DETAILED ANALYSIS OF GEOMETRY EFFECT ON TWO PHASE NATURAL CIRCULATION FLOW UNDER IVR-ERVC

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ABSTRACT

Detailed simulations of a two-phase natural circulation flow in the reactor cavity of OPR (Optimized Power Reactor) 1000 have been conducted to determine the water circulation mass flow rate at the annulus between the outer reactor vessel wall and the insulation using the RELAP5/MOD3 computer code. The detailed design of the insulation configuration of the OPR1000 reactor vessel for IVR (In-Vessel corium Retention) through ERVC (External Reactor Vessel Cooling) has not been decided yet. For this reason, a sensitivity study on the water inlet area, the water circulation outlet area, the steam outlet area, the water level in the reactor cavity, and the annulus length between the outer reactor vessel wall and the insulation has been conducted to suggest the design configuration of the reactor vessel insulation for the IVR-ERVC of the OPR1000. The RELAP5 results have shown that an increase in the water inlet area from 0.1 m^2 to 1.77 m^2 leads to an increase in the water circulation mass flow rate. In addition, an increase in the water circulation outlet area from 0.1 m^2 to 1.49 m^2 leads to a small increase in the water circulation mass flow rate. However, an increase in the steam outlet area from 0.1 m^2 to 0.37 m^2 and the annulus length change from the 0.15 m to 0.22 m do not have an influence on the water circulation mass flow rate. A decrease of the water level in the reactor cavity leads to a decrease in the water circulation mass flow rate.

KEYWORDS
Severe Accident, In-Vessel corium Retention, External Reactor Vessel Cooling,
Two Phase Natural Circulation, Reactor Vessel Insulation Design

1. INTRODUCTION

The IVR (In-Vessel corium Retention) through the ERVC (External Reactor Vessel Cooling) is known to be an effective means for maintaining the reactor vessel integrity during a severe accident in a nuclear power plant [1-3]. This measure has been adopted in low-power reactors, such as the AP600, the AP1000, and the Loviisa nuclear power plant as a design feature for severe accident mitigation [4-9], and in the high-power reactors of the OPR (Optimized Power Reactor)1000 and APR (Advanced Power Reactor)1400 as an accident management strategy [10, 11]. Many studies have been performed to evaluate the IVR-ERVC, but more efforts for a plant specific configuration are necessary to verify this severe accident management strategy.

Fig. 1 shows a schematic diagram of the IVR-ERVC concept for the OPR1000. The success criterion of the IVR-ERVC achievement is determined by a comparison of the thermal load from the corium to the outer reactor vessel with a maximum heat removal rate of the CHF (Critical Heat Flux) on the outer reactor vessel wall. The CHF is determined to fix the maximum heat removal rate through the external coolant at the annulus between the outer reactor vessel wall and the insulation of the reactor vessel. The CHF on the outer vessel wall depends on the water circulation mass flow rate. Some design improvements of the reactor vessel insulation configuration to increase the CHF by a two phase natural circulation flow between the outer reactor vessel wall and insulation material have been proposed to increase the thermal margin for the IVR-ERVC in high-power reactors. The heated lower spherical reactor vessel wall induces a two phase natural circulation flow in the annular gap between the reactor vessel wall and the insulation. In general, an increase in the mass flow rate of the coolant leads to an increase in the CHF at the lower outer reactor vessel wall, which was verified in the SULTAN test [12]. 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, such as, the water inlet area and position, coolant (water and steam) outlet area and position, and the gap geometry between the outer reactor vessel wall and the insulation material.

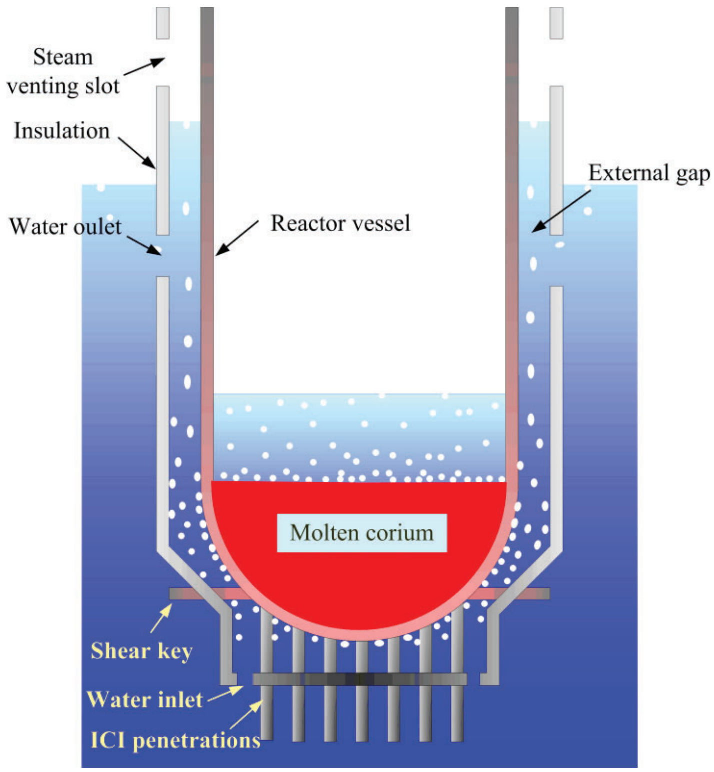

Figure 1. IVR-ERVC concept for the OPR1000.

The OPR1000, a PWR (Pressurized Water Reactor), has been developed by incorporating the latest technologies and the experiences in the construction and operation gained from previous nuclear power plants, including the EPRI ALWR (Advanced Light Water Reactor) requirements. The design features of the OPR1000 are a two-loop RCS (Reactor Coolant System) design and a 2,815 MW core thermal power. The strategy of the OPR 1000 is accident mitigation aiming at retaining the molten core in-vessel first and an ex-vessel cooling of corium second in cases where the reactor vessel fails, reinforcing the principle of a defense-in-depth. When the IVR-ERVC is applied as part of a severe accident management strategy, the cavity will be flooded to the hot leg penetration bottom elevation.
Two phase natural circulation in the reactor cavity of the OPR1000 under IVR-ERVC has been simulated to determine the coolant circulation mass flow rate in the annulus between the outer reactor vessel wall and the insulation of the reactor vessel using the RELAP5/MOD3 computer code [13]. The current OPR1000 has no reactor vessel insulation design for the IVR-ERVC, such as water inlet, water circulation outlet, and steam outlet. The detailed design of the insulation configuration of the future OPR1000 reactor vessel has not yet been decided. For this reason, a sensitivity study on the water inlet area, the water circulation outlet

area, the steam outlet area, and the annulus length between the outer cylinder reactor vessel wall and the insulation has been conducted to suggest the design configuration of the reactor vessel insulation for the IVR-ERVC of the OPR1000. In addition, the water level effect on the water circulation mass flow rate in the reactor cavity has been investigated to suggest an optimal water injection into the reactor cavity for the IVR-ERVC.

2. RELAP5 INPUT MODEL

Fig. 2 shows a RELAP5 input model for a two phase natural circulation analysis in the reactor cavity under the IVR-ERVC conditions, and Table I shows a description of each component of the RELAP5 input model. The RELAP5/MOD3 computer code was used in this simulation. The LWR (Light Water Reactor) transient analysis code, RELAP5, was developed at the INL (Idaho National Laboratory) for the U. S. NRC (Nuclear Regulatory Commission). This code includes analyses required to support rulemaking, licensing audit calculations, evaluations of accident mitigation strategies, evaluations of operator guidelines, and experiment planning analyses. RELAP5 is a highly generic code that, in addition to calculating the behavior of the RCS during a transient, can be used for the 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.

The coolant supplied from the RWST (Refueling Water Storage Tank, Time Dependent Volume No. 106) in the OPR1000 circulates from the cavity water pool (Annulus No. 100) through an annular gap between the outer reactor vessel wall and insulation (Annulus No. 30, 40, 50, 60, 70, 80, and 90). The volume number 105 assumed to be maintained the initial RWST condition. So, the coolant injection temperature is assumed to be 50 °C. In this simulation, it was assumed that the outer water supplied to RWST. The water inlet is a Single Junction 11. The cross flow junctions of No. 63 and 93 are the water circulation outlet and steam outlet, respectively. The spherical and cylindrical reactor vessels are simulated using heat structure numbers 100 and 200, respectively. The reactor power is simulated as a boundary condition of the heat flux at the left side of spherical heat structure number 100. The generated steam is vented into the containment atmosphere (Time Dependent Volume No. 104), which assumed to be maintained atmospheric condition. In all simulations, the initial conditions are assumed to be ambient pressure with no coolant mass flow rate. The coolant level of the reactor cavity maintains a constant value by the RWST water. This input model was verified through the HERMES-HALF (Hydraulic Evaluation of Reactor cooling Me4chanism by External Self –induced flow-HALF scale) test results [14].

In the OPR1000, the configuration of the water inlet, the water circulation outlet, and the steam outlet in the reactor vessel insulation for the IVR-ERVC has not been decided yet. For this reason, the geometry effect on the water circulation mass flow rate was investigated. In the base case calculation, the water inlet area, the water circulation outlet area, the steam outlet area, the water circulation outlet position from the reactor vessel bottom, the steam outlet position from the reactor vessel bottom, and the annulus length from the outer cylinder reactor vessel wall to the insulation are 1.77 m^2, 1.49 m^2, 0.37 m^2, 5.69 m, 8.13 m, 0.22 m, respectively, which were based on a reactor vessel insulation design for the IVR-ERVC of the APR1400 [11]. In addition, the water level from the reactor vessel bottom in the reactor cavity is 6.95 m in the base case analysis. A sensitivity study on the water inlet area from 0.1 m^2 to 1.77 m^2, the water circulation out area from 0.1 m^2 to 1.49 m^2, the steam outlet area from 0.1 m^2 to 0.37 m^2, the annulus length from 0.15 m to 0.22 m, and the water level from 3.35 m to 6.95m were conducted to suggest the design configuration of the reactor vessel insulation for the IVR-ERVC of the OPR1000 by using the RELAP5 computer code.

Fig. 3 shows the annulus area between the outer reactor vessel wall and insulation as a function of height. This area was used as a RELAP5 input. Fig. 4 shows the heat flux from the corium pool to the reactor vessel wall, which is the MAAP4 result [14]. The higher value at approximately 80 degrees comes from the focusing effect of the metallic layer of the corium pool in the lower plenum of the reactor vessel. In this thermal load analysis from the corium pool to reactor vessel wall, a two layer formation of the upper low density metallic layer with a lower high density oxidic layer was assumed.

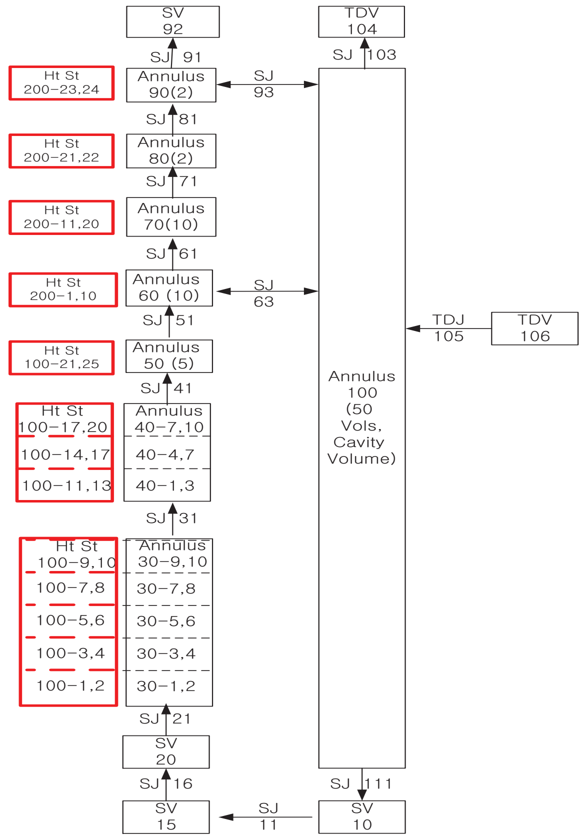

Figure 2. RELAP5 input model for a natural circulation analysis in the reactor cavity.

Table I. Description of each component of the RELAP5 input model

No.	Description
Heat Structure 100	Spherical Reactor Vessel
Heat Structure 200	Cylindrical Reactor Vessel
Single Volume 20	Volume Between the Reactor Vessel Bottom and the Insulation
Annulus 30, 40 ,50	Volume Between the Spherical Reactor Vessel and Insulation
Annulus 60,70, 80, 90 Single Volume 92	Volume Between the Cylindrical Reactor Vessel and Insulation
Annulus 100	Reactor Vessel Outside Cavity Volume
Single Volume 10	Bottom Side Cavity Volume
Single Volume 15	Bottom Cavity Volume under the Reactor Vessel
Time Dep. Volume 104	Containment Atmosphere
Time Dep. Volume 106	Water Source (RWST)
Single Junction 16	Water Inlet
Single Junction 63	Water Circulation Outlet
Single Junction 93	Steam Outlet

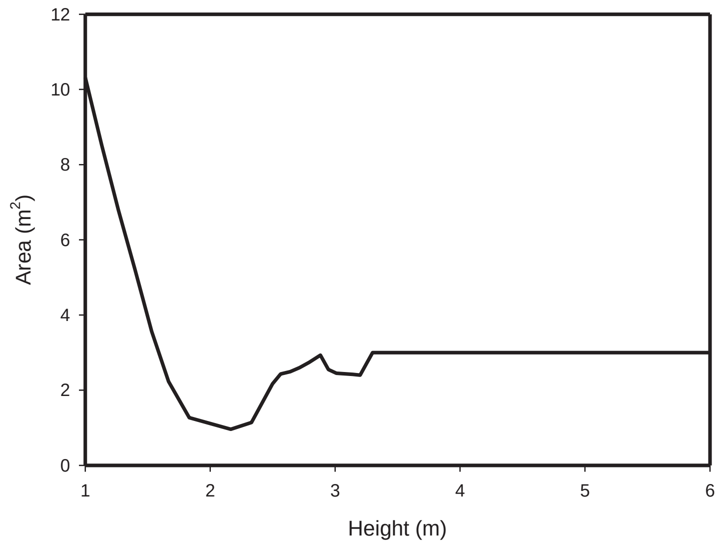

Figure 3. Annulus area between the outer reactor vessel wall and insulation as a function of height.

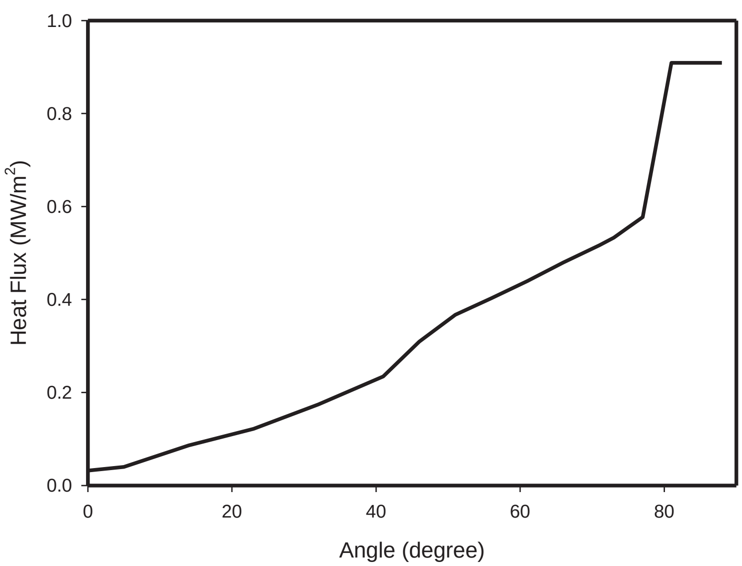

Figure 4. Heat flux to the coolant as a function of angle.

3. RESULTS AND DISCUSSION

Fig. 5 shows the RELAP5 results on the water circulation mass flow rate as a function of time in the base case. An oscillatory coolant flow is generated and the average water circulation mass flow rate is approximately 892 kg/s. This oscillatory coolant flow was showed in the HERMES-HALF experiment [14]. The coolant circulation mass flow rate of the water circulation outlet is two times higher than that of the steam outlet. Figs. 6 and 7 show the RELAP5 results on the local pressure and the average local void fraction as a function of the height, respectively. The local pressure difference between the top and bottom of the cooling channel is approximately 0.67 bars, which leads to the two phase natural circulation flow in the annular gap between the outer reactor vessel wall and the insulation. In general, an increase of the height leads to an increase of the average void fraction due to the bubble generation. However, the average void fraction decreases at some region, because the annulus area between the outer reactor vessel wall and the insulation increases.

Fig. 8 shows the RELAP5 results on the water circulation mass flow rate as a function of the water inlet area. An increase in the water inlet area from 0.1 m^2 to 1.77 m^2 leads to an increase in the water circulation mass flow rate. Figs. 9 and 10 show the RELAP5 results on the local pressure and average local void fraction as a function of the water inlet area, respectively. A decrease in the coolant inlet area leads to a decrease in the local pressure at the lower region and an increase in the average void fraction, which leads to a decrease in the coolant circulation mass flow rate.

Fig. 11 shows the RELAP5 results on the water circulation mass flow rate as a function of the water circulation outlet area. An increase in the water circulation outlet area from 0.1 m^2 to 1.49 m^2 leads to a small increase in the water circulation mass flow rate. Fig. 12 shows the RELAP5 results on the water circulation mass flow rate as a function of the steam outlet area. The steam outlet area change from 0.1 m^2 to 0.37 m^2 does not affect the coolant circulation mass flow rate. Figs. 13 and 14 show the RELAP5 results on the local pressure and average local void fraction as a function of the water inlet area, respectively. The steam outlet area does not affect the local void fraction and the average local void fraction, which affects the two phase natural circulation flow in the annular gap between the outer reactor vessel wall and the insulation.

Fig. 15 shows the RELAP5 results on the water circulation mass flow rate as a function of the annulus length between the outer cylinder reactor vessel wall and insulation. The annulus gap length change from the 0.15 m and the 0.22 m does not have an influence on the water circulation mass flow rate. Fig. 16 shows the RELAP5 results on the water circulation mass flow rate as a function of the water lever in the reactor cavity. A decrease of the water level from 6.95 m to 6.45 m does not affect the water circulation mass flow rate. However, a rapid decrease of the water level from 6.45 m to 3.35 m leads to a rapid decrease in the water circulation mass flow rate. A decrease in the water level leads to an increase in the local pressure at the lower region and an increase in the average void fraction, which leads to a rapid decrease in the water circulation mass flow rate. From the RELAP5 results on the water circulation mass flow rate, it is concluded that the reactor vessel configuration of the present base case is suitable for the IVR-ERVC of the OPR1000.

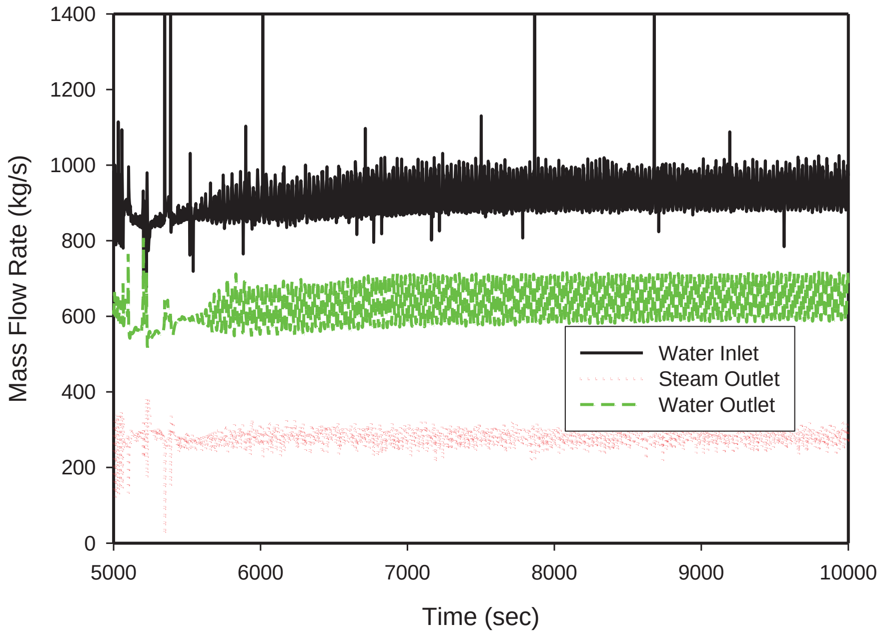

Figure 5. RELAP5 results on the water circulation mass flow rate in the base case.

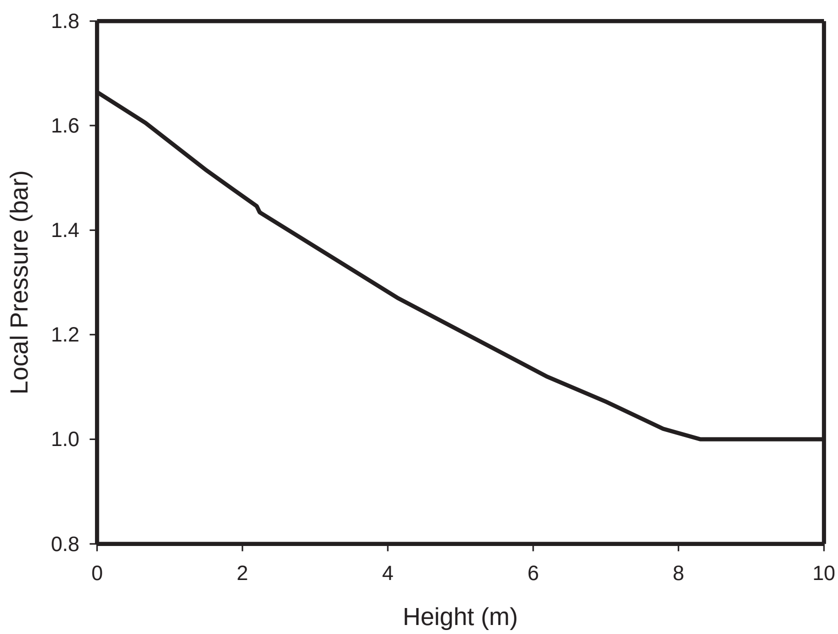

Figure 6. RELAP5 results on the local pressure as a function of height in the base case.

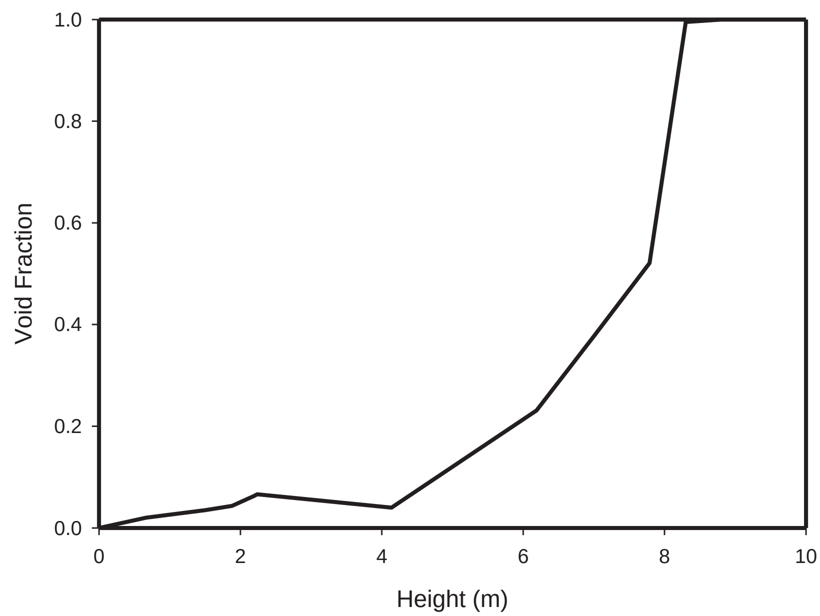

Figure 7. RELAP5 results on the local void fraction as a function of height in the base case.

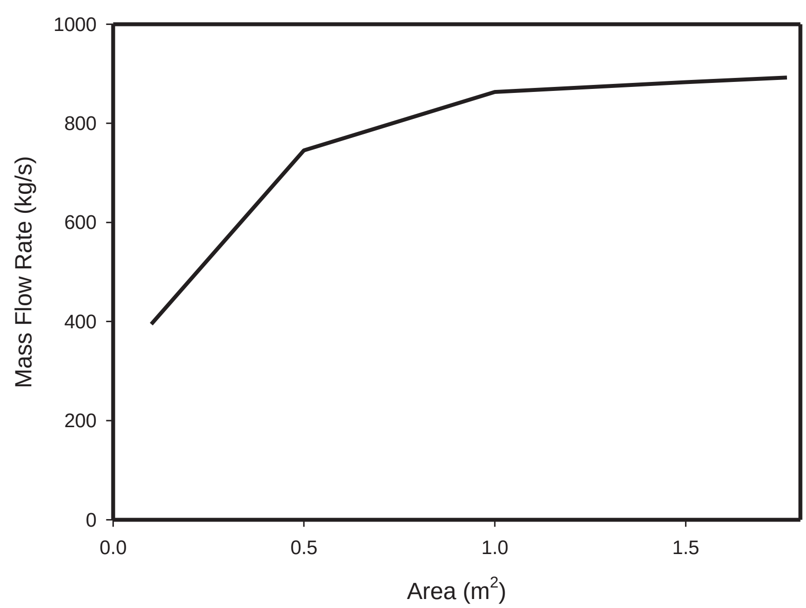

Figure 8. RELAP5 results on the water circulation mass flow rate as a function of water inlet area.

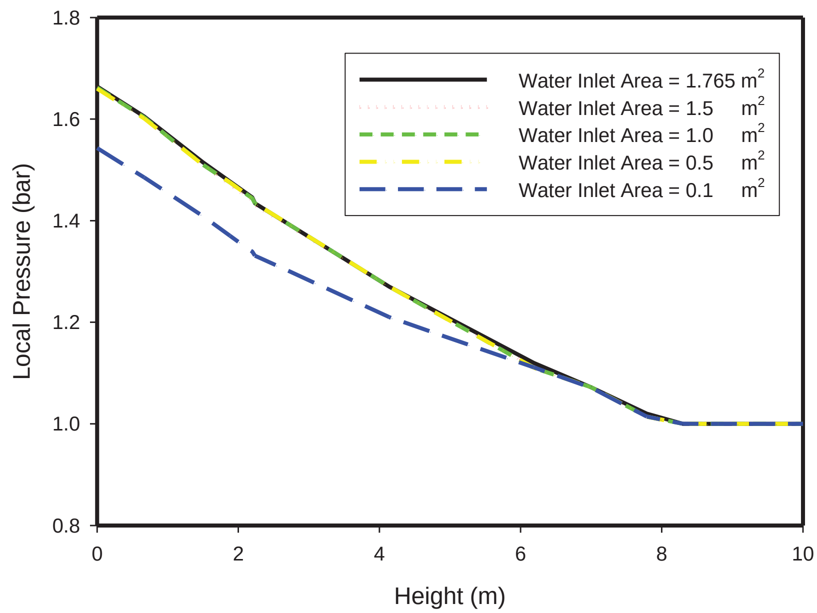

Figure 9 RELAP5 results on the local pressure as a function of height (water inlet area effect).

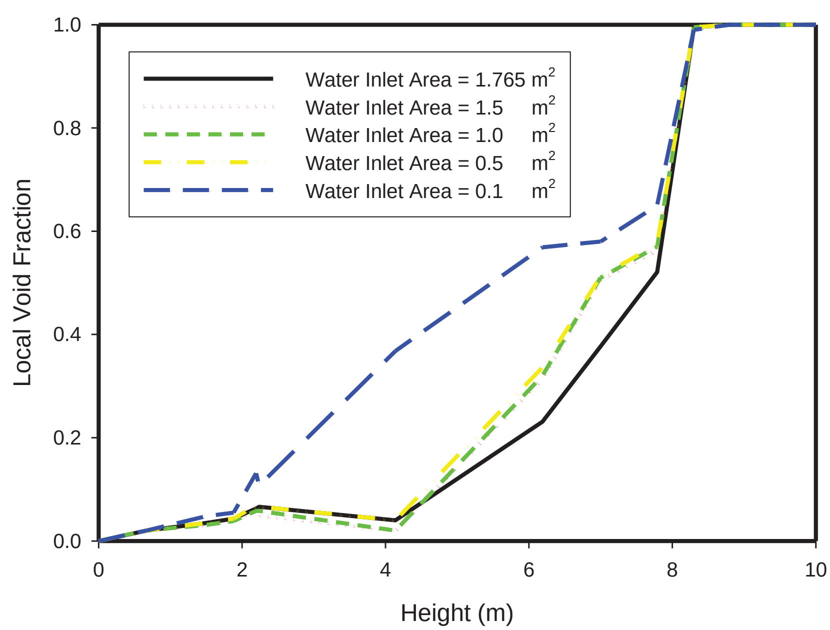

Figure 10 RELAP5 results on the local void fraction as a function of height (water inlet area effect).

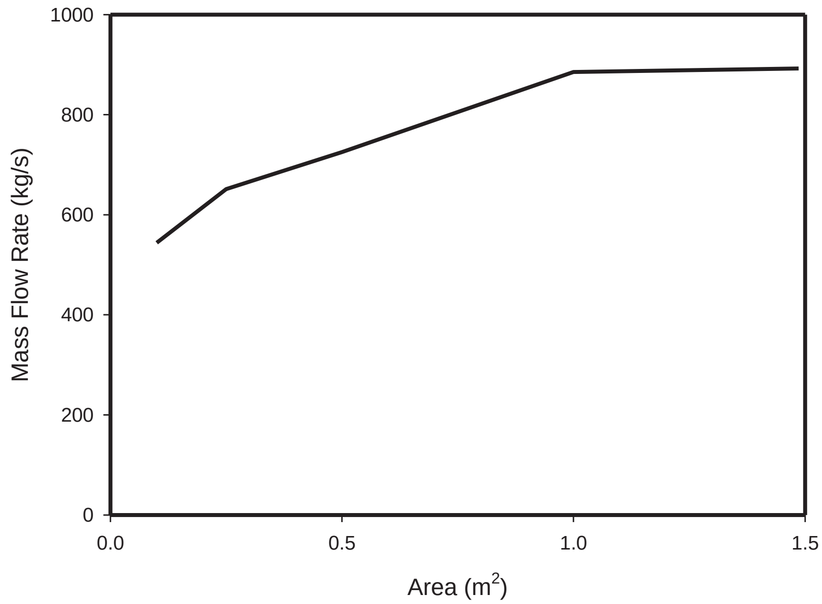

Figure 11. RELAP5 results on the water circulation mass flow rate as a function of water circulation outlet area.

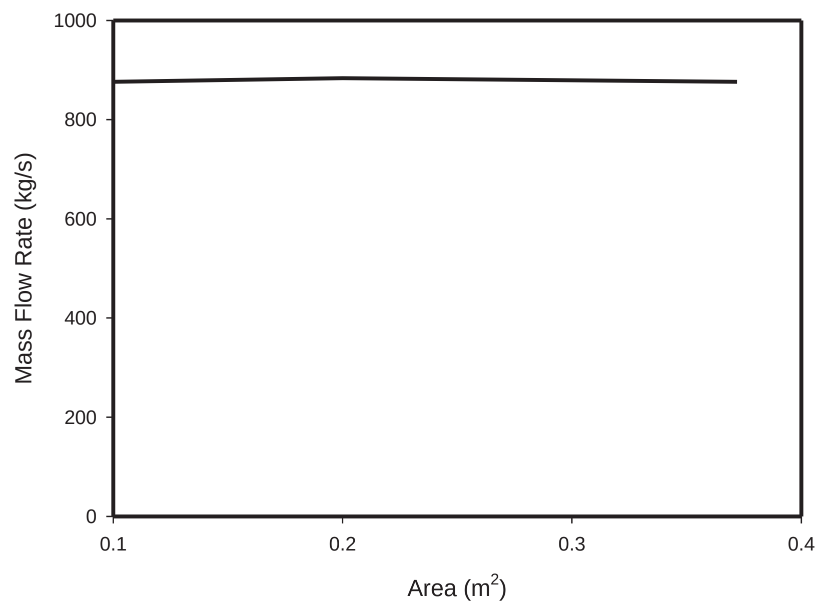

Figure 12. RELAP5 results on the water circulation mass flow rate as a function of steam outlet area.

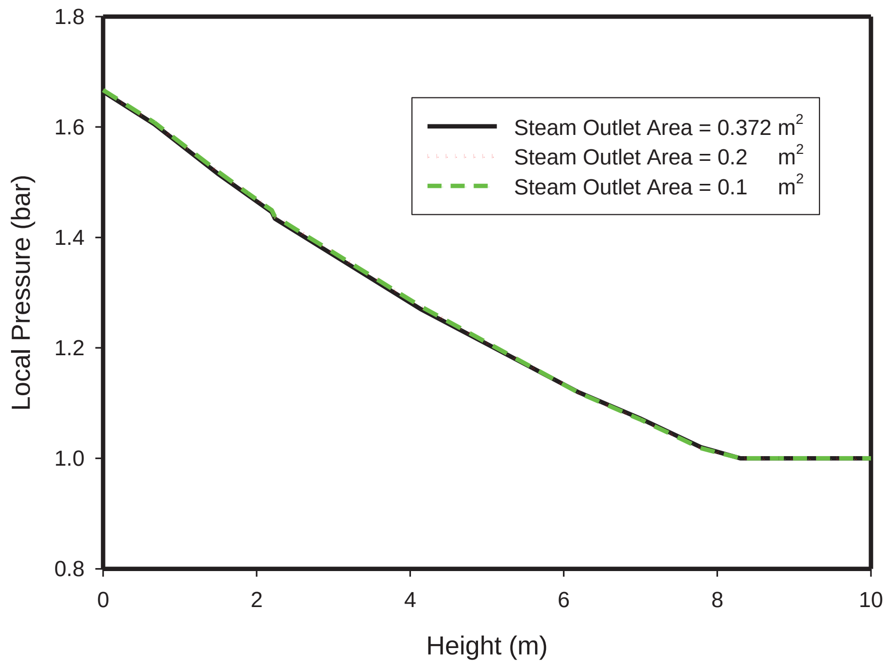

Figure 13 RELAP5 results on the local pressure as a function of height (steam outlet area effect).

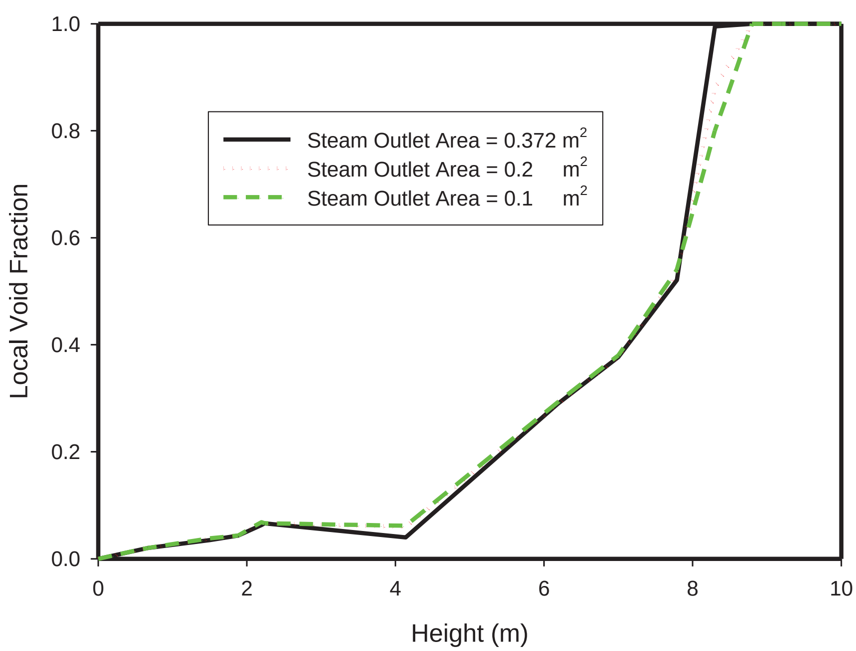

Figure 14 RELAP5 results on the local void fraction as a function of height (steam outlet area effect).

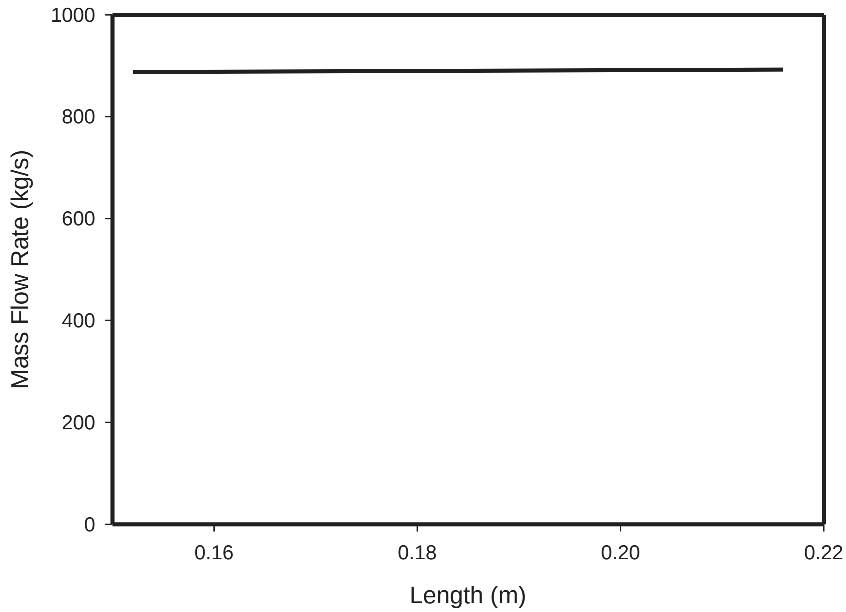

Figure 15. RELAP5 results on the water circulation mass flow rate as an annulus length between the outer cylinder vessel wall and the insulation.

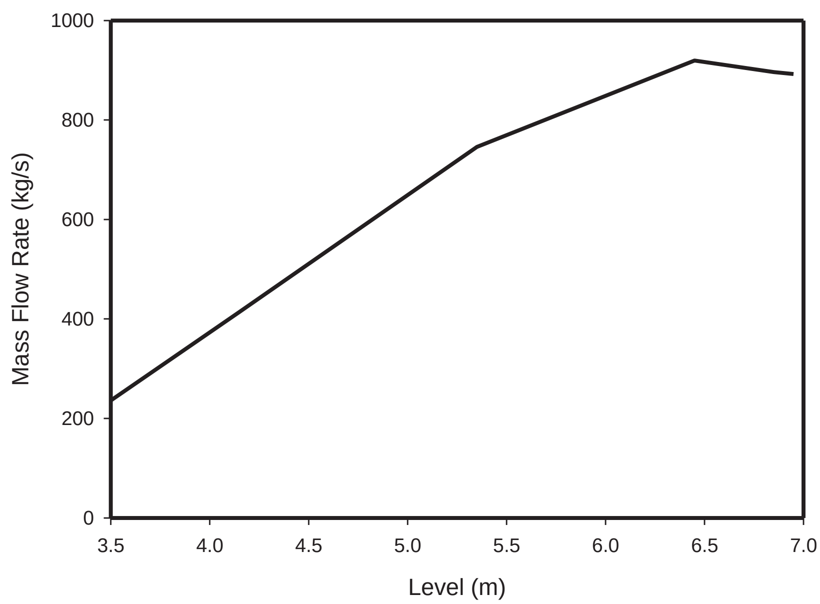

Figure 16. RELAP5 results on the water circulation mass flow rate as a function of the water level in the reactor cavity.

4. CONCLUSIONS

Two phase natural circulation in the reactor cavity of the OPR1000 under IVR-ERVC condition has been simulated to determine the natural circulation mass flow rate in the annulus between the outer reactor vessel wall and the insulation of the reactor vessel using the RELAP5/MOD3 computer code. The present study is focused on sensitivity study on the water inlet area, the water circulation outlet area, the steam outlet area, the water level in the reactor cavity, and the annulus length between the outer reactor vessel wall and the insulation has been conducted to suggest the design configuration of the reactor vessel insulation. The RELAP5 results have shown that as the time increases, an oscillatory coolant natural circulation flow was generated. In the base case, the average water circulation mass flow rate and the local pressure of the water inlet are approximately 892 kg/s and 1.67 bars, respectively. An increase in the water inlet area from 0.1 m^2 to 1.77 m^2 leads to an increase in the water circulation mass flow rate. In addition, an increase in the water circulation outlet area from 0.1 m^2 to 1.49 m^2 leads to a small increase in the water circulation mass flow rate. However, an increase in the steam outlet area from 0.1 m^2 to 0.37 m^2 and the annulus gap thickness change from the 0.15 m to the 0.22 m do not have influence on the water circulation mass flow rate. A decrease of the water level in the reactor cavity leads to a decrease in the water circulation mass flow rate. It is concluded that the reactor vessel configuration of the present base case is suitable for the IVT-ERVC of the OPR1000 from the RELAP5 results on the water circulation mass flow rate. Verification experiments and a more detailed analysis are necessary to apply the IVR-ERVC to the future OPR1000.

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