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ANALYSIS OF AIR-WATER TWO PHASE NATURAL CIRCULATION FLOW BY USING RELAP5/MOD3

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ABSTRACT

Air-water two phase natural circulation flow in the T-HERMES (Thermo-Hydraulic Evaluation of Reactor cooling Mechanism by External Self-induced flow)-1D experiment has been verified and evaluated by RELAP5/MOD3 computer code. The RELAP5 results have shown that an increase in the coolant inlet area leads to an increase in the water circulation mass flow rate. However, the water outlet area has no influence on the water circulation mass flow rate. As the coolant outlet moves to a lower position, the water circulation mass flow rate decreases. The water level has no influence on the water circulation mass flow rate.

INTRODUCTION

The IVR (In-Vessel corium Retention) through the ERVC (External Reactor Vessel Cooling) is known to be an effective means to maintain the integrity of the reactor pressure vessel during a severe accident in a nuclear power plant [1 - 4]. This measure has been adopted in some low-power reactors such as the AP600 and the Loviisa nuclear power plants [5, 6] and in the high-power reactor of the APR (Advanced Power Reactor) 1400 [7] as an accident management strategy for a severe accident mitigation with the aim of retaining the molten core material in-vessel. However, it is known that the thermal margin between the volumetric heat source in the corium pool of the reactor's lower plenum and the heat transfer rate from the lower reactor vessel wall to the coolant in the reactor cavity is not sufficient enough for a high-power reactor like the APR1400, unlike the low-power reactors of the AP600 and the Loviisa nuclear power plants. Therefore, an enhancement of the IVR through the ERVC has been considered extensively in the detailed design stage of the APR1400.

Some design improvements of the reactor vessel/insulation configuration to increase the heat removal rate by a two-phase natural circulation flow between the outer reactor vessel wall and the insulation material have been proposed to increase the thermal margin of the IVR in the APR1400. The lower heated spherical reactor vessel wall induces a two-phase natural circulation flow in the annular gap between the outer reactor vessel wall and the insulation material. In general, an increase in the mass flow rate of the coolant leads to an increase in the CHF (Critical Heat Flux) at the lower outer reactor vessel wall [8, 9]. This results in an increase of the wall heat removal rate caused by the convective coolant circulation flow. This circulation flow is dependent on the configuration of the reactor vessel insulation material, such as the water inlet area and position, the coolant (water and steam) outlet area and position, and the gap geometry between the reactor vessel and the insulation material. For this reason, a detailed study of the coolant flow in the reactor cavity during severe accidents is necessary to evaluate the IVR through the ERVC in the APR1400.

As a part of a study on the thermal hydraulic behavior in the reactor cavity under the ERVC in the APR1400, a large-scale air injection experiment called HERMES-HALF (Hydraulic Evaluation of Reactor cooling Mechanism by External Self-induced flow-HALF scale) has been performed to measure the two-phase natural circulation mass flow rate through the annulus gap between the reactor vessel and the insulation material at KAERI (Korea Atomic Energy Research Institute) [10]. The HERMES-HALF is a non-heating of an air injection and a half-scaled three-dimensional experimental study on a two-phase natural circulation through an annular gap between the reactor vessel and the insulation. The behaviors of the two-phase natural circulation flow in the insulation gap are observed, and the liquid mass flow rates driven by the natural circulation loop are measured.

A T-HERMES-1D study has been launched to evaluate the property and geometry scaling of the HERMES-HALF experimental results. The T-HERMES-1D is a one-dimensional non-heating / heating experimental study on a two-phase natural circulation through the annular gap between the reactor vessel and the insulation under the external vessel cooling during a severe accident. For the property scaling, the non-heating results should be compared with the heating experimental ones. That is, a coolant sub-cooling effect, such as a steam bubble behavior and a flashing effect, and natural circulation flow instability should be evaluated. For the geometry scaling, the 1-D phenomena should be compared with the 3-D ones of HERMES-HALF. Non-heating of the air injection had already been performed, but a heating experiment will be performed soon in the HERMES-1D test facility. In this study, an air-water two phase natural circulation flow in the T-HERMES experiment has been evaluated to verify and evaluate the experimental results by using RELAP5/MOD3 computer code [11].

HERMES-1D TEST FACILITY

Fig.1 shows a schematic diagram of the T-HERMES-1D test section. The height of the main test section is a half scaled-down reactor vessel and an insulation part which is prepared by utilizing the results of a scaling analysis proposed by Cheung[12] to simulate the APR1400 reactor and insulation system. The width of the main test section is 100 mm, therefore the T-HERMES-1D has a rectangular cross section. The facility is design to perform both direct heating and non-heating experiments by changing the bottom region of the reactor vessel wall. To measure the flow void fraction, three differential pressure transmitters are installed on the test section wall.

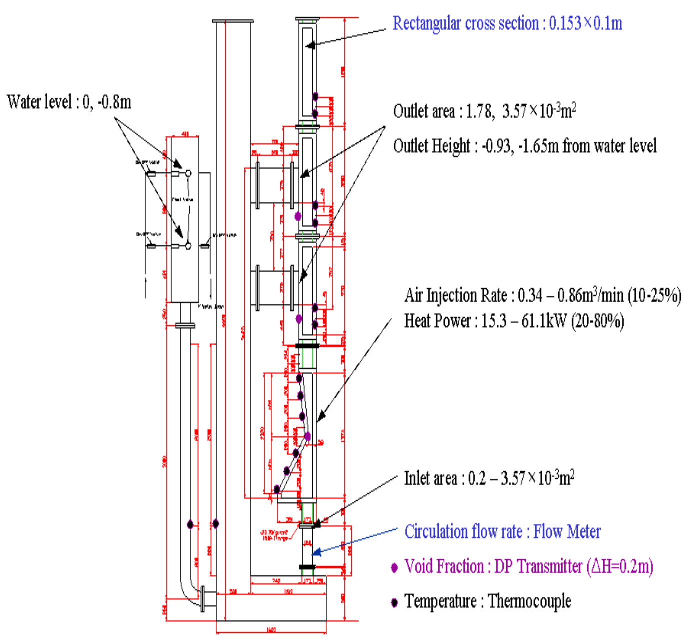

Figure 1 Schematic of the T-HERMES-1D test section

The water inlet pressure condition is controlled by changing the water head level in the reservoir. To maximize the natural circulation flow, water inlets and outlet ports exist in the insulation. The natural circulation flow rate is measured by the turbine flow meter which is installed on the bottom of the inlet hole.

RELAP5 COMPUTER CODE DESCRIPTION AND INPUT MODEL

Fig. 2 shows the RELAP5/MOD3 input model for the T-HERMES-1D. The RELAP5/MOD3 computer code was used in this analysis. The light water reactor (LWR) transient analysis code, RELAP5, was developed at the Idaho National Engineering and Environmental Laboratory (INEEL) for the U. S. Nuclear Regulatory Commission (NRC). The code includes the analyses required to support a rulemaking, the licensing audit calculations, an evaluation of the accident mitigation strategies, an evaluation of the operator guidelines, and an experiment planning analysis. RELAP5 is a highly generic code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for a simulation of a wide variety of hydraulic and thermal transients in both nuclear and non nuclear systems involving mixtures of steam, water, noncondensable gas, and solute.

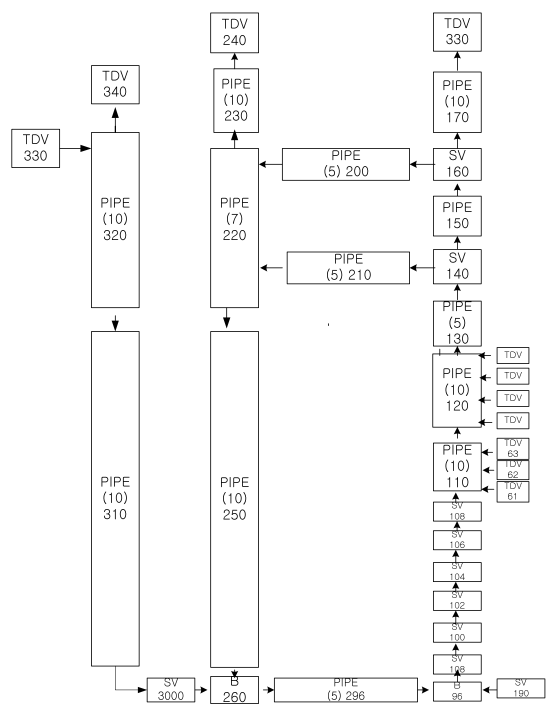

Figure 2 RELAP5/MOD3 input model for the THERMES-1D.

In the RELAP5/MOD3 input model for the THERMES-1D, the annular gap between the vessel and the insulation is simulated by PIPE 110 and 120. Air injectors are simulated by 6 Time Dependent Junctions. The air source was simulated by using 7 Time Dependent Volumes. The water supplied from the outer water source, which is simulated by Time Dependent Volume No. 330, flows through the water supply tank, which is simulated by PIPE No. 320 and 310. The water circulation flow path is simulated by PIPE 220, 250, and 296.

In all the simulations, the initial conditions are assumed to be an ambient pressure and no coolant mass flow rate. The coolant level in the water supply tank maintains constant value by an outer water source. The calculation parameters for the HERMES-1D are a water inlet area from 0.0002 to 0.00357 m^2, a water outlet area from 0.001 to 0.005 m^2, an air injection mass flow rate from 5 to 100 % of the air injection rate which is equivalent to the total heat flux distribution in the lower reactor vessel, a water level from -1.0 m to the normal value, and a water outlet position between low and high. A steady state simulation of approximately 2,000 seconds has been performed for one case.

RESULTS AND DISCUSSION

Fig. 4 shows the RELAP5/MOD3 results for the water circulation mass flow rate as a function of the time. In this condition, the air injection mass flow rate, the water inlet area, the water outlet area and the water outlet position with regards to the water level are 30 % of the total air injection mass flow rate, 0.00357 m^2, 0.00357 m^2, and 0 m, respectively. As the time increases, the water circulation mass flow rate maintains a constant value of approximately 2.1 kg/s.

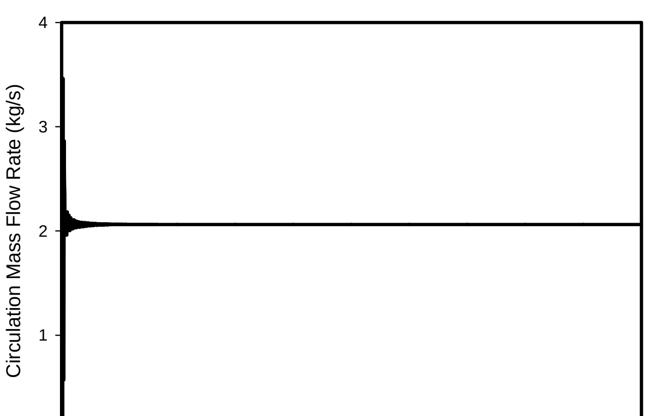

Figure 3 RELAP5/MOD3 results for the water circulation mass flow rate as time increase.

Fig. 4 shows a comparison of the RELAP5/MOD3 results on the water circulation mass flow rate with the experimental data. The RELAP5/MOD3 results on the water circulation mass flow rate are very similar to the experimental data. An increase in the air injection rate to 50 % of the total heat flux leads to an increase in the water circulation mass flow rate. However, an increase in the air injection rate from 50 % to 100 % of the total heat flux leads to a decrease in the water circulation mass flow rate, because of the small water inlet area.

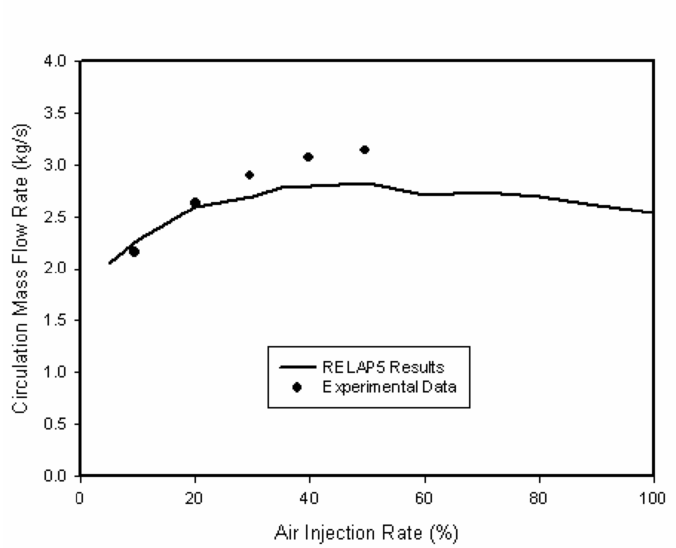

Figure 4 Comparison of the RELAP5/MOD3 results with the experimental data for the water circulation mass flow rate as a function of the air injection rate.

Figs. 5&6 show the local pressure and the local void fraction as function of the height and the air injection mass flow rate, respectively. In this condition, the air injection mass flow rate, the water inlet area, the water outlet area and the water outlet position with regards to the water level are 30 % of the total air injection mass flow rate, 0.00357 m^2, 0.00357 m^2, and 0 m, respectively.

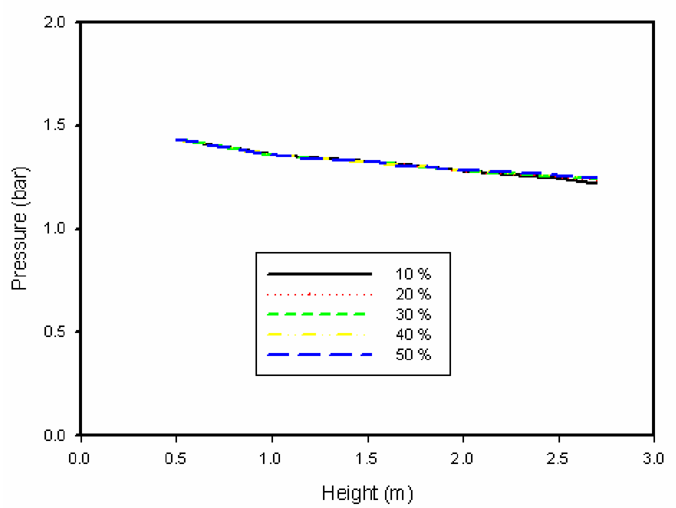

Figure 5 RELAP5/MOD3 results for the local pressure as a function of the air injection mass flow rate.

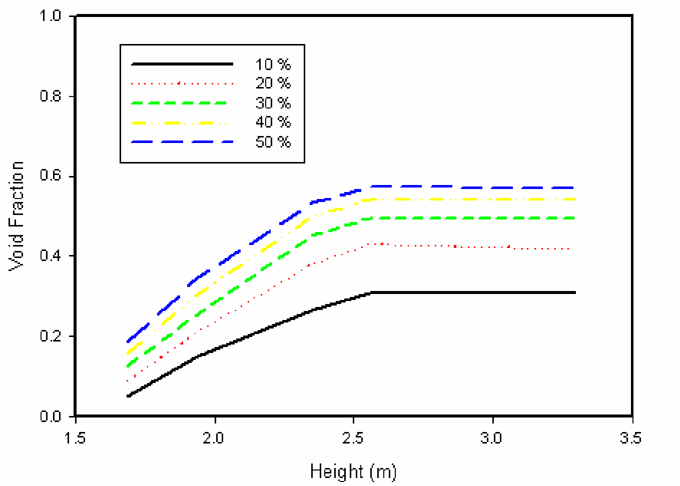

Figure 6 RELAP5/MOD3 results for the void fraction distribution as a function of air the injection mass flow rate.

As the height increases, the local pressure decreases. As the height increases in the air injection part, the void fraction increases. However, the void fraction in the upper part of the air injector maintains a constant value. An increase in the air injection mass flow rate leads to an increase in the local void fraction, but it does not have an influence on the local pressure.

Fig. 7 shows the RELAP5/MOD3 results for the water circulation mass flow rate with a change of the water inlet area from 0.0002 to 0.00375 m^2. In this condition, the water outlet area and the water outlet position with regards to the water level are 0.00375 m^2, and 0 m, respectively.

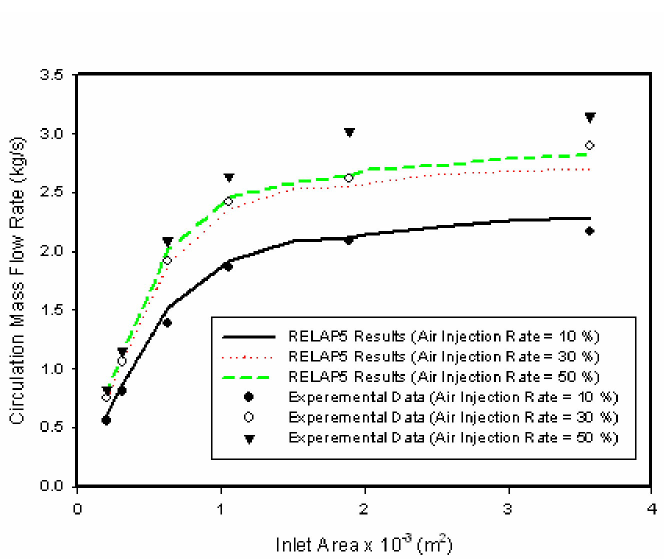

Figure 7 Comparison of the RELAP5/MOD3 results with the experimental data for the water circulation mass flow rate as a function of the inlet area.

As shown in the Fig. 7, the RELAP5/MOD3 results are very similar to the experimental results. In general, an increase in the water inlet area leads to an increase in the water circulation mass flow rate. An increase in the water inlet area from 0.0002 m^2 to 0.001 m^2 leads to a rapid increase in the water circulation mass flow rate. However, an increase in the water inlet area from 0.0002 to 0.00357 m^2 leads to a gradual increase in the water circulation mass flow rate.

Fig. 8 shows the RELAP5/MOD3 results for the water circulation mass flow rate with a change of the water outlet area from 0.001 to 0.005 m^2. In this condition, the water inlet area and the water outlet position with regards to the water level are 0.001052 m^2, and 0 m, respectively. The RELAP5/MOD3 results are very similar to the experimental results. The water outlet area does not have an influence on the water circulation mass flow rate.

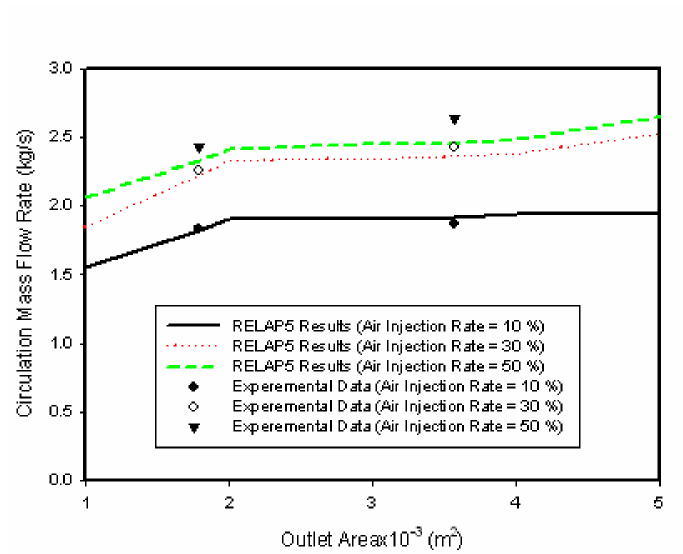

Figure 8 Comparison of the RELAP5/MOD3 results with the experimental data for the water circulation mass flow rate as a function of the outlet area

Figs. 9 & 10 shows water out position effect on the water circulation mass flow rate with a change of the air injection mass flow rate for a low and high water outlet position, respectively. In this condition, the water outlet area and the water outlet position with regards to the water level are 0.00375 m^2, and 0 m, respectively. The RELAP5/MOD3 results are very similar to the experimental results. The water circulation mass flow rate in the high position case is higher than that of the low position case.

RELAP5/MOD3 results are very similar to the experimental results. The water level does not have an influence on the water circulation mass flow rate.

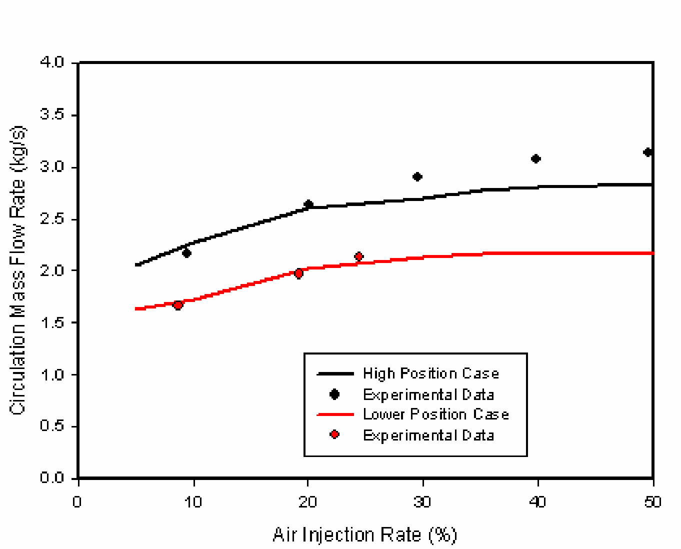

Figure 9 Water outlet position effect on the water circulation mass flow rate at a large inlet area.

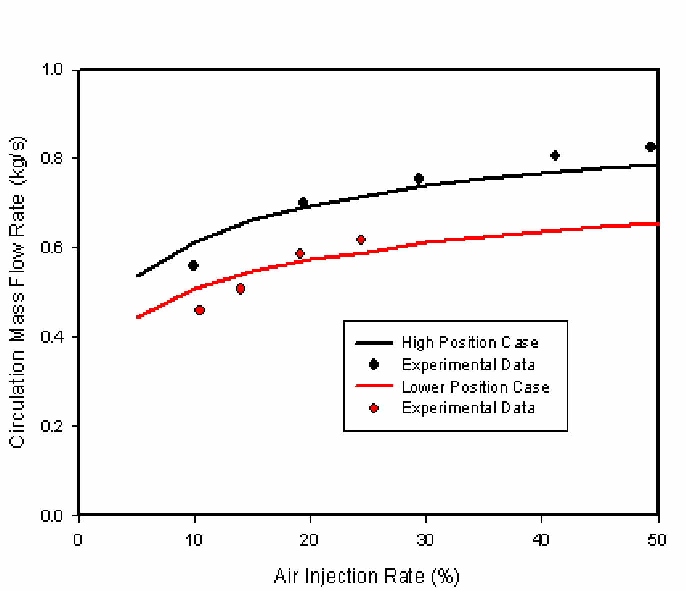

Figure 10 Water outlet position effect on the water circulation mass flow rate at a small inlet area.

Fig. 11 shows the RELAP5/MOD3 results for the water circulation mass flow rate as a function of the water level. The zero level means the normal value in the reactor cavity. In this condition, the water inlet area, the water outlet area and the air injection mass flow rate are 0.0002 m^2, 0.0037515 m^2 and 30 % of the total air injection mass flow rate, respectively. The RELAP5/MOD3 results are very similar to the experimental results. The water level does not have an influence on the water circulation mass flow rate.

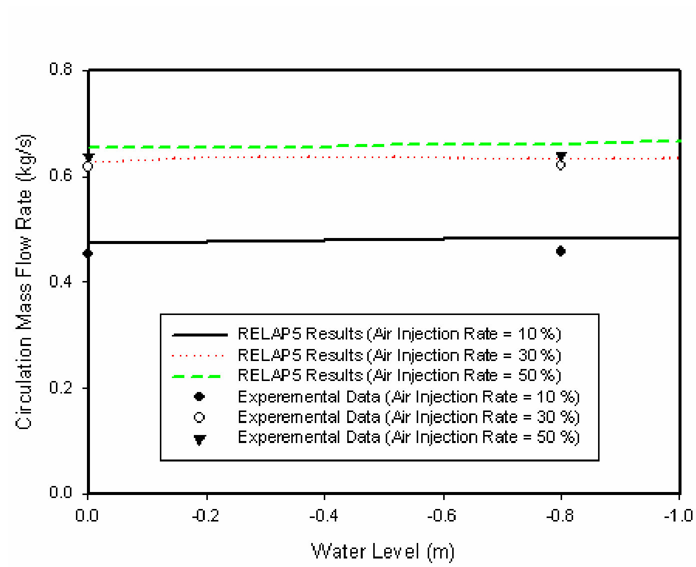

Figure 11 Water level effect on the water circulation mass flow rate.

CONCLUSION

Air-water two phase natural circulation flow in the T-HERMES-1D experiment has been evaluated by using the RELAP5/MOD3 computer code. The RELAP5 results on the water circulation water mass flow rate are very similar to the experimental results. The RELAP5 results have shown that an increase in the air injection rate to 50 % of the total heat flux leads to an increase in the water circulation mass flow rate. However, an increase in the air injection rate from 50 % to 100 % leads to a decrease in the water circulation mass flow rate. As the height increases in the air injection part, the void fraction increases. However, the void fraction in the upper part of the air injector maintains a constant value. An increase in the air injection mass flow rate leads to an increase in the local void fraction, but it has no influence on the local pressure. An increase in the coolant inlet area leads to an increase in the water circulation mass flow rate. However, the water outlet area does not have influence on the water circulation mass flow rate. As the coolant outlet moves to a lower position, the water circulation mass flow rate decreases. The water level has no influence on the water circulation mass flow rate. Detailed analysis of the material scaling of the air-water and steam-water, and the geometry scaling of a half and a full height is necessary to apply these experimental results to an actual APR1400.

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