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3D CFD and FEM Evaluations of RPV Stress Intensity Factor during PTS Loading

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ABSTRACT

Reactor Pressure Vessel (RPV) during Pressurized Thermal Shock (PTS) loading is a critical issue in assessing the safety of nuclear power plants. The most severe situation takes places during Emergency Core Cooling Systems (ECCS) cold water injection in the cold legs due to a Loss-Of-Coolant Accident (LOCA). Conventionally, one-dimensional thermal hydraulic analysis has been performed as well as the simple model fracture mechanics analysis. In the present study, the three-dimensional Computational Fluid Dynamics (CFD) simulation and a comprehensive fracture mechanics analysis are performed. A reference design of a four-loop RPV is applied, and three different cases of the mass flow rates are considered in the analysis. Based on temperature distribution obtained by CFD, the fracture mechanics analysis were carried out to investigate the structural integrity, where submodeling technique is employed. Our results indicate that the worst crack location is identified and the dependence of Stress Intensity Factor (SIF) on the position of RPV is clarified. It is useful information to inspect and maintain the RPV integrity.

KEYWORDS

Reactor Pressure Vessel, Pressurized Thermal Shocks, 3D-CFD, Fracture Mechanics, Stress Intensity Factor

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1. Introduction

The Reactor Pressure Vessel (RPV) structural integrity is most important part of a nuclear power plant. The RPV contains the reactor core and the reactor coolant, which is regarded as irreplaceable. And moreover, the RPV is known to be exposed to neutron irradiation which makes the RPV steels susceptible to brittle [1]. Pressurized Thermal Shock (PTS) occurs in an emergency cooling of the core owing to a Loss-Of-Coolant Accident (LOCA). Constantly, the PTS occurs when cold Emergency Core Cooling (ECC) water is injected inside the cold legs filled with hot water. In this situation, the cold plume will flow into the downcomer and cool down inner surface of the RPV, which leads to high tensile circumferential and axial stresses in the RPV walls. With the neutron irradiation, these high stress may lead the PRV to brittle fracture. As a consequence, it is necessary to evaluate the performance of RPV during PTS loading to keep the reactor safety.

For determination of the stresses resulting during PTS loading situation, an accurate prediction of the temperature distributions is necessary [2]. At present, one-dimensional models are often used in thermal-hydraulic analysis during PTS events. However, the complex mixing phenomena in the downcomer cannot be described accurately by the one-dimensional models [3]. Otherwise, the three-dimensional CFD simulation can able to calculate the temperature distribution formed by mixing phenomena between the cold ECC water and the hot water mixture in the downcomer.

Due to difficulties in three-dimensional modeling, a simple model is used to understand fracture mechanics for RPV analysis. However, if the three-dimensional temperature distributions in the RPV is accounted from CFD simulation, it can be used for the three-dimensional modeling of the RPV and the cracks by Finite Element Method (FEM).

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For the PTS loading, the integrity analysis of RPV is made by a comparison of the mode I SIF with the fracture toughness, K_{IC}. Generally, the Linear Elastic Fracture Mechanics (LEFM) theory is used to calculate of the mode I SIF, K_I.

In the present study, the three-dimensional CFD simulation and a comprehensive fracture mechanics analysis are performed. For CFD simulation, a hypothetical LOCA is assumed in one of the hot legs for a reference design RPV, and ECC water is injected in each cold leg. The mass flow rate takes different values essentially depending on the Safety Injection Pump (SIP) flow. In this CFD simulation, the analysis method of PTS is followed as nearly as possible by the Best Practice Guidelines (BPG) for the application of CFD [4] in nuclear safety analysis. For the structural integrity analysis, the fracture mechanics analysis was performed to obtain the SIF. To do this, the three-dimensional temperature distributions obtained by CFD and submodeling technique were used. Finally, this effort clarified the dependence of SIF on the position of RPV, which is useful for inspection and maintenance of the RPV integrity.

2. Analysis process

Fig. 1 shows an evaluation of the SIF performed in the present study. This analysis consists of four steps: (A) model construction, (B) 3D CFD simulation (thermal-hydraulic analysis), (C) transient thermal stress analysis and mechanical analysis, and (D) fracture mechanic analysis. To do this, ANSYS code [5] is employed.

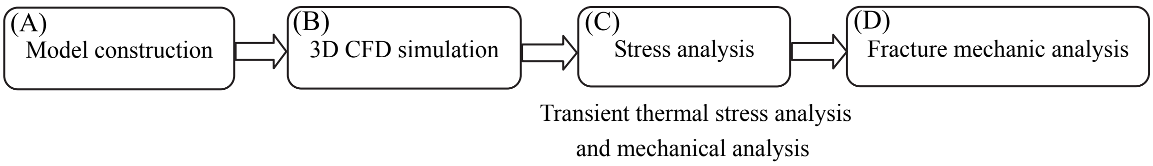

Fig. 1. Description of analysis process of the SIF.

2.1. Model construction and 3D CFD simulation

In a first step, a break in the hot leg is used as the initial and boundary conditions for the CFD simulation. After the break, the system pressure decreases quickly, and then ECC water is injected in each cold leg from the SIP at a temperature of 303 K, which is assumed in this CFD simulation. At a start of the ECC injection, the flow in the loops was in stagnant conditions. SIP takes a value of 20, 40, and 80 kg/s three cases in this CFD simulation. When the CFD simulation starts, the initial temperature was set at 550 K at any points in the system. And the flow in the loops assumes in single phase during the CFD simulations. The initial and boundary conditions are showed in Table 1.

Table 1 Initial and boundary conditions for the CFD model

	Case 1	Case 2	Case 3
SIP, mass flow rate [kg/s]	20	40	80
SIP, temperature [K]		303	
Cold leg, mass flow rate [kg/s]		0	
Initial temperature [K]		550	

The RPV geometry model was constructed and a four-loop PWR nuclear power plant was employed as a reference design. In order to save computation time, 1/4 of the RPV geometry model was taken to simplify the hot leg for CFD simulation. The 1/4 model includes detailed description of the RPV with the SIP injection connected to the cold legs. The neutron shield is located between the core barrel and RPV walls. A detail description of the CFD simulation model is shown in Fig.2.

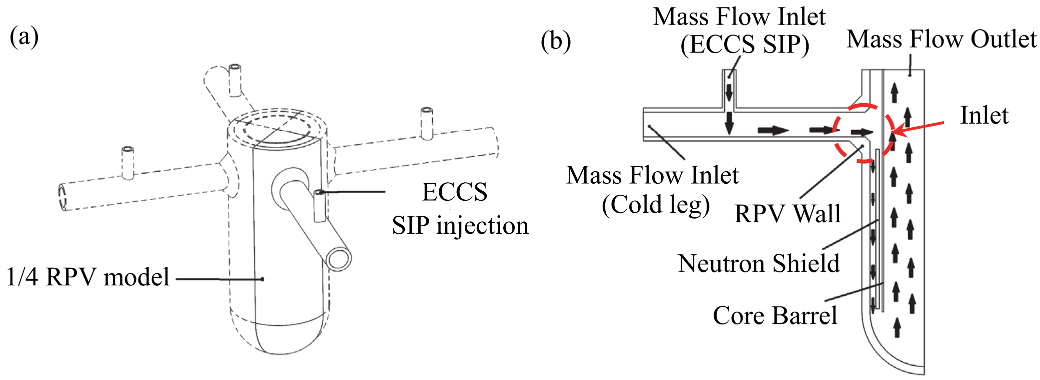

Fig. 2. Description of the CFD simulation model.
(a) 1/4 of the RPV model. (b) CFD simulation schematic diagram.

As to the other boundary conditions, RPV walls, neutron shield and core barrel are used to conjugate heat transfer, and adiabatic boundary conditions are assumed at the outside walls of the RPV. Furthermore, second order upwind schemes and a second order implicit scheme are performed in this simulation. Pressure-velocity coupling is used with the PISO algorithm [5], and the SST-kω turbulence model and buoyancy turbulence modification [4] are used in the present study.

The CFD simulation is performed by following a description of the three cases shown in Table 1. Comparisons of the CFD results of the three cases are shown in Fig.3(a) for the velocity field at the inlet after 440 s (inlet region is shown in Fig.2). And a difference of velocity vectors at the inlet creates a large temperature difference at the RPV walls, as shown in Fig.3(b). From the results of CFD simulation, the 3D feature of the flow in the downcomer confirms the importance of CFD calculation for simulation during PTS loading.

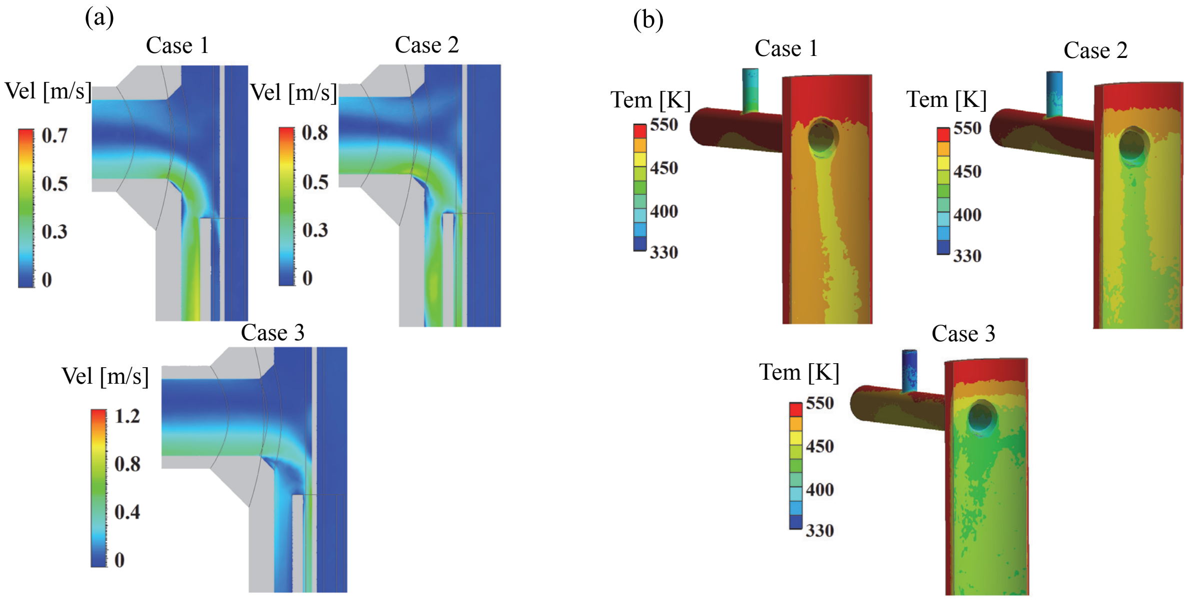

Fig. 3. Example of the results at t = 440 s for Case 1. Case 2. Case 3.
(a) Velocity vectors at the inlet. (b) Temperature on the inner RPV walls.

2.2. Transient thermal stress analysis and mechanical analysis

A 3D-model of RPV used in the CFD simulation is also employed in the stress analysis. The RPV is made of ferritic low alloy steel, and the presence of a cladding has been considered. The thermo-mechanical properties of the RPV material and cladding material at various temperatures are listed in Table 2 [6].

Table 2 Thermo-mechanical properties of the RPV material and cladding material.

Temperature [K]	RPV material						Cladding material					
	273	293	373	473	573	673	273	293	373	473	573	673
Elastic Modulus [GPa]	206	206	199	190	181	172	200	200	194	186	179	172
Density [10^3 kg/m3]	7.6						7.6					
Poisson's ratio	0.3						0.3					
Specific heat capacity [J/(kg K)]	450	450	490	520	560	610	500	500	500	540	540	590
Mean linear thermal expansion coefficient [10^{-6} C^{-1}]	10.3	10.3	11.1	12.1	12.9	13.5	16	16	16	17	17	18
Thermal conductivity [W/(m K)]	44.4	44.4	44.4	43.2	41.8	39.4	15	15	16	17	19	21
Stress free temperature [K]	553						553					

For the transient thermal stress analysis, the CFD simulation provides 3D temperature distributions in the RPV walls to the thermal loads. For transient mechanical analysis, during the PTS the RPV walls are loaded by the pressure history shown in Fig.4 (a). Note that the pressure is a fitting data according to the paper [7]. During the stress analysis, the stresses were evaluated to localize the maximum values and the time. An example of the temperature distribution and stress on the inner wall for the Case 1 can be seen in Fig. 4(b).

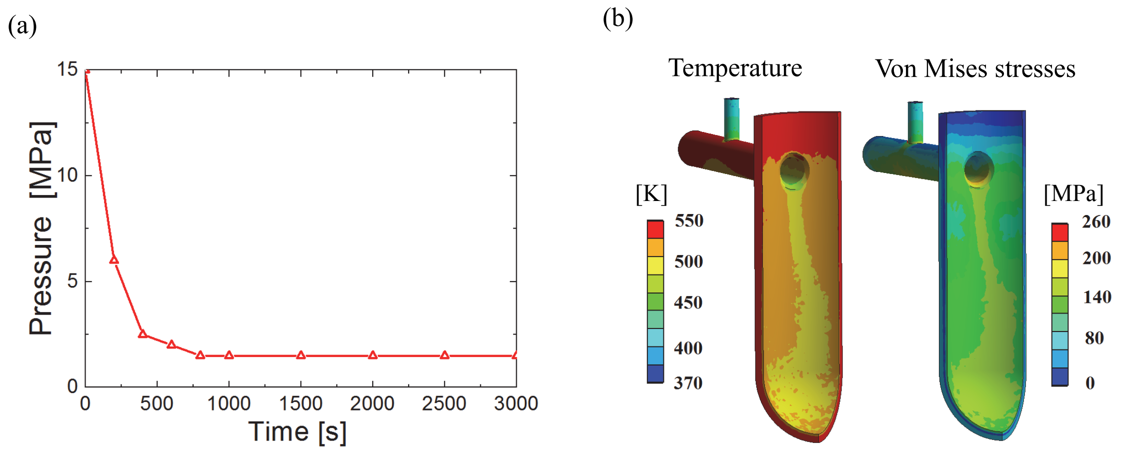

Fig. 4. Stress analysis.
(a) Inner wall pressure evolution on the PTS. (b) Example of temperature and stress on the inner RPV wall after 440 s (Case 1).

2.3. Fracture mechanic analysis

According to the results of stress analysis, cracks are postulated in some regions of the RPV as shown in Fig. 5(a). As a reference to the Case 1, these regions are the inlet, the location of maximum von Mises stresses, inside, outside and border of the cooling plume in core region. And a submodeling technique was applied for the evaluation of K_I by LEFM. Therefore, the submodeling is built for each region of the RPV where the cracks are postulated.

A semi-elliptical surface crack is assumed. The crack sizes are according to the JSME standard 2012 [8]. A semi-elliptical surface crack is presented in Fig. 5(b).

2.4. Analytical Results

Figs. 6(a) and (b) show some examples of analytical results for K_I in Case 1. A detailed submodel is built for A and E regions of the RPV. Circumferential and axial crack orientations are tested for each A and E regions.

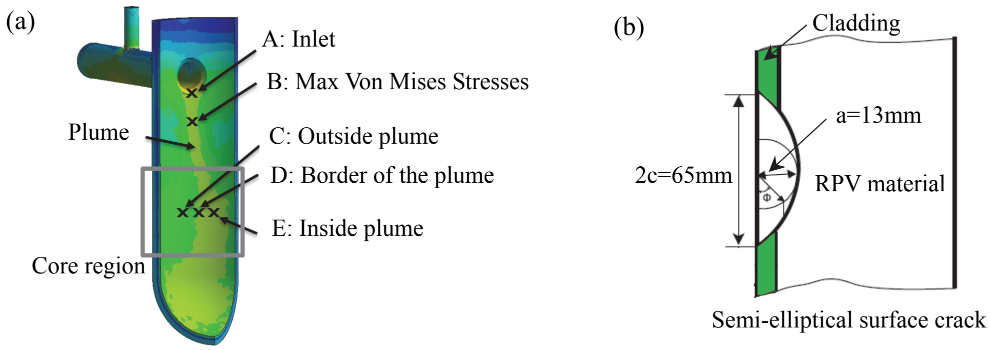

Fig. 5. Fracture mechanic model.
(a) Crack location of the RPV. (b) Semi-elliptical surface crack.

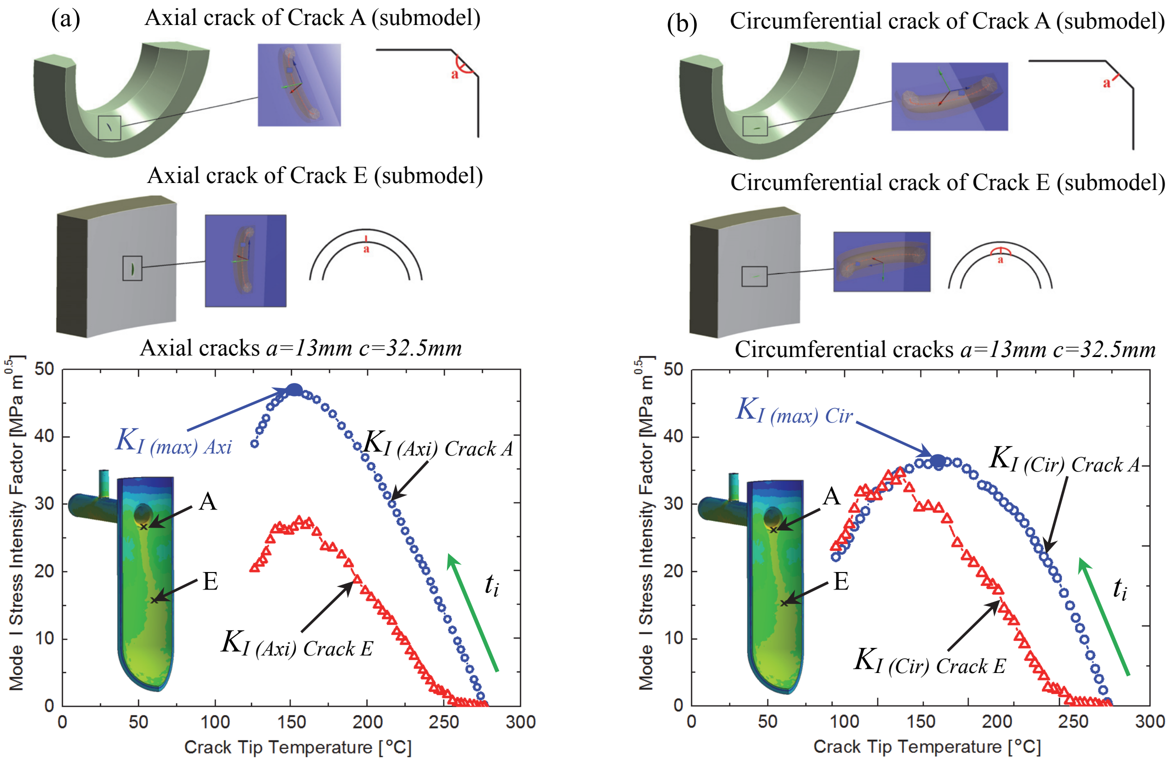

Fig. 6. Example of K_I for the crack deepest point for cracks A and E (Case 1).
(a) Axial cracks. (b) Circumferential cracks.

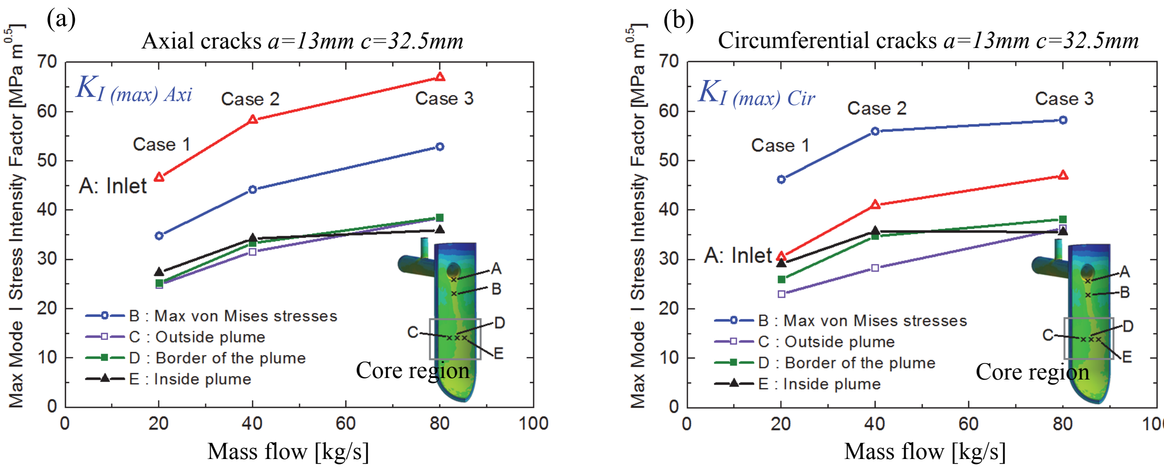

Fig. 7. SIF(max) comparison on the SIP mass flow rates.
(a) Axial cracks. (b) Circumferential cracks.

Fig.7 and Fig.8 show some examples of analytical results for three cases during the different value of the mass flow rates. Figs. 7(a) and (b) show the effect of SIF(max) on the SIP mass flow rates. When the SIP mass flow rate increases, all the orientations of SIF(max) also increase. Figs. 8(a) and (b) show the effect of SIF(max) on the position of RPV. Due to the high irradiation, cracks inside the plume in the core region is considered to be the most "dangerous" position of RPV.

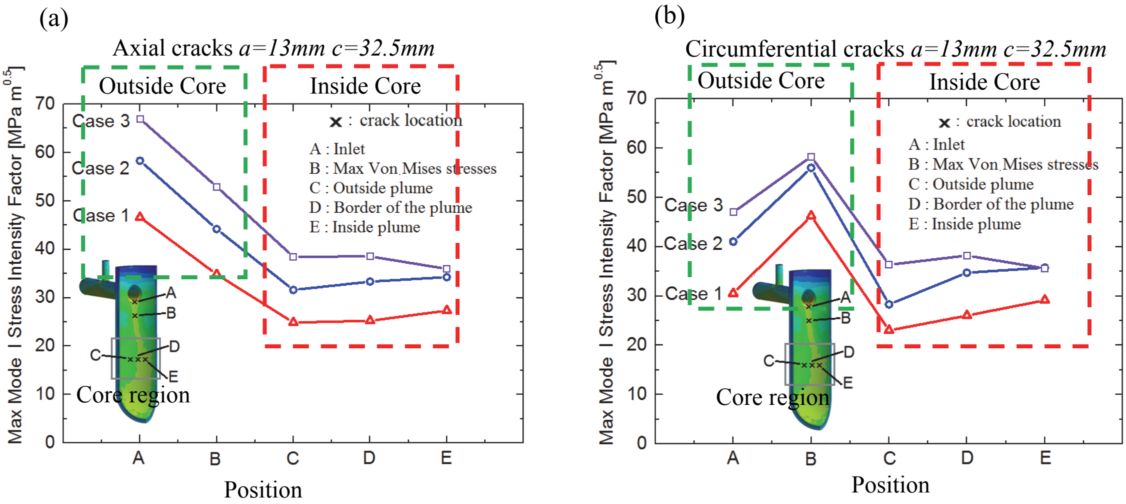

Fig. 8. SIF(max) comparison on the position of RPV.
(a) Axial cracks. (b) Circumferential cracks.

3. Conclusion

We performed 3D-CFD simulation and fracture mechanics analysis of the RPV subjected to PTS loading. The results are as follow:

1. For all the orientations, SIF increases when the SIP mass flow rates increase.
2. Due to the high dose irradiation, cracks inside the plume in the core region are considered to be the most "dangerous" position of RPV.

Our results clearly indicate the most "dangerous" region in RPV. This is useful information to evaluate the effect of irradiation embrittlement and maintain on RPV integrity during a PTS event.

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