Assessment of Condensation Heat Transfer Models of MARS-KS and TRACE Codes Using PASCAL Test

Kyung Won Lee, Aeju Cheong, Andong Shin
Korea Institute of Nuclear Safety
62 Gwahak-ro, Yuseong-gu
Daejeon 34142, Republic of Korea
leekw@kins.re.kr, k495caj@kins.re.kr, k354sad@kins.re.kr

ABSTRACT

We simulated the KAERI PASCAL SS-540-P1 test with MARS-KS V1.4 and TRACE V5.0 p4 codes to assess the code predictability for the condensation heat transfer inside the passive auxiliary feedwater system. The calculated results of heat flux, inner wall surface temperature of the condensing tube, fluid temperature, and steam mass flow rate are compared with the experimental data. The result shows that the MARS-KS generally under-predict the heat fluxes. The TRACE over-predicts the heat flux at tube inlet region and under-predicts it at tube outlet region. The TRACE prediction shows larger total amount of steam condensation by about 3% than the MARS-KS prediction.

1 INTRODUCTION

The advanced power reactor plus (APR+) is a GEN-III+ nuclear power plant, the standard design of which is currently being developed in Korea. The passive auxiliary feedwater system (PAFS) is one of the advanced safety features of the APR+ and is design to replace the conventional active auxiliary feedwater system. During the plant transient, PAFS cools down the secondary side of steam generator, and eventually remove the decay heat of the reactor core by condensing steam in nearly-horizontal U-shaped tubes (passive condensation heat exchanger, PCHX) submerged inside the passive condensation cooling tank (PCCT) [1].

In order to validate the operational performance of the PAFS, Korea Atomic Energy Research Institute (KAERI) has performed the experimental investigation using the PASCAL (PAFS Condensing heat removal Assessment Loop) facility [1-3]. Several analytic works with thermal-hydraulic system codes have also been performed [2-5].

This study aims at assessing the condensation models of MARS-KS and TRACE codes using the PASCAL test. For this purpose, the calculation results of various parameters are compared with the experimental data.

1.1 MARS-KS and TRACE Codes

The MARS (Multi-dimensional Analysis of Reactor Safety) code has been developed by KAERI for the realistic multi-dimensional thermal-hydraulic system analysis of reactor transients. The backbones of MARS are the RELAP5/MOD3.2.1.2 and the COBRA-TF. The two codes were consolidated into a single code. In addition, a generic multi-dimensional fluid model has been developed and implemented to the RELAP5 system analysis module to overcome some limitation of the COBRA-TF three-dimensional (3-D) vessel module [6]. The Korea Institute of Nuclear Safety (KINS) uses and maintains the KINS Standard version of MARS (MARS-KS) for the regulatory audit calculation.
The TRACE (TRAC/RELAP Advanced Computational Engine) is the latest in a series of advanced, best-estimate reactor systems codes developed by U.S. NRC for analyzing transient and steady-state neutronic-thermal-hydraulic behaviour in light water reactors. A 3-D flow calculation can be simulated within the reactor vessel or the other components where 3-D phenomena take place [7].

1.2 Condensation Models in MARS-KS and TRACE Codes

For the steam condensation without noncondensable gas at inclined surface, the MARS-KS uses the maximum of Nusselt (laminar) model and Shah (turbulent) model [6]. The TRACE uses the Kuhn-Schrock-Peterson empirical correlation (laminar) and modified Gnielinski’s correlation (turbulent) [7].

2 FACILITY DESCRIPTION

Figure 1 shows the design of PASCAL facility. The main components of the facility are the test section of PCHX, the steam-supply and condensate-return line, and the PCCT as shown in Fig. 1(a). To simulate the geometry of the PAFS, a single U-shaped PCHX tube with the length of 8.4 m is submerged in the PCCT. The tube has an inclination of 3 degrees to prevent the water hammer from occurring. The dimension and material of the tube are the same as the prototype. The inner and outer diameters of the PCHX are 44.8 mm and 50.8 mm, respectively. The PCHX is made of stainless steel 304.

The width and depth of the PCCT are 6.7m and 0.112 m, respectively. The height of the PCCT is 11.484 m. The steam generator with 540kW thermal power provides the steam to the PCHX. The condensate flows back to the steam generator.

![Figure 1: Design of PASCAL facility](image-url)
In the PASCAL test, the major measuring parameters are the flow rates of the steam and the condensate, the loop temperature and pressure, the collapsed water level and the local water temperature of PCCT pool. To evaluate the local heat fluxes and the heat transfer coefficients, the temperatures of fluid and tube surface are measured at 11 points along the PCHX length as shown in Fig. 1(b). A total of 9 thermocouples are installed at each measurement point as shown in Fig. 1(c).

3 DESCRIPTION OF MARS-KS AND TRACE MODELS

Figure 2 shows the MARS-KS and TRACE input models. In the MARS-KS model, the PCHX is modeled using the PIPE component with the 28 nodes. The inclination of each node is determined in consideration of the tube shape. The steam-supply line and the condensate-return line are modeled using the time dependent volumes and the single volumes. The PCCT is modeled using the multi-dimensional component with one node in x coordinate direction (x1), 16 nodes in y coordinate direction (y1~y16), and 22 nodes in z coordinate direction (z1~z22). The steam discharge line is connected to the upper side of 1st-16th-22nd node. The heat structure component is used to model the heat transfer between the PCHX and the PCCT.

The TRACE input model has the same nodalization as the MARS-KS input model. The steam-supply line is modelled using the FILL component. The condensate-return and the steam discharge lines are modeled with the BREAK components. The PCCT is modeled with the 3-D vessel component with x(1)-y(16)-z(22) nodes.

The form loss coefficients at each junction of PCCT are determined by the sensitivity test so that the calculated temperature distribution of fluid in the PCCT is similar to the measured data. In both input models, the heat structure thermal properties and boundary conditions are the same. The injected mass flow rate of steam is the same as the measured value.
RESULTS AND DISCUSSION

The transient calculation were run for the SS-540-P1 test. The calculated values are taken at the quasi-steady state condition when the collapsed water level of PCCT reaches 9.3 m. The calculated results of heat flux, inner wall surface temperature, fluid temperature inside PCHX, and steam mass flow rate are compared with the experimental data. The measured values are extracted from Ref. [2]. The MARS-KS V1.4 and TRACE V5.0 patch4 are used.

4.1 Heat Flux

Figure 3 shows the calculated and measured distribution of heat flux at tube inner surface along the PCHX length. In the experiment, the measured heat flux of the top region inside tube was larger than that of the bottom region. This is due to the fact that the top part of the tube is filled with the steam flow and the condensate flows in the bottom region. The distribution of heat flux at the upper half of PCHX was almost uniform, and the values gradually decreased at the lower half of PCHX along the tube length. The average (arithmetic mean) values of heat fluxes at the top inner wall and the bottom inner wall in the experiment were 457.8 and 412.9 kW/m², respectively.

With the similar inclination trend, the MARS-KS generally under-predicts the heat flux. The maximum difference is observed at the bent region in the middle (measurement point 6 in Fig. 1(b)). The TRACE, on the other hand, overestimates the heat flux at the upper half of PCHX and under-predicts it at the lower half of PCHX. The difference between the TRACE prediction and the data is about 30% at the PCHX inlet region. When compared with the MARS-KS results, the change rate of heat flux along the tube is relatively large. The average (arithmetic mean) values of heat fluxes in the MARS-KS and TRACE predictions are 391.2 and 439.4 kW/m², respectively.

4.2 Inner Wall Surface Temperatures

Figure 4 shows the distribution of tube inner wall surface temperature. In the experiment, the trend of surface temperature distribution was similar to that of heat flux.
As expected from the temperature results, the MARS-KS does a good job of approximating the temperature distribution of inner surface with it being a little more close to the bottom side temperature. However, similar to the results of heat flux, the TRACE overestimates the inner wall surface temperature at the upper half of PCHX and under-predicts the temperature at the lower half of PCHX.

### 4.3 Fluid Temperature inside PCHX

Figure 5 shows the fluid temperatures at tube centre (measurement point C in Fig. 1(c)) and at the vicinity of tube bottom (measurement point E) along the PCHX length. In the experiment, while the saturated temperatures were measured at the tube centre along the PCHX length, the subcooled temperatures were measured at the vicinity of tube bottom (measurement point E). Therefore a stratified flow appeared along the whole length of tube. As the steam flowed toward the outlet, the condensate temperature gradually decreased. The temperature of bottom region at the bent region (measurement point 6 in Fig. 1(b)) jumped to about saturated
temperature due to the thermal mixing, and then the condensate temperature gradually decreased along the tube.

As shown in Fig. 5, both codes provide good estimate for the steam temperatures. For the condensate temperature, the TRACE provides reasonable temperature trend. However, the TRACE is incapable of reproduce the temperature jump at the bent region due to the fact that the one-dimensional system code does not simulate the thermal-mixing. The difference in condensate temperature between TRACE prediction and the data at the lower part of PCHX is about 20K.

The MARS-KS result for the condensate temperature show the significant difference between the predicted values and data. The MARS-KS prediction shows very little difference in condensate temperatures throughout the PCHX, and fails to predict the decreasing condensate temperature along the tube length. It under-predicts the condensate temperature at the upper part of PCHX and over-predicts the temperature at the tube outlet region.

4.4 Condensation Rate

Figure 6 shows the MARS-KS and TRACE predictions for the mass flow rates of steam along the PCHX length. The values are normalized to the injection flow rate of steam. The TRACE prediction shows larger amount of steam condensation than the MARS-KS prediction. The MARS-KS shows that the steam flow rate is almost linearly decreased along the PCHX length. However, the TRACE results show that the condensate rate at the upper part of PCHX is larger than at the lower part of PCHX. While the TRACE result shows that about 91.2% of injected steam flow is condensed inside PCHX, the MARS-KS result shows about 88.2% of steam flow is condensed.

5 CONCLUSIONS

The applicability of condensation model of MARS-KS and TRACE codes to the nearly-horizontal condensing tube are assessed against the KAERI PASCAL test. The calculated results of heat flux, inner wall surface temperature, fluid temperature inside PCHX, and steam mass flow rate are compared with the experimental data. The MARS-KS generally under-predict the heat fluxes. The TRACE, on the other hand, overestimates the heat flux by about 30% at the PCHX inlet.
region and under-predicts it at the lower half of PCHX. The MARS-KS does a good job of approximating the temperature distribution of inner surface. However, the TRACE overestimates the inner wall surface temperature at the upper half of PCHX and under-predicts the temperature at the lower half of PCHX. Both codes provide good estimate for the steam temperatures. While the TRACE provides reasonable trend of condensate temperature, the MARS-KS fails to predict the decreasing condensate temperature along the tube length. While the TRACE result shows that about 91.2% of injected steam flow is condensed inside PCHX, the MARS-KS result shows about 88.2% of steam flow is condensed.

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