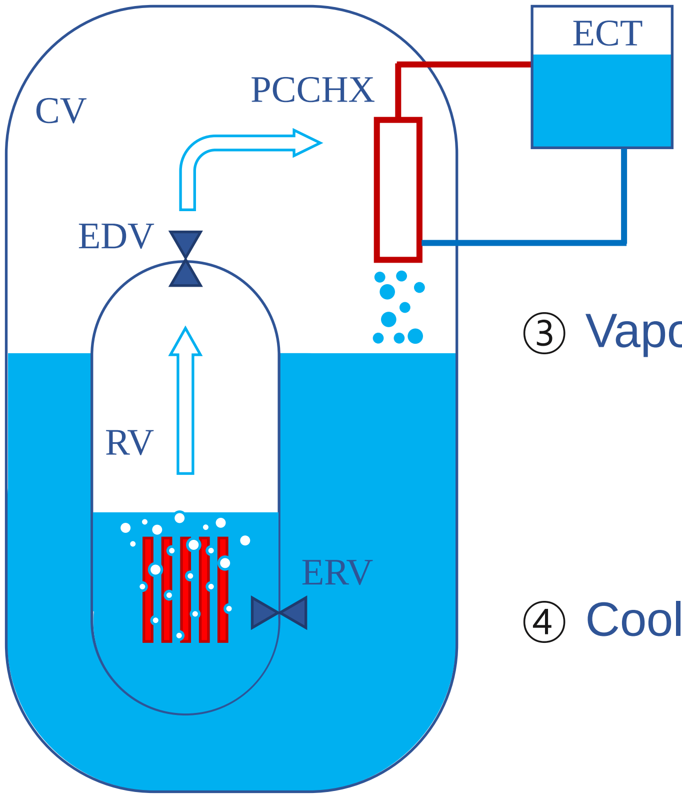
[77MWe SMR concept of Nuscale]

- SMR development is underway mainly in many countries due to its superior safety and various applications compared to large-scale nuclear reactors
- The main equipment is placed inside a single containment container
- The passive cooling safety system is commonly planned to be installed

● Passive Core Cooling System

② Coolant discharge via EDV

① Coolant boiling in core



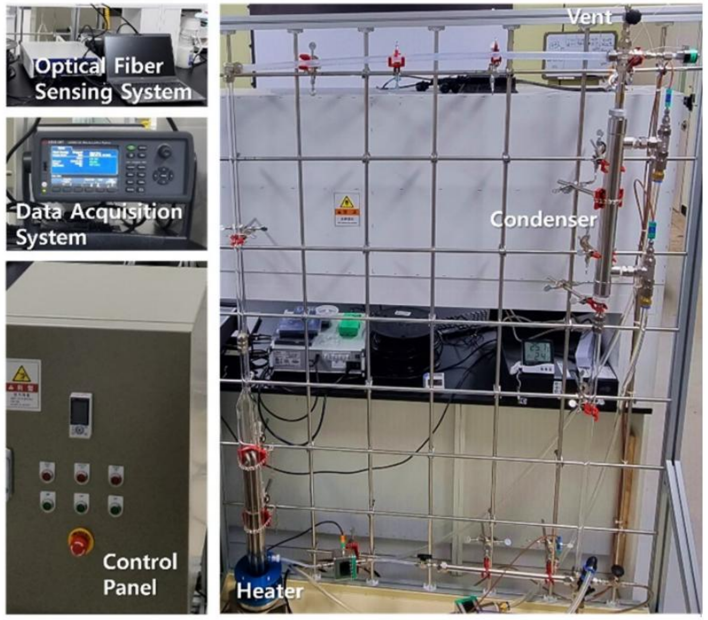
③ Vapor condensation with PCCHX

④ Coolant inflow through ERV

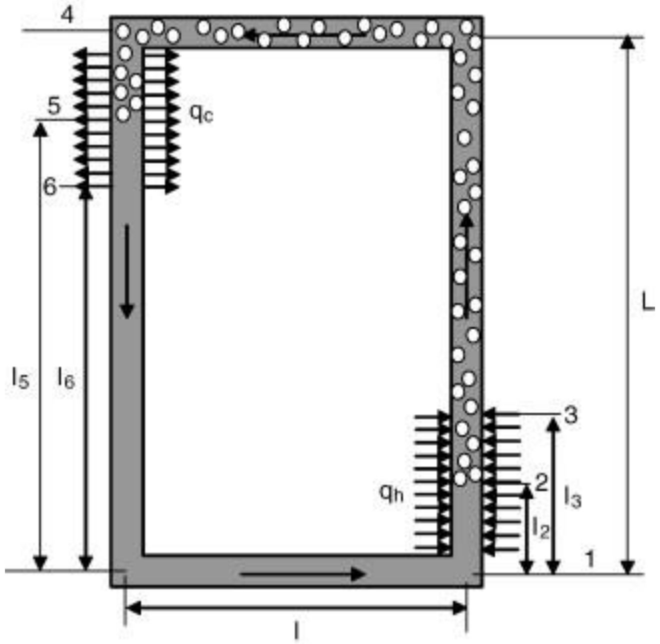
[Principle of cooling by natural force without external power in case of SMR coolant discharge accident]

- Coolant circulate in order of ① → ② → ③ → ④ → ① → ② → … without external power supply and decay heat from nuclear fuel, and it is called natural circulation.
- It is essential to predict the natural circulation flow rate for nuclear fuel cooling in SMR design.

● Prior Research



[Experiment of natural circulation (Jeong et al.)]



[Geometry of 1D calculation (Rao et al.)]

- Several experiments of natural circulation in a loop with non-condensable gas were conducted (Jeong et al.(2023), Yang et al.(2023), etc.)
- Numerical studies were mainly performed with one-dimensional codes. (Rao et al. (2006), Furci & Baudouy (2016), etc.)
- Very few studies used CFD for the natural circulation in a loop with non-condensable gas exists.

- **Purpose of the study**

- Development of natural circulation prediction model considering non-condensable gas effect

- Model verification through simulation of natural circulation by comparison of natural circulation flow rate with experimental results

Liquid-Gas Interfacial Mass Transfer Equation

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_l) = -\Gamma_e - \Gamma_c$$

$$\frac{\partial}{\partial t}(\alpha_g \rho_g Y_v) + \nabla \cdot (\alpha_g \rho_g \mathbf{u}_g Y_v) = -\nabla \cdot \alpha_g \mathbf{J}_v + \Gamma_e + \Gamma_c$$

- Mass diffusion coefficient

$$\mathbf{J}_v = -(\rho D_{v,m} + \frac{\mu_t}{Sc_t})\nabla Y_v - D_{T,v}\frac{\nabla T}{T}$$

- Mass fraction of steam

$$Y_v = M_v / \left(M_v + M_g\right)$$

- **Liquid-Gas Interfacial Mass Transfer Equation**

  - **Mass transfer term of evaporation**

$$\Gamma_e = \lambda_c \alpha_l \rho_l \frac{\left(T_l - T_{sat}\right)}{T_{sat}}$$

  - **Mass transfer term of condensation**

$$\Gamma_c = \lambda_c \alpha_g \rho_g Y_{vg} \frac{\left(T_{v,sat} - T_g\right)}{T_{v,sat}}$$

- **Momentum equation**

$$\frac{\partial(\alpha_g \rho_g \mathbf{u}_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g \mathbf{u}_g \mathbf{u}_g) = -\alpha_g \nabla p + \nabla \cdot \bar{\bar{\boldsymbol{\tau}}}_g + \mathbf{f}_i + \Gamma_e \mathbf{u}_g + \Gamma_c \mathbf{u}_l + \alpha_g \rho_g g$$

$$\frac{\partial(\alpha_l \rho_l \mathbf{u}_l)}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_l \mathbf{u}_l) = -\alpha_l \nabla p + \nabla \cdot \bar{\bar{\boldsymbol{\tau}}}_l - \mathbf{f}_i - \Gamma_e \mathbf{u}_g - \Gamma_c \mathbf{u}_l + \alpha_l \rho_l g$$

- **Interfacial forces**

$$\mathbf{f}_i = \mathbf{f}_{drag} + \mathbf{f}_{lift} + \mathbf{f}_{wl} + \mathbf{f}_{td}$$

- **Interfacial forces**
  - Drag: Ishii (1979)

$$\mathbf{f}_{drag} = -\frac{1}{8} C_d \rho_l a_i \,|\mathbf{u}_v - \mathbf{u}_l|\,(\mathbf{u}_v - \mathbf{u}_l)$$

  - Lift : Tomiyama (1998)

$$\mathbf{f}_{lift} = -C_{lift} \rho_l \alpha_v (\mathbf{u}_l - \mathbf{u}_v) \times (\nabla \times \mathbf{u}_l)$$

  - Wall lubrication: Antal et al. (1991)

$$\mathbf{f}_{wl} = C_{wl} \rho_l \alpha_v (\mathbf{u}_l - \mathbf{u}_v)_{\parallel}^{2} \mathbf{n}_w$$

  - Turbulent dispersion: Burns et al. (2004)

$$\mathbf{f}_{td} = -C_{td} \frac{3}{4} C_D \frac{\alpha_v \rho_l}{d_b} |\mathbf{u}_v - \mathbf{u}_l| \frac{\nu_l^t}{\sigma} \left(\frac{1}{\alpha_v} + \frac{1}{\alpha_l} \right) \nabla \alpha_v$$

- **Energy equation**

$$\frac{\partial}{\partial t}\left[\alpha_g\rho_g\left(e_g+\frac{\mathbf{u}_g^2}{2}\right)\right]+\nabla\cdot\left[\alpha_g\rho_g\mathbf{u}_g\left(h_g+\frac{\mathbf{u}_g^2}{2}\right)\right]$$

$$=\nabla\cdot\left(\alpha_g k_{eff,g}\nabla T_g\right)+\nabla\cdot(\bar{\bar{\boldsymbol{\tau}}}_g\cdot\mathbf{u}_g)-p\frac{\partial\alpha_g}{\partial t}+\Gamma_e h_g+\Gamma_c h_{g,sat}$$

$$\frac{\partial}{\partial t}\left[\alpha_l\rho_l\left(e_l+\frac{\mathbf{u}_l^2}{2}\right)\right]+\nabla\cdot\left[\alpha_l\rho_l\mathbf{u}_l\left(h_l+\frac{\mathbf{u}_l^2}{2}\right)\right]$$

$$=\nabla\cdot(\alpha_l k_{eff,l}\nabla T_l)+\nabla\cdot(\bar{\bar{\boldsymbol{\tau}}}_l\cdot\mathbf{u}_l)-p\frac{\partial\alpha_l}{\partial t}-\Gamma_e h_{l,sat}-\Gamma_c h_l$$

Turbulent model

- Realizable k-ε model
- Liquid phase turbulent kinetic energy(k) and dissipation rate(ε)

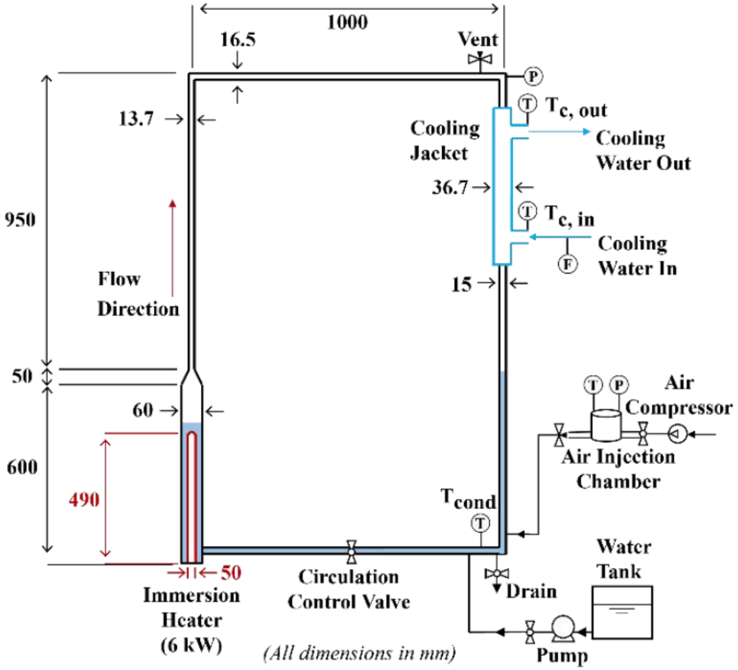
$$\frac{\partial}{\partial t}(\alpha_l \rho_l k_l) + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_l k_l) = \nabla \cdot \left\{ \alpha_l (\mu_l + \mu_l^t / \sigma_k) \nabla k_l \right\} + \alpha_l P_{k,l} - \alpha_l \rho_l \varepsilon_l$$

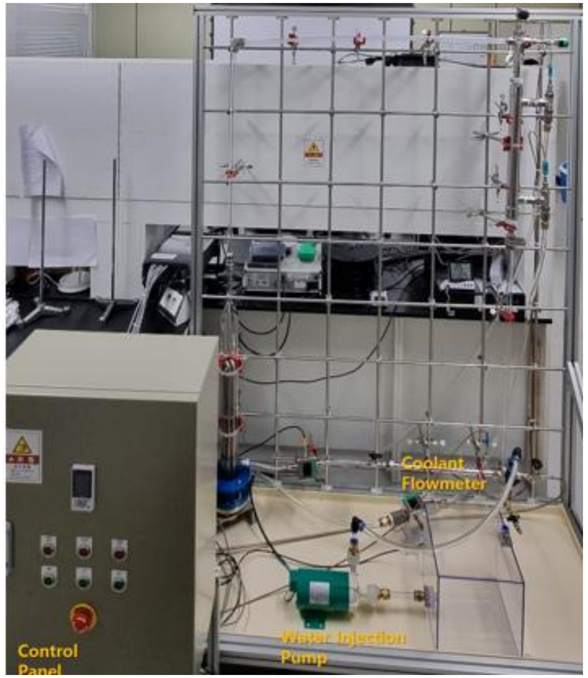
$$\frac{\partial}{\partial t}(\alpha_l \rho_l \varepsilon_l) + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_l \varepsilon_l) = \nabla \cdot \left\{ \alpha_l (\mu_l + \mu_l^t / \sigma_\varepsilon) \nabla \varepsilon_l \right\} + \alpha_l \frac{\varepsilon_l}{k_l} (C_{\varepsilon 1} P_{k,l} - C_{\varepsilon 2} \rho_l \varepsilon_l)$$

- Liquid phase turbulent viscosity : Sato (1979)

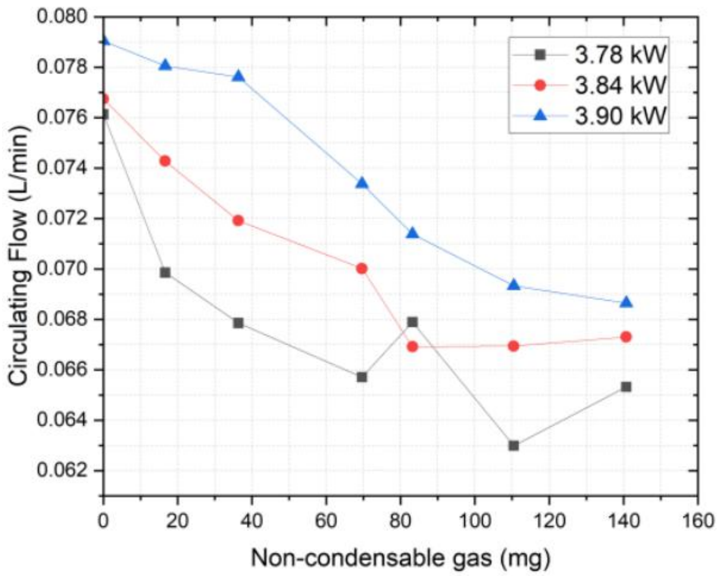
$$\mu_l^t = \rho_l C_\mu k_l^2 / \varepsilon_l + 0.6 \rho_l \alpha_v d_b \,|\, \mathbf{u}_v - \mathbf{u}_l \,|$$

Jeong et al. (2009)





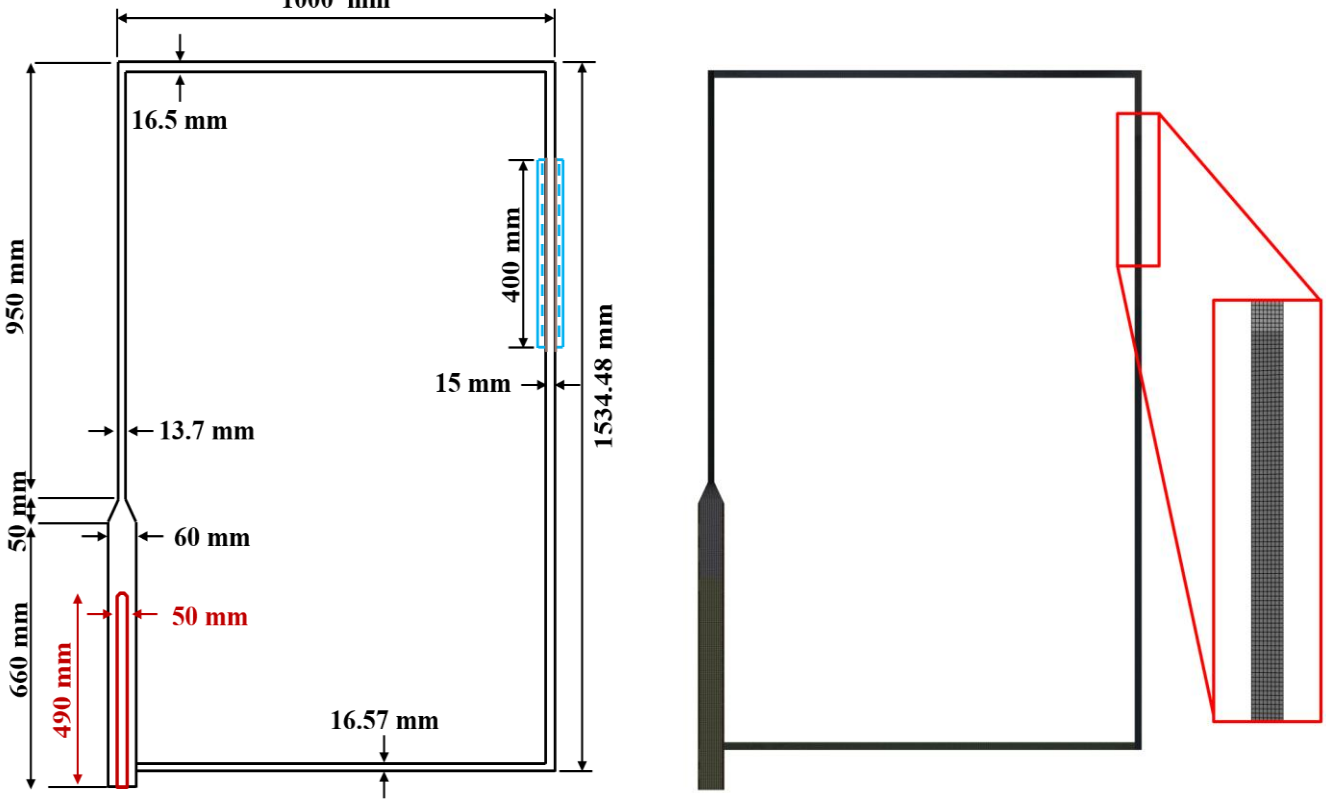
[Schematic diagram and picture of a natural circulation experimental device]



[Experimental results of circulation flow rate reduction]

- Working fluid : Water
- Non-condensable gas : air
- Loop shaped 2-D flow field is produced by modeling the interior of the experimental device

Flow field and mesh



[Overview of flow field for numerical simulation and mesh shape]

- Evaporator : Area of 490mm length, 50mm width inside of a chamber at left-bottom
- Condensor : Area of 400mm length, 15mm width at right-above of the loop
- In initial conditions, half of the loop is filled with water and the other half is filled with gas

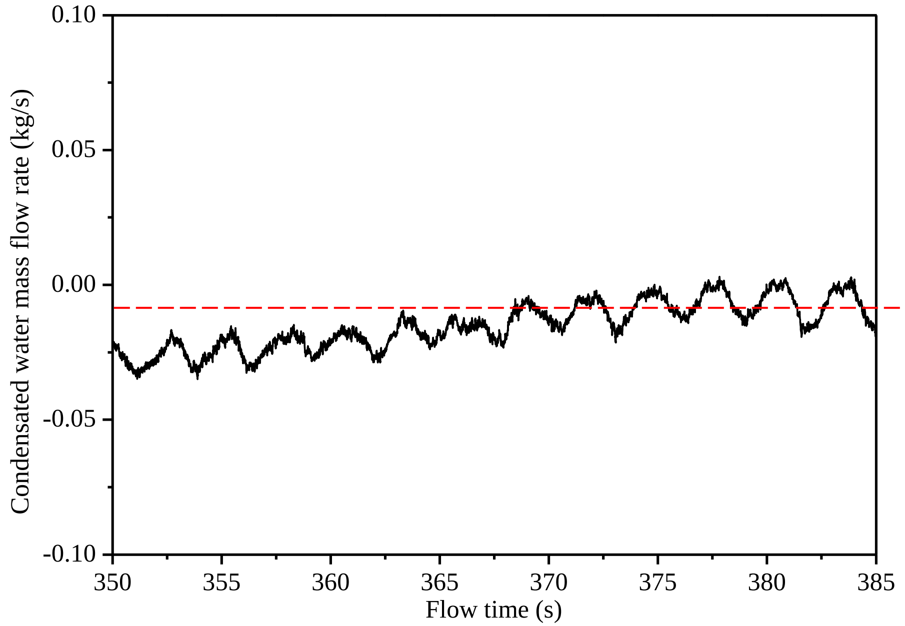
Numerical condition

- Choose from experimental conditions

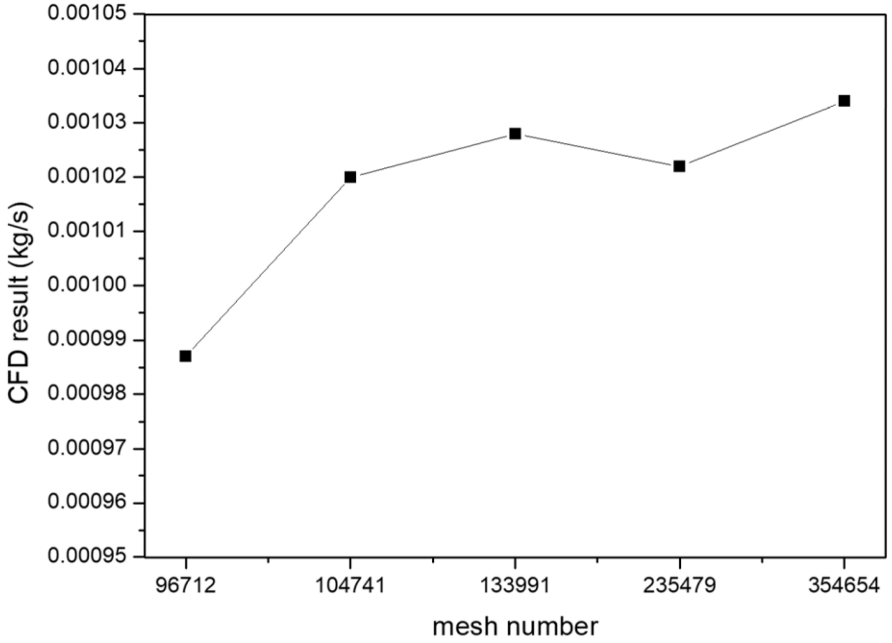
Test ID	N-00-H-01	N-01-H-01	N-03-H-01	N-06-H-01
NCG (mg)	0	16.65	69.6	140.74
Pressure (bar)	1.005	1.012	1.073	1.260
Heat (kW)	3.78	3.78	3.78	3.36
Cool (kW)	2.63	2.61	2.65	2.64
T_{cond} (°C)	81.77	68.58	52.79	32.51
G_{cir} (kg/s)	0.001269	0.001164	0.001095	0.001089

- Validation of the feasibility of the model and grid convergence test were conducted under condition only with pure vapor conditions (N-00-H-01) without non-condensable gases
- Numerical analysis of three conditions with different amounts of non-condensable gas were conducted to compare the changes in circulation flow rate

Grid convergence test



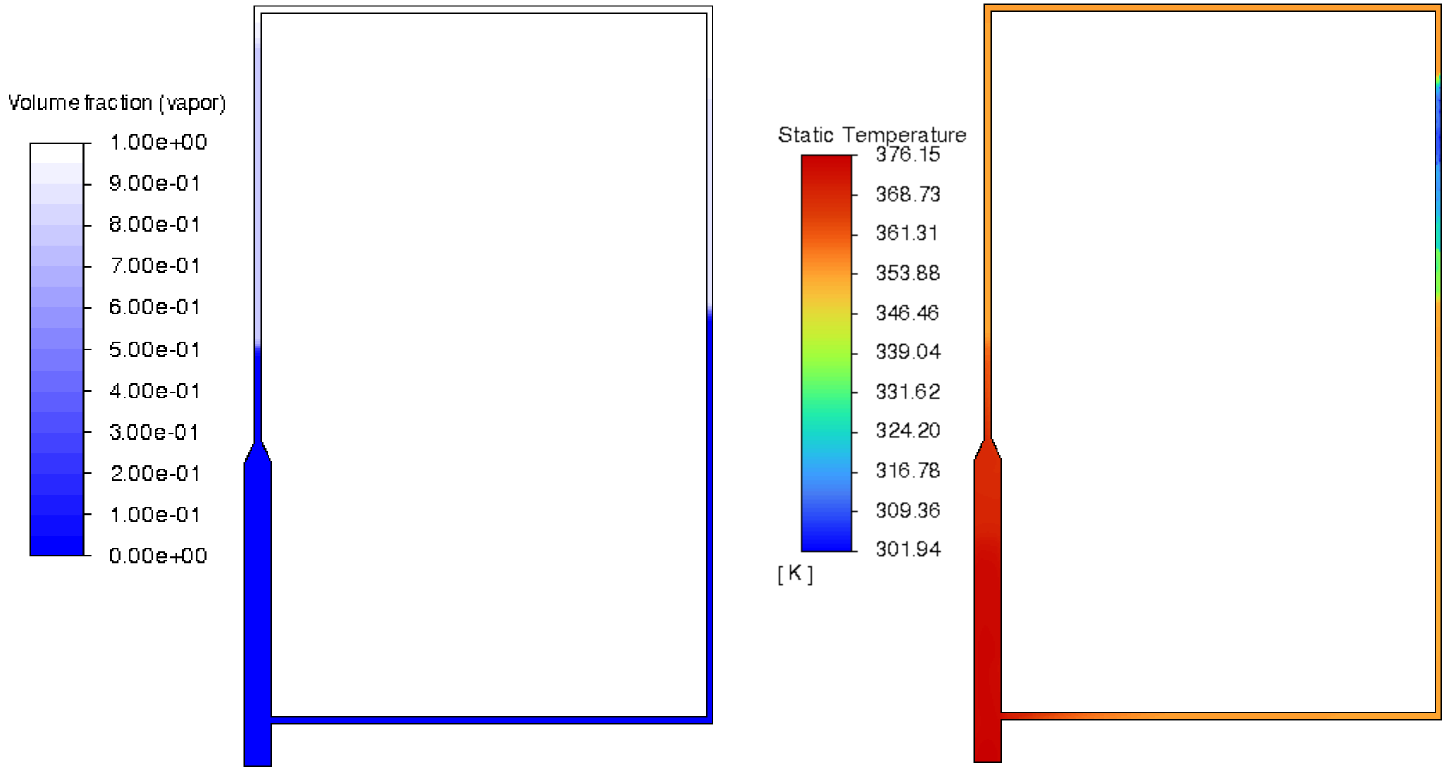
[Changes in mass flow rate at outlet of condenser]



[Results of the grid convergence test of 5 grids]

- Performed a grid test by creating five grids with different grid densities and numbers
- Calculated the average mass flow rate at the bottom of the condenser and compared the results
- Used 133,991 grids as it was judged to show sufficient convergence

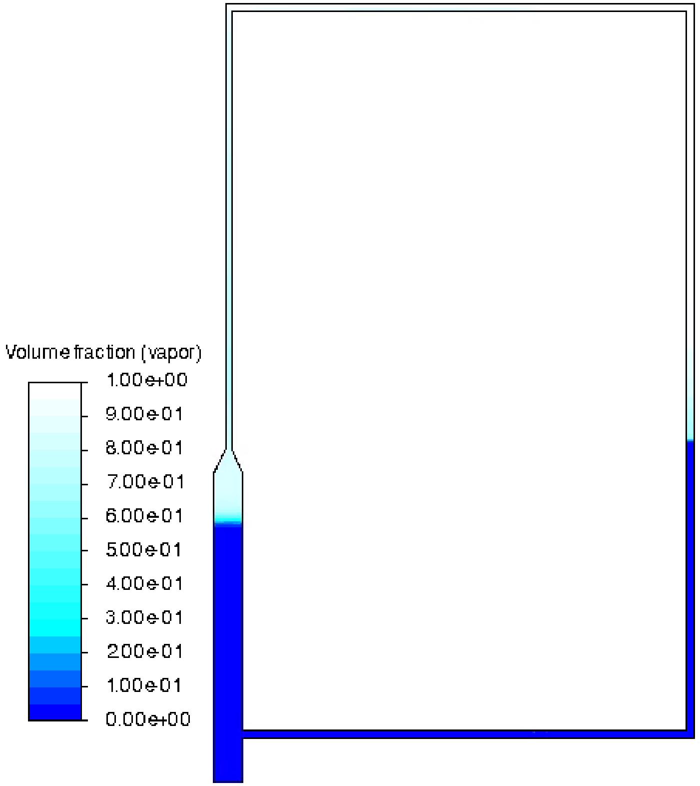
● pure vapor condition



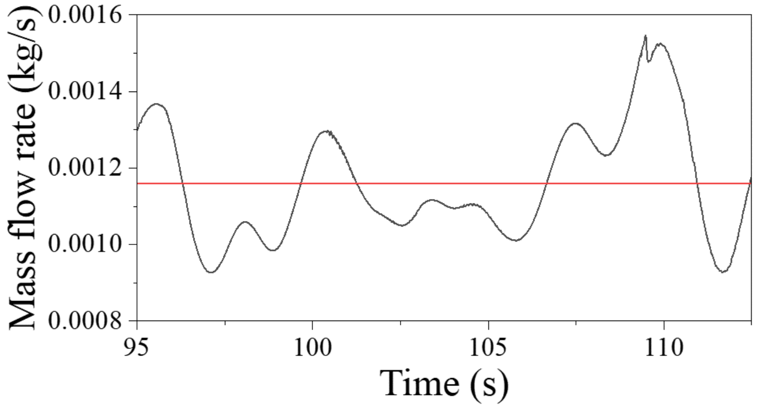
[vapor volume fraction and temperature distribution of the pure vapor condition (N-00-H-01)]

- A numerical analysis is conducted until the equilibrium of evaporation and condensation is achieved, then circulating flow data was collected
- As a result of numerical analysis, the circulating flow rate is 0.001028 kg/s, which is very similar to the experimental value of 0.001269 kg/s

● Natural circulation with non-condensable gases



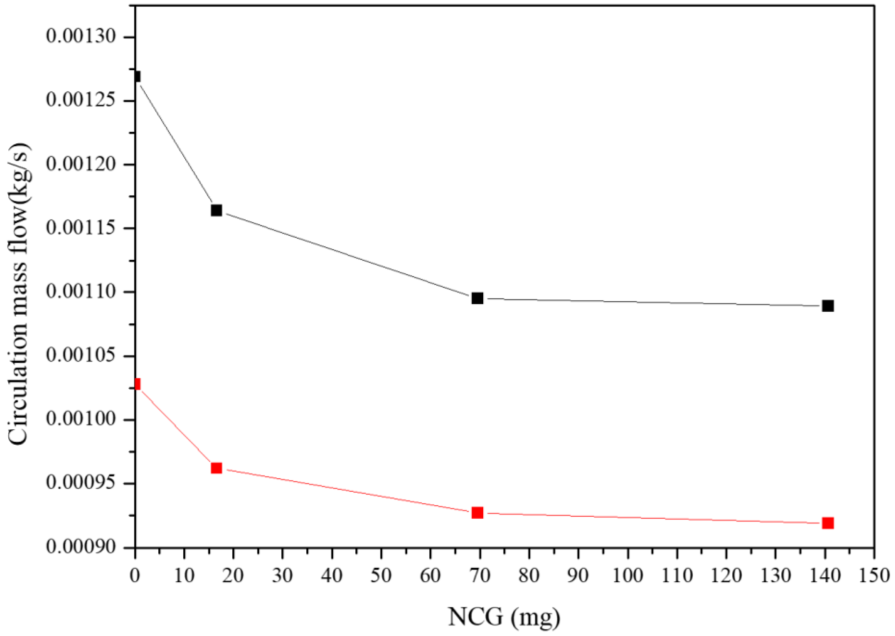
[Behavior of gas phase volume fraction after equilibrium]



[Circulating flow rate and average value over time (N-03-H-01)]

- The water level of equilibrium tends to be lower than the pure vapor condition
- Since equilibrium tends to fluctuate more irregularly than in pure vapor conditions, the circulating flow rate uses a time averaged value

● Natural circulation with non-condensable gases



Test ID	NCG (mg)	$G_{c,EXP}$ (kg/s)	$G_{c,CFD}$ (kg/s)
N-00-H-01	0	0.001269	0.001028
N-01-H-01	16.65	0.001164	0.000962
N-03-H-01	69.6	0.001095	0.000927
N-06-H-01	140.74	0.001089	0.000919

[Comparison of circulation flow rate according to the amount of non-condensable gas between numerical and experimental results]

- Numerical results obtained very similar to the circulating flow rate of the experiment
- The tendency to decrease the circulating flow rate with increasing non-condensable gas is almost the same as in the experiment

  → It is judged that the natural circulation with non-condensable gas existence was successfully simulated

Conclusion

- **Non-condensable gas degrades condensation performance, affecting circulation flow rate of natural circulation**

- **A numerical model for two-phase evaporation-condensation natural circulation is constructed to perform numerical analysis**

- **As a result of numerical simulation, the tendency of the natural circulation flow rate to decrease due to the increase of non-condensable gas was very similar to that of the experiment.**

- **The model used in this study was judged to be suitable for the numerical analysis of natural circulation in a loop with non-condensable gas existence**