

Effect of Non-condensable Gas in Nearly Pure Steam Condensation Experiments and the Need for Its Quantification

Chang Won Lee*, Jong-Hyuk Lee

Korea Atomic Energy Research Institute, 111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea

*Corresponding author: cwlee94@kaeri.re.kr

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1. Introduction

Wall condensation on the heat exchanger tubes is a key phenomenon in the design and safety analysis of the Passive Containment Cooling System (PCCS) in the innovative Small Modular Reactor (i-SMR). This condensation heat transfer directly affects the containment vessel (CV) pressure and the temperature of the recirculated coolant. To minimize heat loss, the i-SMR CV is maintained under near-vacuum conditions during normal operation. Given this operating characteristic, the non-condensable gas (NCG) in the CV stays at a very low pressure of about 0.1 bar. Therefore, the conditions applied to the i-SMR PCCS during an accident differ significantly from the thermal-hydraulic conditions of the PCCS in conventional commercial PWRs. Specifically, under accident scenarios, the pressure in the CV is expected to range from approximately 5 to 50 bar. The corresponding NCG mass fraction is nearly zero. However, since no experimental data are available for these specific conditions, the validation of system analysis codes such as SPACE has been conducted mainly under low-pressure steam-air mixture conditions.

In actual experiments, a pure-steam condition should be regarded as an ideal target rather than a condition that can be fully achieved. A completely NCG-free environment is difficult to establish because residual air may remain in the system after filling and heat-up, and dissolved gases in the feedwater may be released during the experiment. In addition, complete venting of the system is practically unattainable, resulting in very low concentrations of NCG in the test section.

Accurate control and direct measurement of such low NCG concentrations are also challenging. Although gas sampling can be performed at selected locations, these local measurements may not be representative of the overall gas composition in a facility designed to simulate containment conditions. Therefore, the NCG concentration is commonly estimated indirectly from measured pressure and temperature. The saturated steam partial pressure is determined from the measured gas temperature, and the NCG partial pressure is then obtained from the difference between the measured total pressure and the saturated steam pressure. The NCG mass fraction can subsequently be estimated from these partial pressures using the corresponding thermodynamic properties.

In the Pusan National University (PNU) condensation experiment, which was recently used as a validation problem for SPACE, the NCG mass fraction was analyzed and reported [1]. In contrast, the experimental literature by Ma et al. [2] mentions the NCG effect but provides neither a quantitative estimate of the NCG mass fraction nor an uncertainty analysis. A major challenge is that, at very low NCG mass fractions, measurement uncertainties in pressure and temperature can significantly influence the estimated NCG mass fraction. Moreover, the heat transfer coefficient exhibits high sensitivity under such low NCG mass fraction conditions.

In this paper, the effect of a very low NCG mass fraction on the prediction of the heat transfer coefficient is evaluated for the PNU condensation experiment [1]. This evaluation is performed using three analysis tools: a system code (SPACE), CFD (containmentFOAM), and an analytical model. Additionally, the extent to which the experimental measurement uncertainty propagates is assessed.

2. Effect of NCG in previous SPACE validation results

The condensation experiments of PNU and of Ma et al. were used to validate the wall condensation model of the SPACE code. Since both experiments were conducted with pure steam conditions as the target, the initial analyses assigned boundary conditions on the assumption that no NCG was present in the test section. The ratio of the calculated to the measured values (P/M) has therefore been interpreted as the predictive performance of the condensation model itself (Fig. 1). When the validation results of the two experiments are examined condition by condition, however, the prediction error appears mainly at particular conditions.

2.1 PNU experiment — correlation between the NCG fraction and the prediction error

In the PNU experiment, the mass fraction of residual NCG was analyzed and reported. It was estimated by comparing the measured pressure with the steam partial pressure calculated from the measured gas temperature. According to this analysis, the steam partial pressure at the 3 bar condition is clearly lower than the measured pressure. This indicates that the residual NCG fraction was relatively high at this condition. It should be noted

that no anomaly in the venting procedure or in the conduct of the test was reported.

The SPACE results with the pure steam assumption show the largest overprediction of the heat transfer coefficient at the conditions where a high NCG fraction was analyzed (Fig. 1(a)). This suggests that the NCG neglected in the analysis acted as an interfacial diffusion resistance in the actual test and thereby suppressed heat transfer.

2.2 Experiment of Ma et al. — inference from measurement bias

In the experiment of Ma et al., the overprediction is pronounced at the low-pressure conditions, but the cause cannot be identified because the NCG fraction is not reported. The test conditions can nevertheless be inferred from the measured values alone. The test section has no superheater, so the bulk gas cannot exceed the saturation temperature. However, the measured gas temperature is about 2 K higher than the saturation temperature throughout the high-pressure conditions (Fig. 2). If this 2 K is taken as a measurement bias and the same correction is applied to the low-pressure conditions, the steam partial pressure becomes lower than the measured pressure. At low pressure, the slope of the saturation curve is small, so the same bias has a larger relative influence on the estimated partial pressure. Ultimately, the overprediction of the condensation HTC in the analysis of the Ma experiment may come either from the condensation model itself or from a very low mass fraction of NCG that was not included in the analysis.

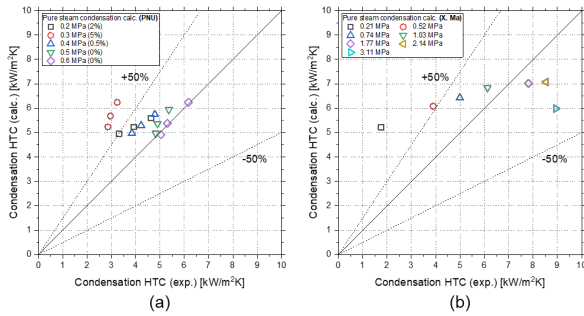


Fig. 1. Calculation results of pure steam condensation (a: PNU tests, b: Ma tests)

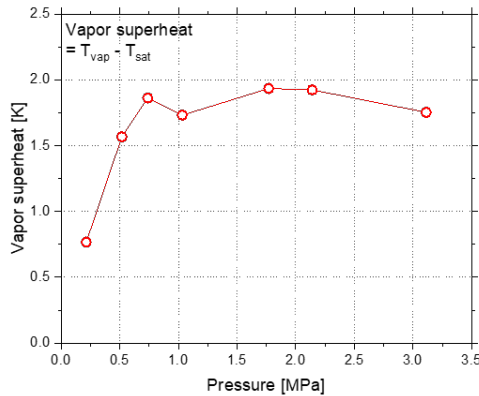


Fig. 2. Vapor superheat from measured temperature and

pressure in Ma tests

3. Calculation methodology

3.1 Calculation model setup

In this study, the 3 bar condition of the PNU experiment (Table I) was analyzed using the system code SPACE, the CFD code containmentFOAM, and an in-house analytical model. In all analyses, the measured wall temperature, averaged over the condensing surface, was imposed as a uniform boundary condition. Air was considered as the NCG species. The NCG content was specified as the initial bulk mass fraction (air mass fraction, AMF), which was kept identical across the three tools. As shown in Fig. 3(a), the SPACE model represents the PCCS tube as a heat structure. The vapor region where condensation occurs is modeled as a single large volume, similar to the i-SMR CV analysis model. The NCG content is given as an initial mass fraction, so the total mass of air remains constant during the steady-state calculation. In the CFD analysis, a 2.5-degree wedge-type mesh with a symmetry boundary condition was used, as shown in Fig. 3(b). The near-wall mesh was refined so that y^+ remains below 1. The diffusion layer model of containmentFOAM was used to calculate the condensation rate at the film surface [3]. The liquid film itself was directly solved with a one-dimensional film model. The film equations are solved along the wall, and heat conduction across the film thickness is included. The thermal resistance of the film is therefore taken into account. The SST k- ω model was adopted for turbulence, and the turbulent Schmidt number was set to 0.8. The sensitivity of the condensation rate to this value was small. The in-house analytical model is based on the heat and mass transfer analogy, as shown in Fig. 4. The models listed in Table II were used to calculate the main variables. The condensation mass flux is accumulated along the wall to obtain the local film flow rate. The film thickness is then evaluated from the Nusselt film solution. At each node, the interface temperature is iterated until the heat flux conducted through the film balances the latent and sensible heat from the gas mixture. The condensing surface was treated as a vertical flat plate. A tube curvature correction could be applied, but its effect is negligible for the present tube diameter. In the SPACE and CFD analyses, the calculation was considered to reach steady state when both the heat transfer coefficient and the pressure remained constant.

Table I: Computational conditions

Pressure [MPa]	Wall sub. [K]	Bulk temp. [K]	AMF [-]
0.300	16.1	405.6	0.005 ~ 0.05
0.300	24.6	405.5	
0.301	33.7	405.7	

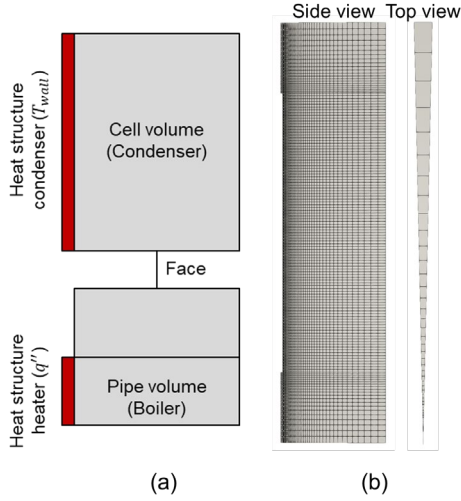


Fig. 3. Nodalization and meshes
(a: SPACE, b: containmentFOAM)

3.2 Calculation conditions

A special-grade Type T thermocouple, commonly used in condensation experiments, has a tolerance of ± 0.5 K. With this tolerance, the NCG mass fraction at 3 bar ranges from 3 to 7% around the nominal value of 5%. If the pressure measurement error is also included, the range widens to 1–9%. Meanwhile, the analyses using the nominal value reported in the experiment consistently underpredicted the heat transfer coefficient in all three analysis tools. The sensitivity of the heat transfer coefficient was therefore evaluated by varying the NCG mass fraction over the range of 0.5 to 5%.

Table II: Closure models for in-house code

Parameters	Models
Gas-side transfer coefficients (Nu, Sh)	Churchill-Chu correlation (local form), with heat and mass transfer analogy
Condensation rate	Diffusion-layer theory; vapor partial-density driving force
Sensible heat flux	Ackermann correction
Film thickness and thermal resistance	Nusselt laminar falling-film solution
Interface condition	Thermodynamic equilibrium $p_{v,i} = p_{sat}(T_i)$
Gas mixture properties	IAPWS-95 properties, Wilke mixing rule, Marrero–Mason diffusivity

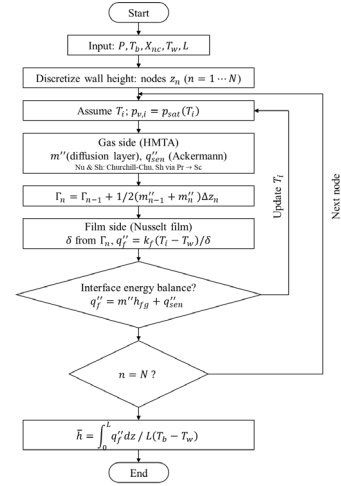


Fig. 4. Flow chart of in-house condensation analysis code

4. Calculation results

As shown in Fig. 5, when the mass fraction decreases from 5% to 0.5%, the heat transfer coefficient increases by approximately 60% in the in-house analytical model, 81% in SPACE, and 63% in the CFD analysis. The three tools have different fidelities and implementations, but they show a consistent trend and a similar magnitude of sensitivity. This confirms that the strong dependence is not specific to a particular code.

Note that the change caused by the NCG mass fraction is far larger than the difference among the analysis tools. At low NCG mass fractions, the predicted heat transfer coefficient is governed by the uncertainty of the NCG boundary condition rather than by the model uncertainty. Therefore, comparing the calculated results with the measured HTC under nominal conditions alone does not fully reflect the model's performance.

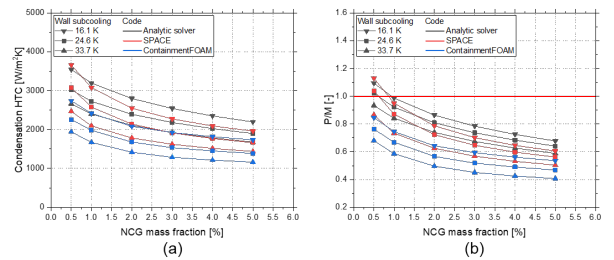


Fig. 5. Calculation results by using three tools
(a: Condensation HTC, b: P/M)

5. Conclusions

This study demonstrated that a small amount of NCG may remain in condensation experiments designed to achieve nominally pure-steam conditions. The effect of uncertainty in the NCG mass fraction on the predicted heat transfer coefficient was subsequently evaluated using three complementary analysis approaches: a system code, CFD, and an analytical model. The main conclusions are summarized as follows.

First, in the PNU experiment, even small measurement uncertainties in temperature and pressure lead to a wide range of the estimated NCG mass fraction. This effect becomes stronger as the NCG mass fraction becomes lower. A single nominal value is therefore not enough to fix the boundary condition for the analysis.

Second, the sensitivity analysis with the three tools showed that the predicted heat transfer coefficient changes strongly with the NCG mass fraction in the low-fraction range. This change was much larger than the differences among the tools. The prediction is therefore governed by the NCG boundary condition rather than by the choice of the analysis tool.

Third, accurately measuring and estimating very low NCG mass fractions remain challenging in both experiments and analyses. Therefore, condensation experiments should report the estimated NCG mass fraction together with its associated uncertainty, while the reproducibility of the experimental conditions should be assessed through repeated tests. Code validation should likewise account for the uncertainty range in the NCG mass fraction rather than relying solely on a single nominal value.

The Korea Atomic Energy Research Institute plans separate effect tests (SET) on the outer wall of single-tube and bundled-tube heat exchangers with very low NCG concentrations. In these tests, the uncertainties of the primitive variables, such as temperature and pressure, will be quantified in detail. These data will therefore be more useful for evaluating the uncertainty of the NCG mass fraction.

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During the preparation of this work, the authors used Claude (Anthropic) in order to translate the manuscript from Korean into English and to improve readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the paper.

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