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ANALYSIS OF TWO PHASE NATURAL CIRCULATION FLOW IN THE REACTOR CAVITY UNDER EXTERNAL REACTOR VESSEL COOLING

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Abstract

As part of a study on a two-phase natural circulation flow between the outer reactor vessel and the insulation material in the reactor cavity under an external reactor vessel cooling of APR (Advanced Power Reactor) 1400, a K-HERMES-HALF (Hydraulic Evaluation of Reactor cooling Mechanism by External Self-induced flow-HALF scale) experiment was performed at KAERI (Korea Atomic Energy Research Institute) using an air injection method. This experiment was analyzed to verify and evaluate the experimental results using the RELAP5/MOD3 computer code. In addition, the geometry scaling on full height & full sector, and a material scaling between air-water and steam-water two phase natural circulation flow, have been performed for an application of the experimental results to an actual APR1400. The RELAP5/MOD3 results on the water circulation mass flow rate are very similar to the experimental results, in general. The water circulation mass flow rate of the full height & full sector case is approximately 7.6-times higher than that of the K-HERMES-HALF case. The water circulation mass flow rate of the air injection case is 20-50 % higher than that of the steam injection case at 20 % of the injection rate.

Introduction

The IVR (In-Vessel corium Retention) through ERVC (External Reactor Vessel Cooling) is known to be an effective means for maintaining the integrity of the reactor pressure vessel during a severe accident in a nuclear power plant [1, 2]. This measure has been adopted in some low-power reactors such as the AP600 & AP1000, and the Loviisa nuclear power plants [3, 4] as a design feature, and in the high-power reactor of the APR (Advanced Power Reactor) 1400 as an accident management strategy for severe accident mitigation with the aim of retaining the molten core material in-vessel [5]. The APR1400 is an evolutionally advanced light water reactor based on the experience and technology of the KSNP (Korean Standard Nuclear Power Plant). 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 for the high-power reactor of the APR 1400, unlike the low-power reactors of the AP600 and the Loviisa nuclear power plants. Therefore, an enhancement of the IVR through the ERVC is considered extensively in the detailed design stage of the APR 1400.

Some design improvements of the vessel/insulation configuration for increasing 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 for the IVR in the APR1400. The heated lower 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 [6]. 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, 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 part of a study on the thermal hydraulic behavior in the reactor cavity under the IVR-ERVC in the APR1400, a large-scale air injection experiment of the K-HERMES-HALF (Hydraulic Evaluation of Reactor cooling Mechanism by External Self-induced flow-HALF scale) was performed to measure the two-phase natural circulation mass flow rate through the annulus gap between the outer reactor vessel and the insulation material, the bubble dynamics, and the void fraction distribution along the annulus at KAERI (Korea Atomic Energy Research Institute). Steady-state simulations of this experiment have been performed to verify the experimental data and to investigate the coolant behavior between the reactor vessel wall and the insulation material using the RELAP5/MOD3 computer code [7] in the present study. This large-scale experiment using a half-height and half-sector model of the APR1400 uses a non-heating method of the air injection. For this reason, it is necessary to evaluate the geometry scaling on full height & full sector, and a material scaling between air-water and steam-water two phase natural circulation flow, for an application of the experimental results to an actual APR1400. In the geometry scaling, two cases, a half height & half sector, and a full height & full sector, have been performed. In the material scaling, two cases, an air injection and steam injection, have been performed to compare the air injection experimental results with the steam injection case.

1. K-HERMES Test Facility

K-HERMES-HALF tests using a half-height and half-sector model of the APR1400 were performed to observe and evaluate the two-phase natural circulation phenomena through the annulus gap between the outer reactor vessel and the vessel insulation material, and finally to propose the enhanced designs for the coolant inlets and upper steam venting slots in the reactor vessel insulator of the APR1400. Since the heating method is very difficult and expensive for a large scale and three-dimensional spherical test section, the non-heating method of an air injection was decided upon in this test. In the APR1400, penetration of 61 ICI (In-Core Instrumentation) nozzles and 4-shear keys are installed in the reactor vessel. For a natural circulation flow path, it is suggested that the water inlets and venting slots should be installed in the insulation wall. A schematics diagram of the K-HERMES-HALF experimental facility is shown in Fig. 1. The facility consists of 3 parts, namely, a main test section, an air supply system, and a water recirculation system. 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 [8] to simulate the APR1400 reactor and insulation system. By a scaling analysis, the vessel diameter, height, water level, shear key size, and ICI nozzle diameter are linearly scaled-down to half scale. The radius of the vessel is 1.269 m, and the annular gap size is 0.153 m, which is equivalent to the 0.216 m gap in the APR1400 reactor. Due to the conical configurations of the insulation material, the minimum gap region between the reactor vessel and the insulation is located at 56.6° based on the

vertical axis of the reactor vessel. The minimum gap size is set at 0.063 m. The annular and minimum gap sizes are $\sqrt{1/2}$ scaled-down.

By considering the symmetrical feature of the reactor vessel and the insulation system, the main part is only simulated for the half section of the APR1400 reactor. For visualization, windows made of polycarbonate are installed on the annular insulation part. The ICI nozzles and shear keys are also simulated in this test section. A water reservoir is prepared to realize an equivalent pressure condition of the lower water inlet. That is, the inlet pressure condition is controlled by changing the water head level in the reservoir. For maximizing the natural circulation flow, water inlets and outlet ports exist in the insulation. To simulate the water inlets, there are 23 holes in the central part, and 35 holes in the circumferential part of the water inlet plate. Each hole with a diameter of 75 mm can be plugged; therefore, the areas and positions of the inlets are adjustable.

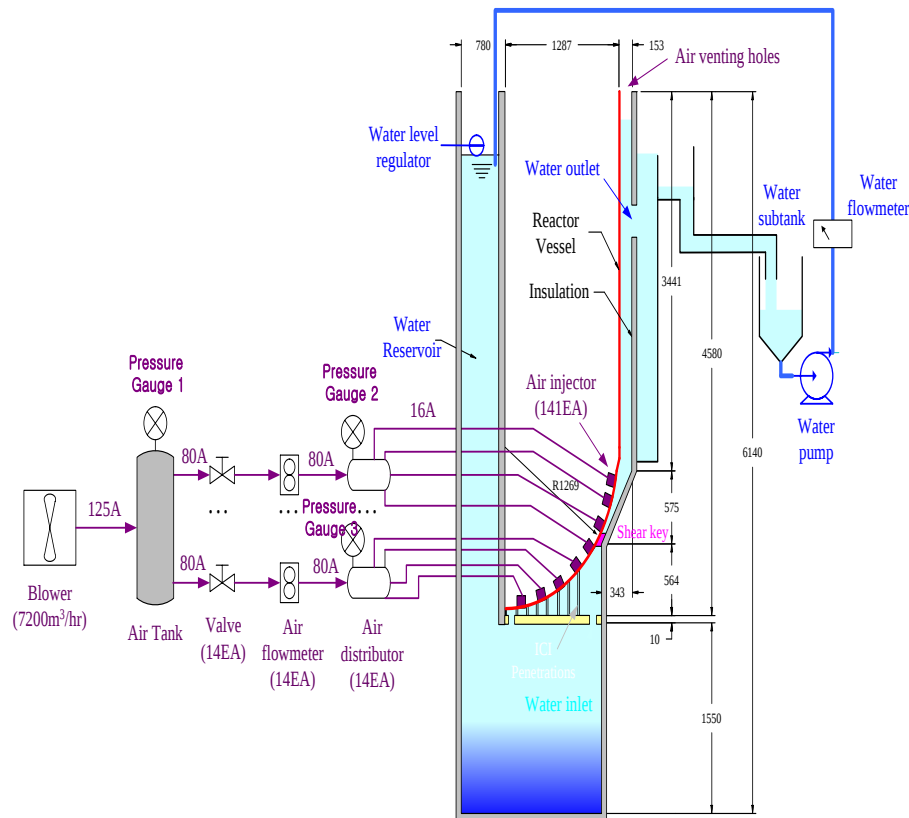


Figure 1 Schematic diagram of the K-HERMES-HALF experimental facility.

The natural circulation flow is discharged through three outlets in the insulation. The three outlets have rectangular shapes, which are located at a 45, 90, and 135 degrees of longitude on the annular section of the reactor vessel wall. The area and vertical position of each outlet are adjustable. The flooded water through the outlet is accumulated in the sub-tank, and the water in the sub-tank is then transferred to the water reservoir by a water pump. Since the flooded water through each outlet port is independently re-circulated by the water recirculation system, the natural circulation flow in the experimental section has no effect on the water recirculation system. The recirculation flow rate is measured by a water flow meter which is installed on the recirculation water pipe between the pump

and water reservoir.

In the K-HERMES-HALF experiment, a two-phase flow is not generated by a direct heating method but by a non-heating method of air injection. For the non-heating experiment, an equivalent amount of air is injected through 141 air injectors by an air supply system. The air is generated by a blower system, and the air path branches off from 14 air distributors by air ducts with an 80 mm inner diameter. The air flow rate toward each air distributor is controlled and measured by an air control valve and air flow meter. The air passing by the air distributors is supplied to the gap region through 141 air injectors installed on the lower head reactor vessel wall. Each air injector is made of a G2 glass filter, which generates fine air bubbles. The equivalent air injection diameter from each air injector is 70 mm. The experimental heat distribution for calculating the air injection rate is obtained using the MAAP4 computer code, and is shown in Fig. 2. Because of the higher heat flux in the top region of the vessel, more injectors are arranged in the top region of the lower head vessel. The injected air flow-rate was determined using the mass and energy balance between the heat flux distribution and gas injection rate.

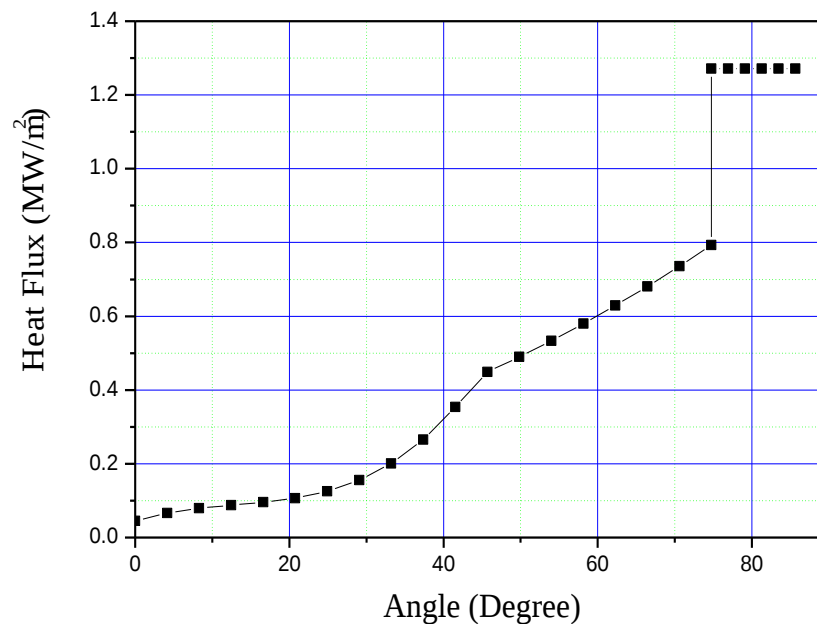


Figure 2 Heat flux distribution along the latitudinal position of the lower head vessel wall using the MAAP4 computer code.

2. RELAP5 Input Model

The RELAP5/MOD3 computer code was used in this simulation. A light water reactor (LWR) transient analysis code, RELAP5, was developed at the Idaho National Laboratory (INL) for the U. S. Nuclear Regulatory Commission (NRC). The code includes the analyses required to support rulemaking, licensing audit calculations, evaluation of accident mitigation strategies, evaluation of 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, and solute. Figure 3 shows the RELAP5/MOD3 input model for an analysis of the K-HERMES-HALF experiment and scaling.

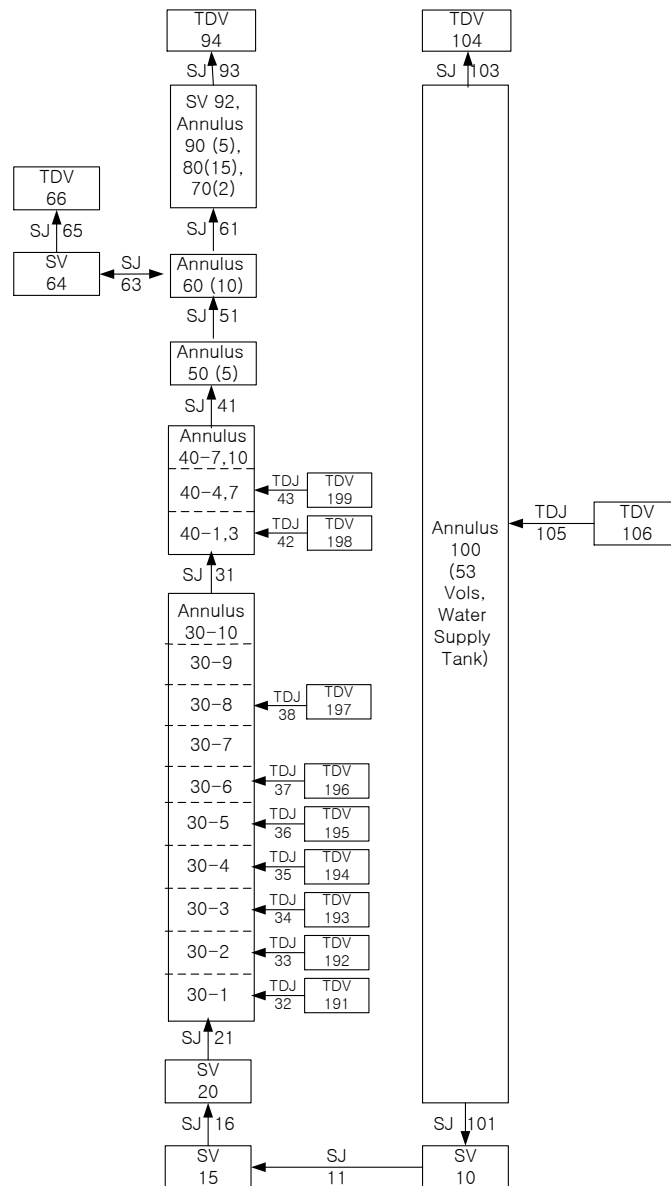


Figure 3 RELAP5/MOD3 input models for analysis of the K-HERMES-HALF experiment and scaling.

In the RELAP5 input model, the water supplied from the outer water source, which is simulated by Time Dependent Volume No. 106, flows through the water supply tank, which is simulated by Annulus No. 100, as well as the gap between the outer reactor vessel and the vessel insulation, which is simulated by Annulus No. 30, 40, and 50, to the outer tank, which is simulated by Time Dependent Volume No. 66. The air or steam was injected through 9 Time Dependent Junctions. A water inlet, air outlet, and water outlet were simulated using three Single Junctions of No. 16, 63, and 93, respectively. The air source was simulated by using 9 Time Dependent Volumes of No. 191-199. A cylindrical gap was simulated by Annulus No. 60, 70. The heat flux from the spherical reactor vessel to the outer

coolant was simulated by the steam and air injection mass flow rates. In all simulations, the initial conditions are assumed to be an ambient pressure and no water mass flow rate, and the supplied water temperature is maintained at 20 °C. In the geometry scaling analysis, water inlet area, water outlet area, and air (or steam) outlet area are shown in Table 1. The area of the full height & full sector case is the same in the APR1400.

Table 1. Area of water inlet, water outlet, and air (or steam) outlet in the scaling analysis.

	K-HERMES -HALF	Full Height & Half Sector	Full Height & Full Sector
Water Inlet Area (m ²)	0.317	0.897	1.793
Water Outlet Area (m ²)	0.297	0.840	1.680
Air (or Steam) Outlet Area (m ²)	0.216	0.840	1.680

3. RELAP5 Results and Discussion

3.1 RELAP5 Results on the K-HERMES Test

Figure 4 shows the RELAP5/MOD3 results on the water circulation mass flow rate as a function of time. In this condition, the air injection mass flow rate, water inlet area, and water outlet area are 13.0 % of the total heat flux distribution, 0.317 m² and 0.297 m², respectively. As the time increases, the water circulation mass flow rate maintains a constant value of approximately 330 kg/s. The mass flow rate through the air outlet hole is very small due to the air venting. A uniform oscillatory coolant flow was generated in the upper part of the test section.

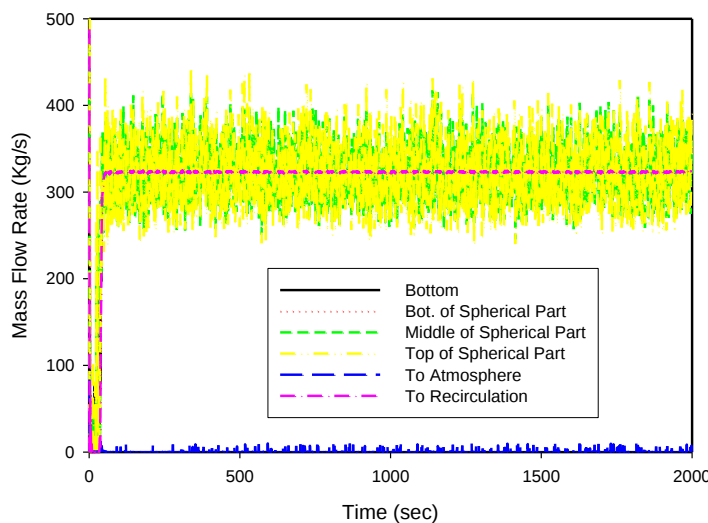


Figure 4 RELAP5/MOD3 results on the water circulation mass flow rate.

Figures 5 and 6 show the local pressure and local void fraction as a function of time, respectively. As the time increases, the local pressure maintains a constant value with a small oscillation. The local pressure in the bottom of the test section maintains approximately 1.35 bars. As the time increases, the void fraction of the cylindrical and spherical parts maintains a constant value of 0.6 and 0.18, respectively.

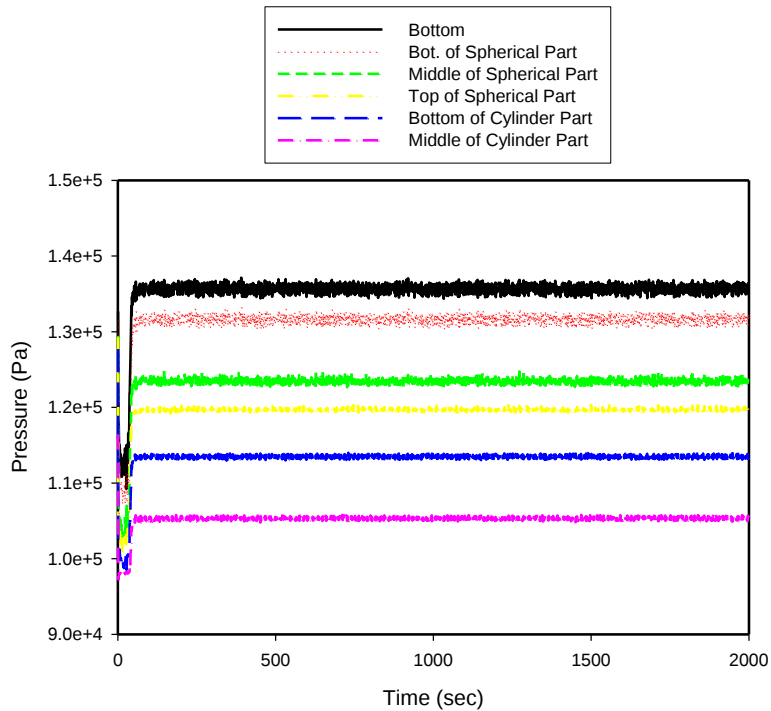


Figure 5 RELAP5/MOD3 results on the local pressure.

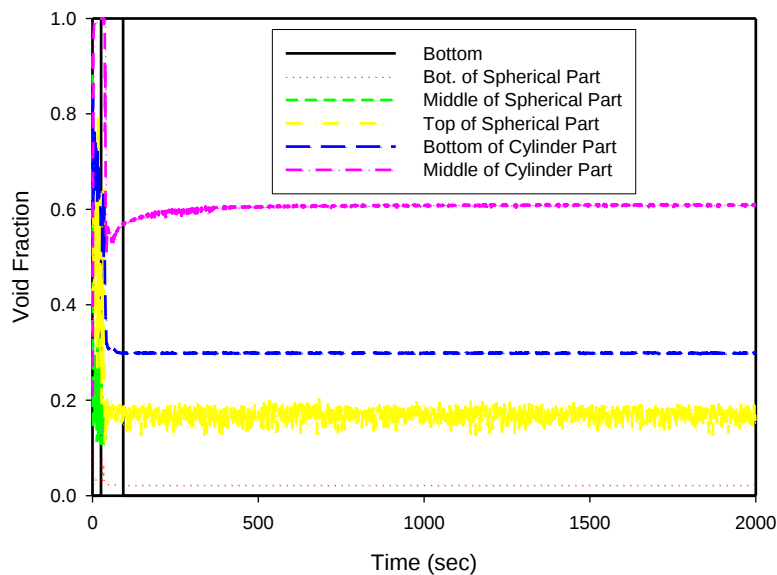


Figure 6 RELAP5/MOD3 results on the local void fraction.

Figure 7 shows a comparison of the RELAP5/MOD3 results with the experimental results on the water circulation mass flow rate as a change in air injection mass flow rate. In this condition, the water inlet area and water outlet area are 0.0264 m² and 0.297 m², respectively. The RELAP5/MOD3 results are very similar to the experimental results. An increase in the air injection mass flow rate leads to an increase in the water circulation mass flow rate. In the high air injection case, the water circulation mass flow rate does not increase, because of oscillatory flow.

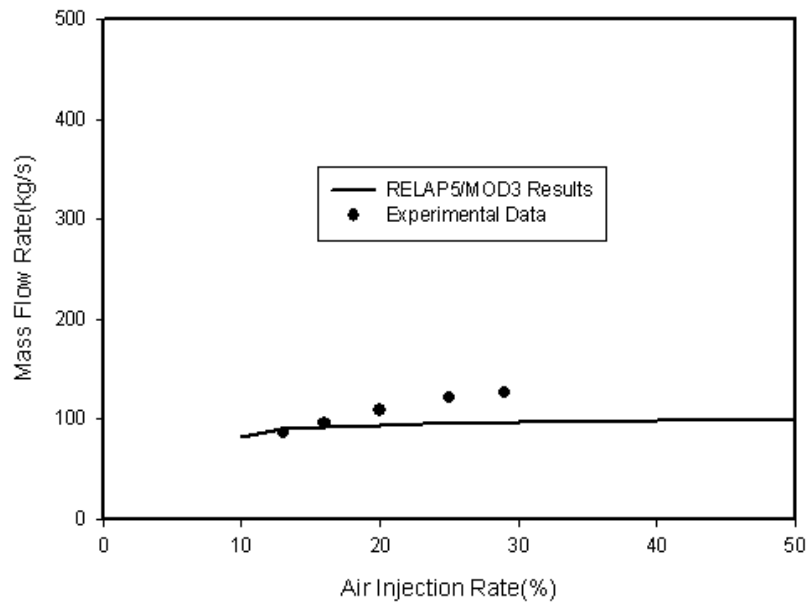


Figure 7 RELAP5/MOD3 results of the water circulation mass flow rate as a function of air injection mass flow rate.

Figure 8 shows a comparison of the RELAP5/MOD3 results with test results on the local void fraction. The minimum gap region is the 57 ° from the reactor vessel bottom, as shown in Figure 1. An increase in the air injection mass flow rate leads to increases in the local pressure and a pressure difference between the lower and upper parts, which results in an increase in the water circulation mass flow rate. In general, the RELAP5/MOD3 results are very similar to the experimental results.

3.2 RELAP5 Results on the Scaling Analysis

Table 2 shows the RELAP5 results on the water circulation mass flow rate in the geometry scaling analysis. The water circulation mass flow rate of the full height & half sector case is 3.8-4.0 times higher than that of the K-HERMEL-HALF case due to the height increases. The water circulation mass flow rate of the full height & full sector case is approximately 7.6-times higher than that of the K-HERMEL-HALF case due to the height and sector increases. Table 3 shows the RELAP5 results on the water circulation mass flow rate in the material scaling analysis; the water circulation mass flow rate of the air injection case is 20-50 % higher than that of the steam injection case at 20 % of the injection rate, due to steam condensation and the density difference between the air and the steam. The density of the air is two times higher than that of the steam. The steam is condensed by supplied sub-cooling water in

the steam injection case, but not in the air injection case. However, the water circulation mass flow rate of the steam injection case is higher than that of the air injection case at the 100 % injection rate due to oscillatory flow in the air injection case.

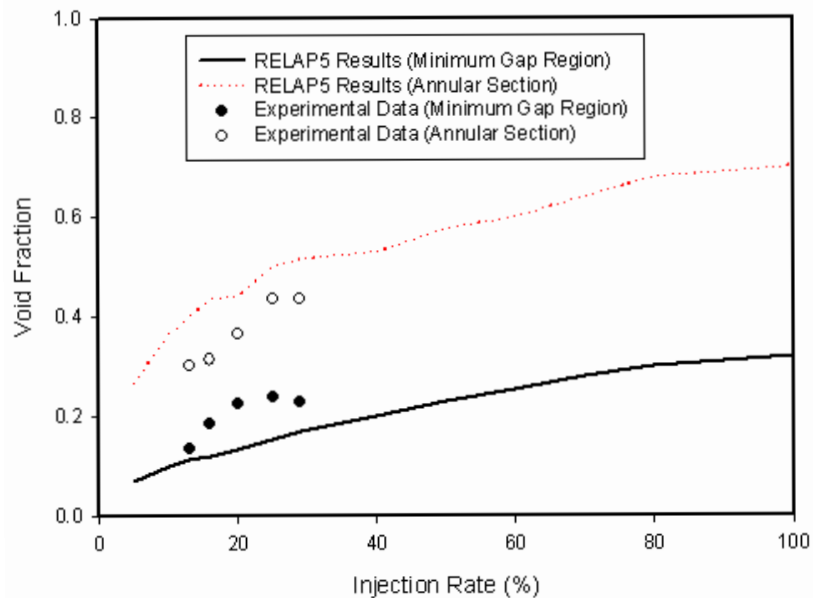


Figure 8 RELAP5/MOD3 results of the local void fraction as a function of air injection mass flow rate.

Table 2. RELAP5 results of the water circulation mass flow rate in the geometry scaling analysis.

Air Injection Rate	K-HERMES -HALF (kg/s)	Full Height & Half Sector (kg/s)	Full Height & Full Sector (kg/s)
100 %	253.5	940.3	1295.8
50 %	288.0	1120.8	2193.5
20 %	277.7	1110.9	2113.8

Table 3. RELAP5 results on the water circulation mass flow rate in the material scaling analysis.

Injection Rate	K-HERMES-HALF (kg/s)		Full Height & Half Sector (kg/s)		Full Height & Full Sector (kg/s)	
	Air	Steam	Air	Steam	Air	Steam
100 %	253.5	273.9	940.3	1050.3	1295.8	2080.4
50 %	288.0	270.7	1120.8	958.7	2193.5	1625.8
20 %	277.7	191.3	1110.9	906.4	2113.8	1595.7

Figures 9 and 10 show the RELAP5/MOD3 results of the local pressure in the K-HERMES-HALF case and full height & full sector case. The local pressure of the full height & full sector case is higher than that of the K-HERMES-HALF case due to the water depth.

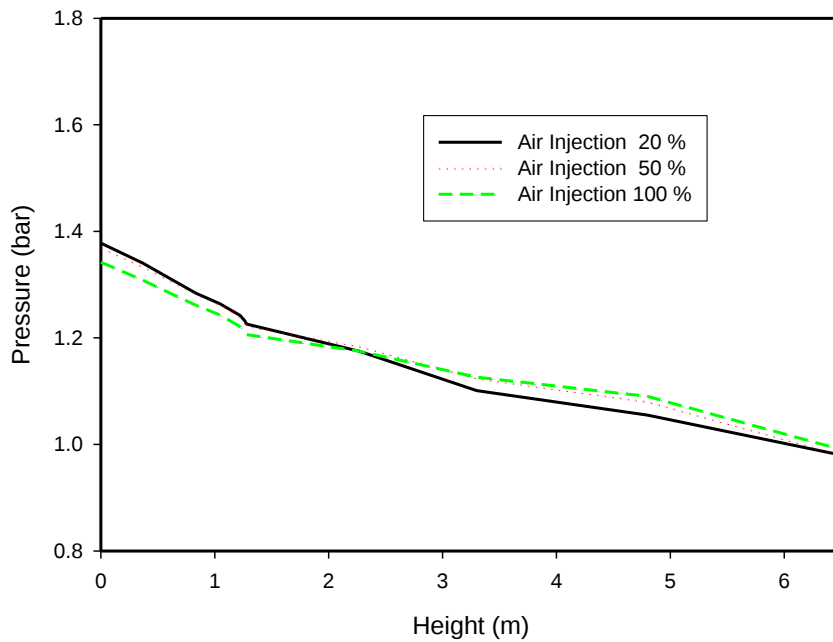


Figure 9 RELAP5 results of the local pressure in the K-HERMES-HALF case.

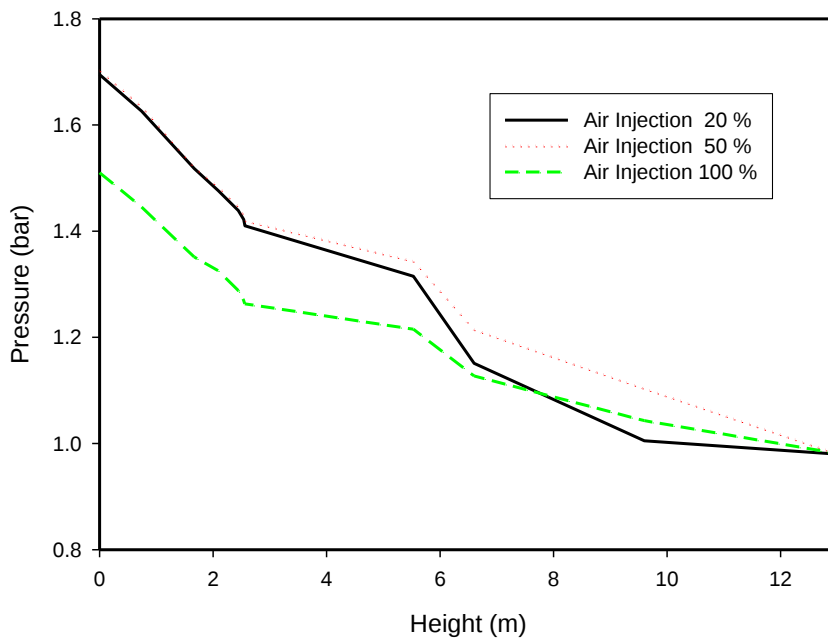


Figure 10 RELAP5 results of the local pressure in the full height and full sector case.

As shown in Fig. 11, the local void fraction of the air injection case is higher than that of the steam injection case at the upper part of the test section due to steam condensation. In 20 % steam injection case, the void fraction of the upper part reaches 1.0 than other cases due to steam condensation.

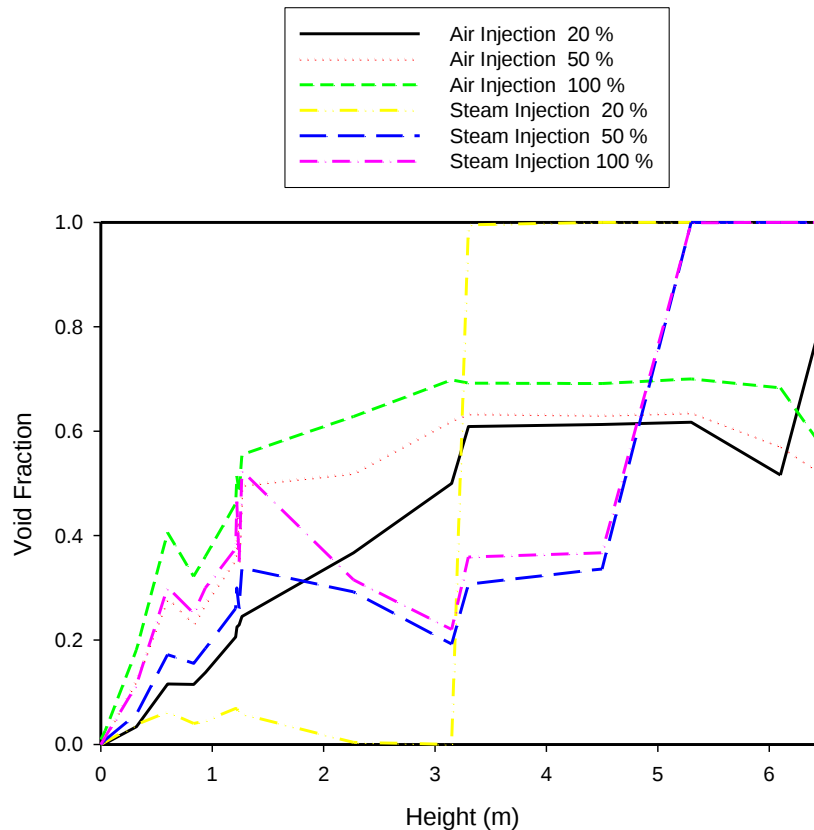


Figure 11 RELAP5 results of the local void fraction at 20 % of the injection rate.

4. Conclusion

As part of a study on a two-phase natural circulation flow between the outer reactor vessel and the insulation material in the reactor cavity under the IVR-ERVC of APR1400, a K-HERMES-HALF experiment has been analyzed to verify and evaluate the experimental results using the RELAP5/MOD3 computer code. Detailed analysis on the geometry scaling of a half & sector and a full height & sector and the material scaling of the air-water and steam-water two-phase flow, have been performed to apply the experimental results to an actual APR1400. The RELAP5/MOD3 results have shown that the water circulation mass flow rate is very similar to the experimental results, in general. An increase in the air injection mass flow rate leads to increases in the local pressure and a pressure difference between the lower and upper parts, which results in an increase in the water circulation mass flow rate. The water circulation mass flow rate of the full height & full sector case is approximately 7.6- times higher than that of the K-HERMEL-HALF case. The water circulation mass flow rate of the air injection case is 20-50 % higher than that of the steam injection case at 20 % of the injection rate. A

three-dimensional analysis of natural circulation flow will be necessary to evaluate the effects of the shear key and the ICI nozzle on the water circulation mass flow rate.

ACKNOWLEDGMENTS

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5. References

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