Evaluation of SPACE Predictive Capability for Horizontal In-Tube Condensation under Low Pressure and Low Mass Flux Conditions

Sang Gyun Nam*, Seong-Su Jeon, Soon-Joon Hong
FNC Tech., 13 Heungdeok 1-ro, 32F, Giheung-gu, Yongin-si, Gyeonggi-do, 16954, Korea
sgnam55@fnctech.com

1. Introduction

The major design principle for nuclear power plants (NPPs) is defense in depth. To implement this safety concept, the design of NPPs includes active, passive, and inherent safety features. The Passive Auxiliary Feedwater System (PAFS), one of the passive safety systems, cools down the reactor coolant system (RCS) and prevents core damage by supplying sufficient condensate to the steam generator (SG). Fig. 1 shows the heat exchanger of the PAFS. The steam from the SG flows into the PAFS heat exchanger, and the condensate returns to the SG. In-tube condensation, natural convection, and boiling heat transfer deliver the energy from the RCS to the pool. Therefore, heat transfer in the PAFS heat exchanger is a major parameter for designing and operating the PAFS.

This study presents assessment of horizontal in-tube condensation, the primary heat transfer phenomenon for PAFS, under various test conditions using the SPACE code, a thermal-hydraulic (T/H) system code.

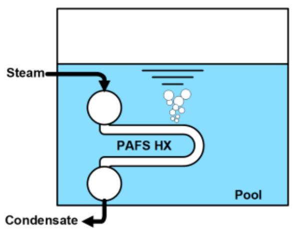

Fig. 1. Schematic of the PAFS heat exchanger

2. Description of reference experiment

At Purdue University, experiments were conducted to study steam condensation in horizontal heat exchangers [1]. The purpose of this experimental facility was to support the design of the horizontal PCCS (Passive Containment Cooling System). The schematic diagram of the test section is shown in Figure 2. The condenser tube has an OD 31.7 mm, a wall thickness of 2.1 mm, and a heat transfer length of 3.0 m. Steam with non-condensable gas (NC gas) was introduced into the condenser tube and condensed by a water jacket, which then flowed into the annulus (with an OD 63.5 mm). The tests were conducted under low-pressure, post-LOCA conditions [1]. The experimental conditions are summarized in Table 1.

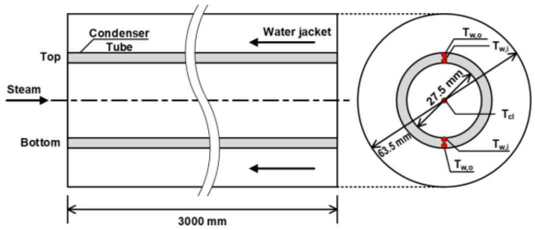

Fig. 2. Schematic of Purdue University test section

In order to evaluate horizontal in-tube condensation in PAFS, this study used experimental data from low NC gas conditions as reference tests, which are presented in Table. 2. During an actual accident, the air mass fraction of NC gas would be very low as most of the vapor is introduced into the PAFS heat exchanger.

Table. 1. Purdue-PCCS experimental conditions

Parameter	Range
Primary Side (Steam / Air)	
Pressure (kPa)	100 – 400
Steam flow rate (g/s)	6.0 – 46.0
NC gas mass fraction (%)	0 – 20
Secondary Side (Water)	
Pressure (kPa)	200
Flow rate (kg/s)	1.48
Temperature (℃)	45.0

Table. 2. Reference experiments

Test No.	Pressure [kPa]	Steam flow [g/s]	Air mass fraction [%]
6	100	6.0	2
3	100	11.5	1
20	200	6.0	1
101	200	11.5	1
24	400	11.5	1
27	400	23.0	1

3. Simulation of Purdue-PCCS experiment

3.1 SPACE nodalization

Figure 3 shows the nodalization utilized in the Purdue-PCCS experiment. In order to simplify the experimental facility, only the primary side of the test section and the drain line were simulated. The horizontal test section was divided into 30 nodes, each with a length of 0.1 m. The injection of air-steam mass fraction, flow rate, and pressure were controlled using the TFBC component. Additionally, the secondary side was replaced with a boundary condition of the heat structure (HS200).

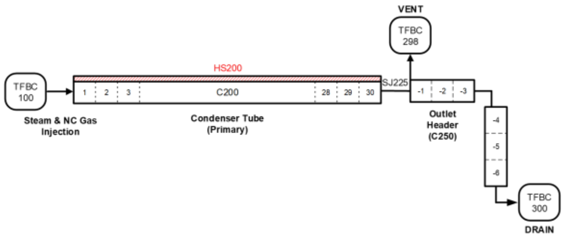

Fig. 3. Purdue-PCCS experiment nodalization

3.2 Models of the wall condensation in SPACE

In the SPACE code, four models are used for wall condensation heat transfer: the Colburn-Hougen model is the default model, the No-Park model is used as an alternative model, the Vierow-Schrock model is employed as a temporary model, and the PAFS model is included in the wall condensation model. In this study, only the Colburn-Hougen model was used. The Colburn-Hougen model states that the total heat transfer from the steam-NC gas layer to the liquid-steam interface can be modeled as the heat transfer through the condensation film [2].

3.3 Comparison with MARS-KS

Previous research (Jeon et al., 2013) assessed the horizontal in-tube condensation models using the MARS code. The MARS code was found to predict the overall heat transfer rate in the Purdue-PCCS experiment well, but it generally underestimated the local heat transfer rate in the main condensation region. In the present study, the analysis capability of horizontal in-tube condensation heat transfer for Test 6 was compared using MARS-KS code and SPACE code. As shown in Fig. 4, the calculation results of MARS-KS and SPACE were very similar, indicating that the calculation capability of the SPACE code is comparable to that of the MARS-KS code. However, both codes still underestimated the local heat transfer rate in the main condensation region.

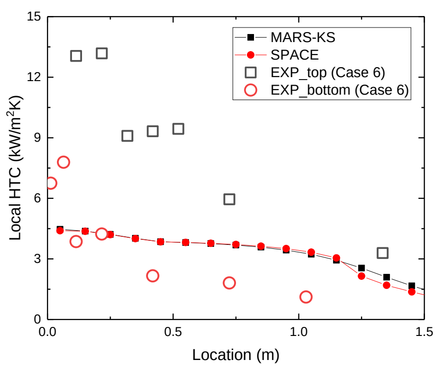

Fig. 4. Comparison with MARS-KS and SPACE

3.4 Assessment of the default model in SPACE

In this study, six cases of the Purdue-PCCS test were simulated using the default model in SPACE. The study obtained local heat transfer coefficients for in-tube condensation along the axial location, and the calculation results are summarized in Fig. 5. The default model predicted the overall heat transfer rate, obtained by the summation of the wall heat transfer rate of the condenser tube using the built-in function “qwall”, within 5% of the experimental data. The overall heat transfer rate of the experiments is reported in the reference thesis [4]. However, in the main condensation region, specifically at the inlet of the condenser tube, the default model underestimated the experimental results.

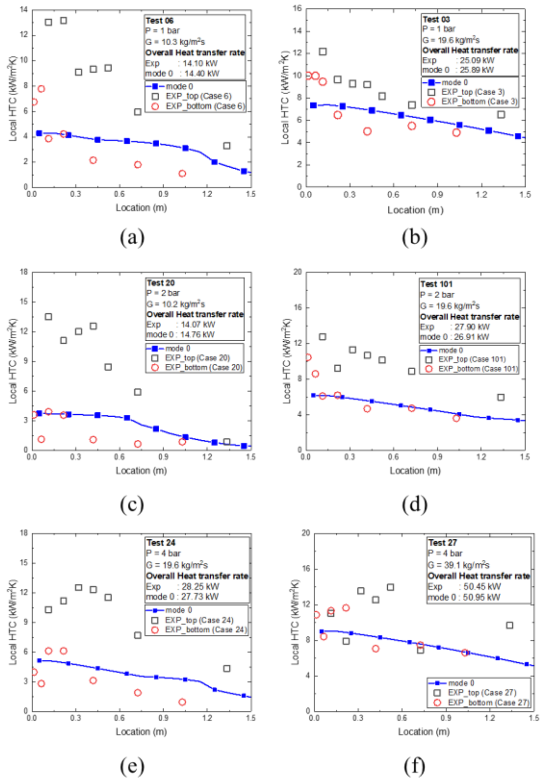

Fig. 5. Calculation results of the SPACE: (a) test06, (b) test03, (c) test20, (d) test101, (e) test24, (f) test27

4. Conclusion

In this study, the assessment of the horizontal in-tube condensation using SPACE code was performed to evaluate its prediction capability for the Purdue-PCCS experiment. From the assessment, the following conclusions are drawn.

(1) The SPACE code accurately predicted the overall heat transfer rate in the Purdue-PCCS experiment, similar to the MARS-KS code.

(2) The default model for the wall condensation in SPACE appropriately estimated the overall heat transfer rate in the experiment. However, it underestimates the heat transfer rate in the main condensation region.

REFERENCES

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