加圧熱衝撃事象における圧力容器内き裂の応力拡大係数の 3D-CFD＆FEM 解析

3D-CFD & FEM analysis of RPV stress intensity factor for cracks subjected to PTS phenomena

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Abstract

The integrity of the Reactor Pressure Vessel (RPV) subjected to Pressurized Thermal Shocks (PTS) by cold water injection through the cold leg owing to a Loss-Of-Coolant Accident (LOCA). Fracture Mechanics (FM) analysis evaluation for cracks of the inner surface in the RPV during PTS events, which is important in assessing the safety of nuclear power plants. Conventional, one-dimensional thermal hydraulic analysis and simple model fracture mechanics analysis has been performed.

In the present study, the three-dimensional Computational Fluid Dynamics (CFD) simulations and Fracture Mechanics analysis is performed. And it revealed the dependence of distributed for Stress Intensity Factor (SIF) occurred to the cracks.

Keywords: Computational Fluid Dynamics, Fracture Mechanics, Pressurized Thermal Shocks, Stress Intensity Factor, Reactor Pressure Vessel

1. Introduction

The Reactor Pressure Vessel (RPV) contains the reactor core and the reactor coolant, the RPV structural integrity is most important part of a nuclear power plant. Furthermore, the RPV is exposed to neutron irradiation, which causes embrittlement of the ferritic steels and makes the material susceptible to brittle fracture[1]. Pressurized Thermal Shock (PTS), which occurs by cold Emergency Core Cooling (ECC) water injection through the cold leg owing to a Loss-Of-Coolant Accident (LOCA). In this situation, the cold plume will flow into the downcomer and cool down inner surface in the RPV, which lead to high tensile circumferential stresses in the RPV walls. With the neutron irradiation, these circumferential stresses may lead the PRV to brittle fracture. Therefore, the RPV has to thermal hydraulic analysis and fracture mechanics analysis

One-dimensional models cannot realistically represent the complex mixing phenomena in the downcomer[2]. The three-dimensional Computational Fluid Dynamics (CFD) simulations are capable to account the temperature distribution in the downcomer. The Fracture Mechanics（FM）for RPV analysis is also used to a simple model. However, if the three-dimensional temperature distributions in the RPV is accounted from CFD simulations, it can used the three-dimensional modeling of the RPV and the cracks by Finite Element Method (FEM).

The PTS integrity analysis of RPV is according to the comparison of the Stress Intensity Factor (SIF) with the fracture toughness, K_{IC}.

In the present study, the three-dimensional Computational Fluid Dynamics (CFD) simulations and Fracture Mechanics (FM) analysis is performed to PTS in the RPV. The acquired results for the three-dimensional temperature distributions from CFD for the FM analysis to obtained the SIF. And it revealed the dependence of distributed for SIF occurred to the cracks.

2. Computational Fluid Dynamics simulations

2.1 Initial and boundary conditions

In this study, a break in the hot leg are used to the initial and boundary conditions for the CFD simulations. After the break,

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the injection Emergency Core Cooling (ECC) water is injected in each cold leg from the Safety Injection Pumps (SIP) at a temperature of T K. T K as an assumption, it takes 303 K in this CFD simulations. At the start of the ECC injection, the flow in the loops was in stagnant conditions. The ECC from SIP reaches a value of M kg/s in each loop and it remains it. M kg/s also as an assumption, it takes 20 kg/s, 40 kg/s and 80 kg/s, three cases in this CFD simulations. When the CFD simulations start, the initial temperature was 550 K and it was assumed everywhere 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, M [kg/s]	20	40	80
SIP, T [K]	303	303	303
Cold leg, M [kg/s]	0	0	0
Initial pressure [Mpa]	6.9		
Initial temperature [K]	550		

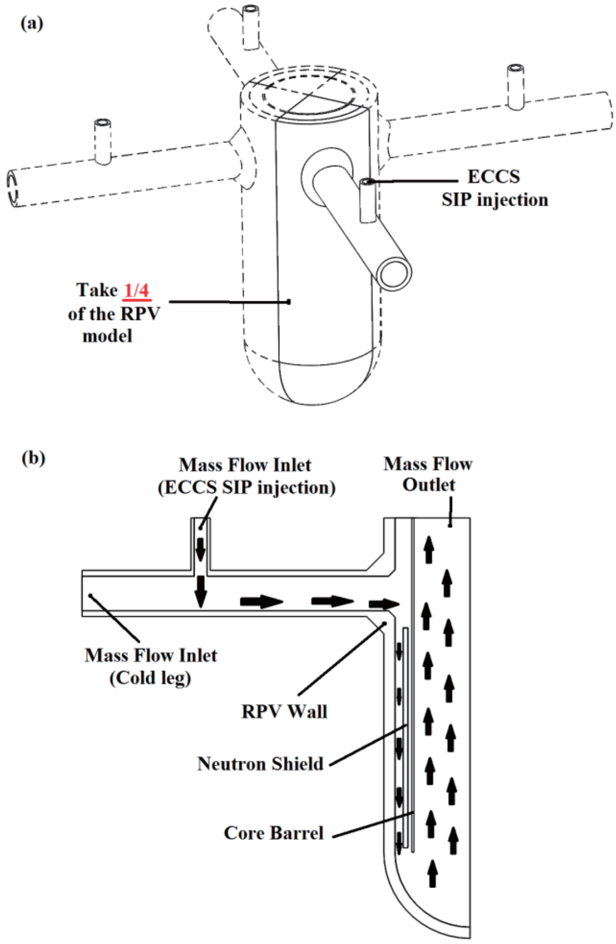

Fig.1 Description of the CFD simulations model. (a) 1/4 of the RPV model. (b) CFD simulations schematic diagram.

2.2 Geometry model description

The RPV geometry model is constructed of a design for a four-loop PWR nuclear power plant. In order to save computation time, it construct 1/4 of the RPV geometry model and simplifies the hot leg for CFD simulations. Details description of the CFD simulations model is shown in Fig.1.

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.

2.3 Numerical model and mesh

The CFD simulations are performed using ANSYS Fluent. The mesh is composed of 0.96 million cells. A mesh as shown in Fig.2.

Fig.2 Numerical grid for CFD.

2.4 Results

The CFD simulations are performed according to description of the three cases shown in Table 1. Comparisons of the results of the three cases are shown in Fig.3 for the velocity field at the inlet.

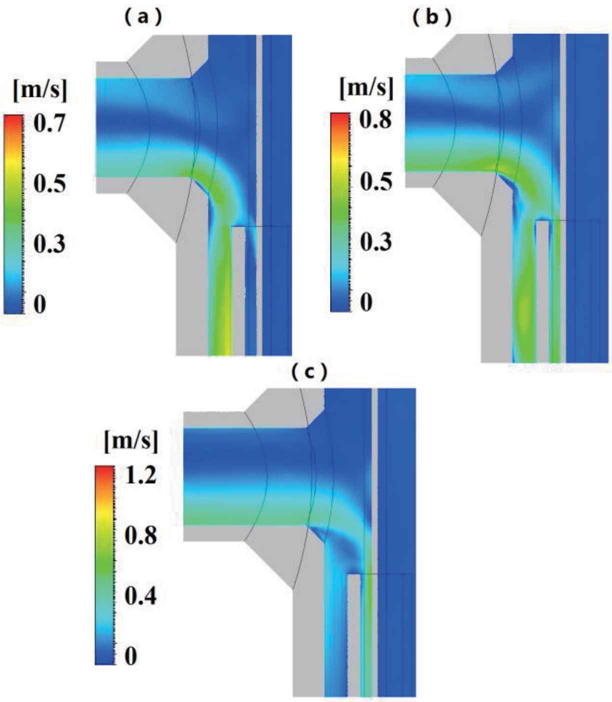

Fig.3 Velocity vectors at the inlet at t = 440 s. (a) Case 1. (b) Case 2. (c) Case 3.

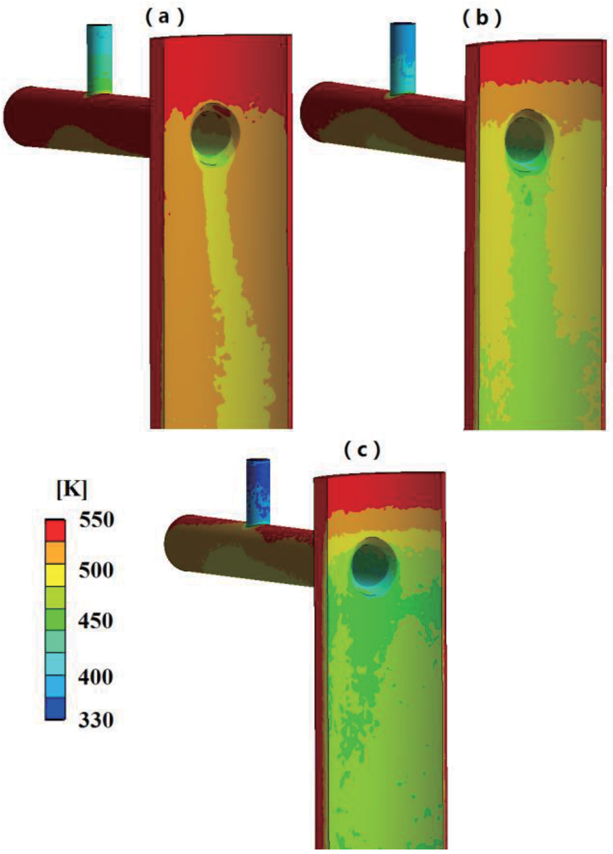

Fig.4 temperature on the inner RPV wall at t = 440 s. (a) Case 1. (b) Case 2. (c) Case 3.

For Case 1, the ECC from SIP reaches a value of 20 kg/s, the plume falls down it direct contact with the RPV. For Case 2, the ECC from SIP reaches a value of 40 kg/s, it is twice than Case 1, the plume falls down it splits at the neutron shield. For Case 3, the ECC from SIP reaches a value of 80 kg/s, it is fourth than Case 1, the plume falls down it direct contact with the core barrel. The different of velocity vectors at the inlet creates large temperature difference at the RPV walls is shown in Fig.4.

And the 3D feature of the flow in the downcomer confirms the importance of CFD calculations for simulation of the PTS phenomena. One-dimensional analysis estimates only average fluid temperature at each node in the downcomer and it cannot estimate the cooling effect by the plume. Therefore, One-dimensional analysis is not conservative for the thermal loads for the fracture mechanics analysis.

3. 3D mechanical model

The Linear Elastic Fracture Mechanics (LEFM) analyses are performed using the FEM code ANSYS Workbench. The 3D model of the RPV which contains its most important geometric properties. The CFD simulations provide 3D temperature distributions in the RPV walls to the thermal loads for the LEFM analysis. The LEFE mesh is built using hexahedron elements. The same RPV geometry is used in CFD analysis and RPV structural mechanical analysis. The RPV geometry by the FE mesh is shown in Fig.5. Material mechanical properties are showed in Table 2[3].

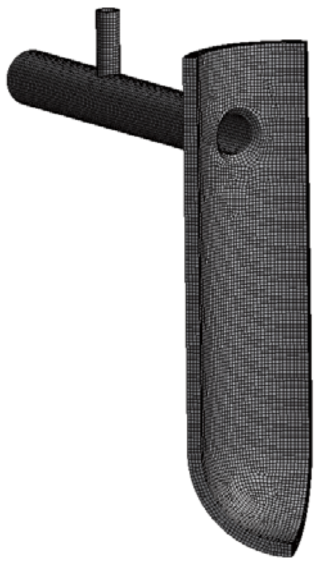

Fig.5 RPV mesh of the mechanical model.

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The stresses were evaluated to localize the maximum values and the time. An example of the temperature distribution and stresses on the inner wall for the Case 1 can be seen in Fig.6.

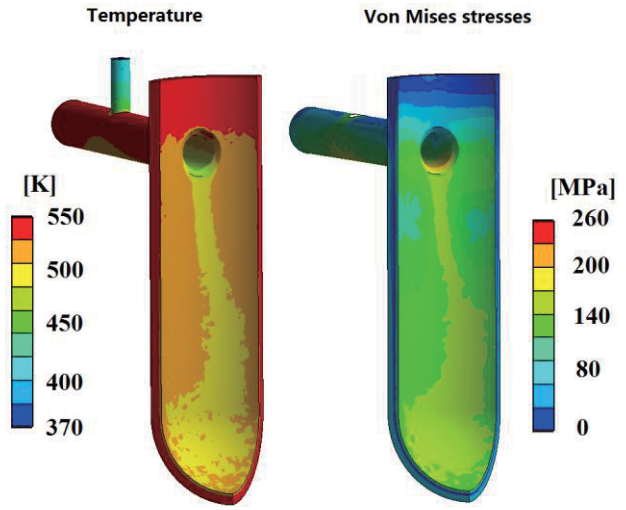

Fig.6 Example of temperature and stress on the inner RPV wall after 440 s (Case 1).

Table 2 Thermo-mechanical properties of the RPV material.

Temperature [K]	273	293	373	473	573	673
Elastic Modulus [GPa]	206	206	199	190	181	172
Density [10^3 kg/m^3]	7.6	7.6	7.6	7.6	7.6	7.6
Poisson's ratio	0.3	0.3	0.3	0.3	0.3	0.3
Specific heat capacity [J/(kg K)]	450	450	490	520	560	610
Mean linear thermal expansion coefficient [10^{-6} C^{-1}]	10.3	10.3	11.1	12.1	12.9	13.5
Thermal conductivity [W/(m K)]	44.4	44.4	44.4	43.2	41.8	39.4
Stress free temperature [K]	280.3					

4. Fracture mechanic analysis

Cracks are postulated in some regions of the RPV as shown in Fig.7. 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. A 3D submodel is built for each region of the RPV where the cracks are postulated.

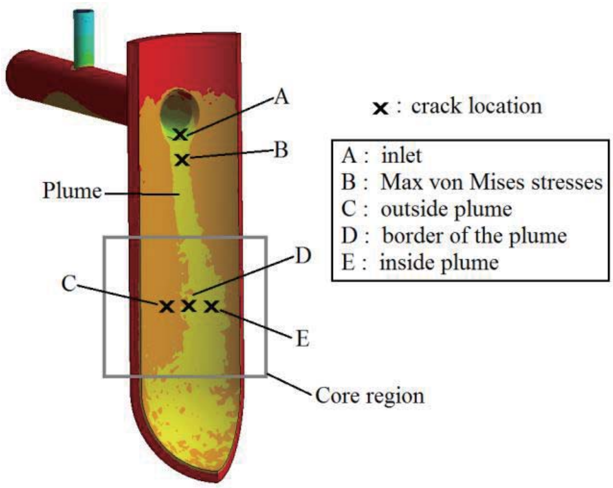

Fig.7 Crack location of the RPV.

A semi-elliptical surface crack is assumed. The crack is according to the JSME standard 2012[4]. A semi-elliptical surface crack as presented in Fig.8.

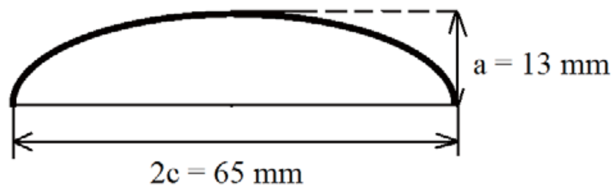

Fig.8 semi-elliptical surface crack.

From mechanics analysis, the inlet is a critical location in the RPV due to its maximum values of circumferential stress. The submodel crack details for this region are shown in Fig.9. The integrity analysis relevant parameter, K_I, at deepest crack point, are shown in Fig.10 for the Case 1, Case 2 and Case 3 analysis. The inlet is not in a high irradiated area. Therefore, it is assumed to be neglected.

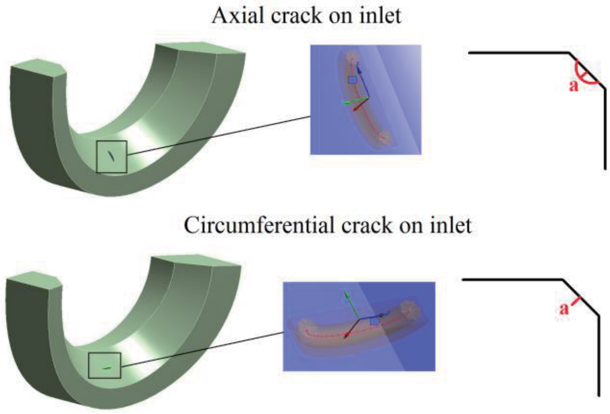

Fig.9 Submodel crack details: inlet.

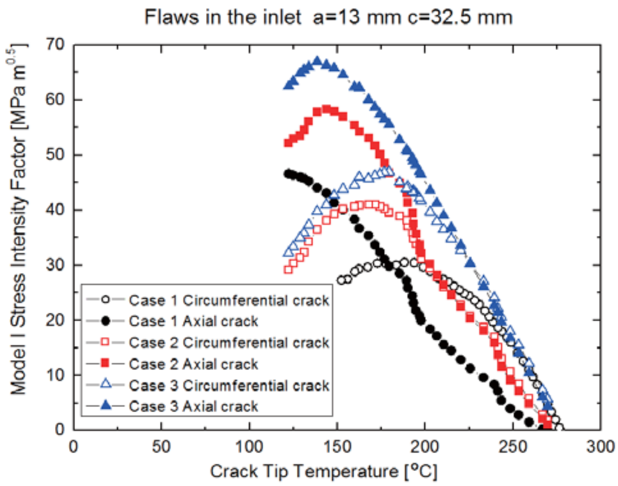

Fig.10 K_I for the crack deepest point in the inlet

The first postulated crack in the wall is at the maximum von Mises stresses which appears below the inlet and could be observed in Fig.7. That location is usually regarded as the worst point from the structural. The submodel crack details for this region are shown in Fig.11. The integrity analysis relevant parameter, K_I, at deepest crack point, are shown in Fig.12 for the Case 1, Case 2 and Case 3 analysis.

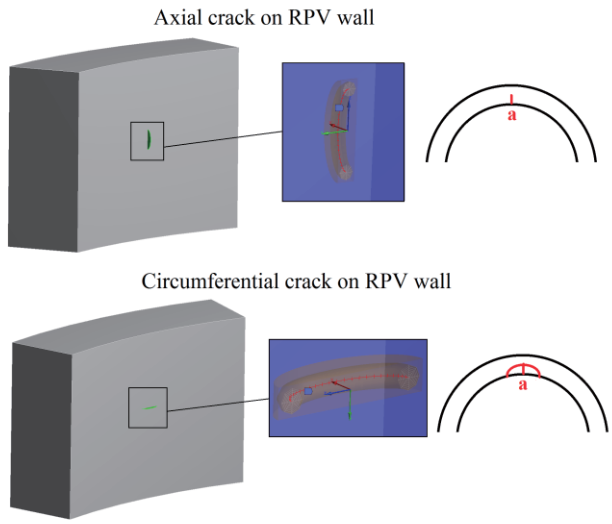

Fig.11 Submodel crack details: wall region (crack postulated at the point of maximum von Mises stresses point, inside, outside and border of the plume in the core region).

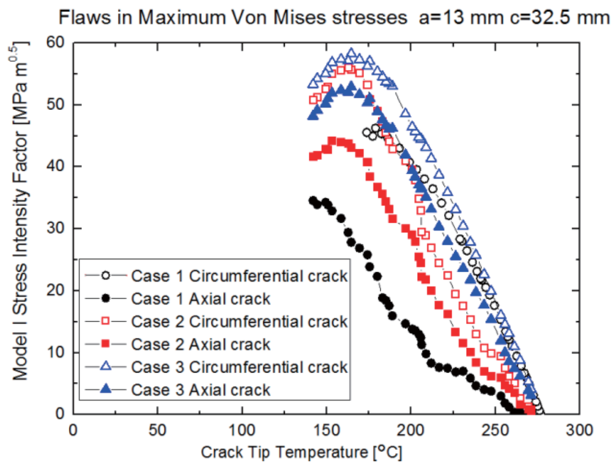

Fig.12 K_I for the crack deepest point for maximum von Mises stress point in the inner surface of the wall

The maximum von Mises stresses for the model are outside the core region (Fig.7). Consequently the core region should be studied because of the high irradiation. For studying the effect of the plume on SIFs, postulated cracks in the core region have been assumed inside the plume, border of the cooling plume and also outside the plume.

The second postulated crack in the wall for flaws inside the plume in the core region are shown in Fig.13 for the Case 1, Case 2 and Case 3 analysis. The SIF of this regions lead to consider this point as the most dangerous.

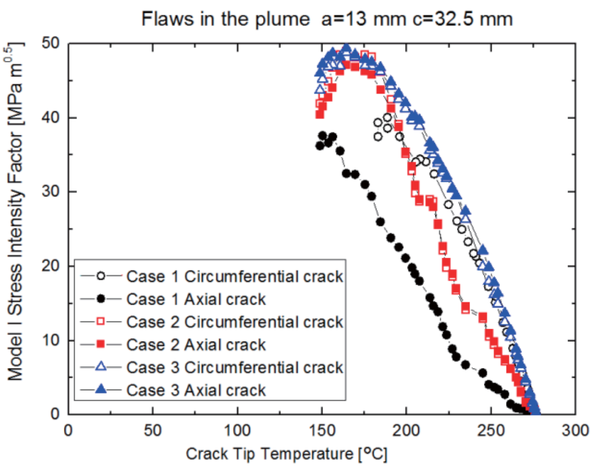

Fig.13 K_I for the crack deepest point for cracks in the plume influenced core region wall

The third postulated crack in the wall for flaws border of the plume in the core region are shown in Fig.14 for the Case 1, Case 2 and Case 3 analysis.

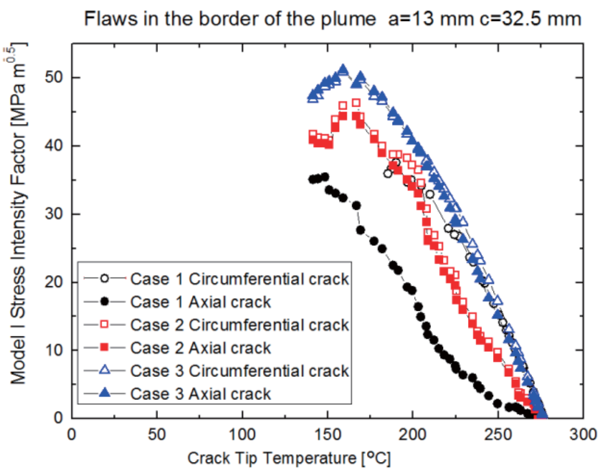

Fig.14 K_I for the crack deepest point for cracks border of the plume influenced core region wall

The fourth postulated crack in the wall for flaws outside the plume in the core region are shown in Fig.15 for the Case 1, Case 2 and Case 3 analysis.

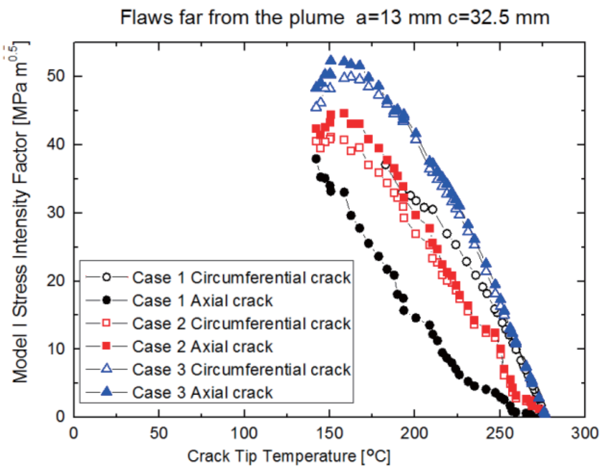

Fig.15 K_I for the crack deepest point for cracks outside the plume influenced core region wall

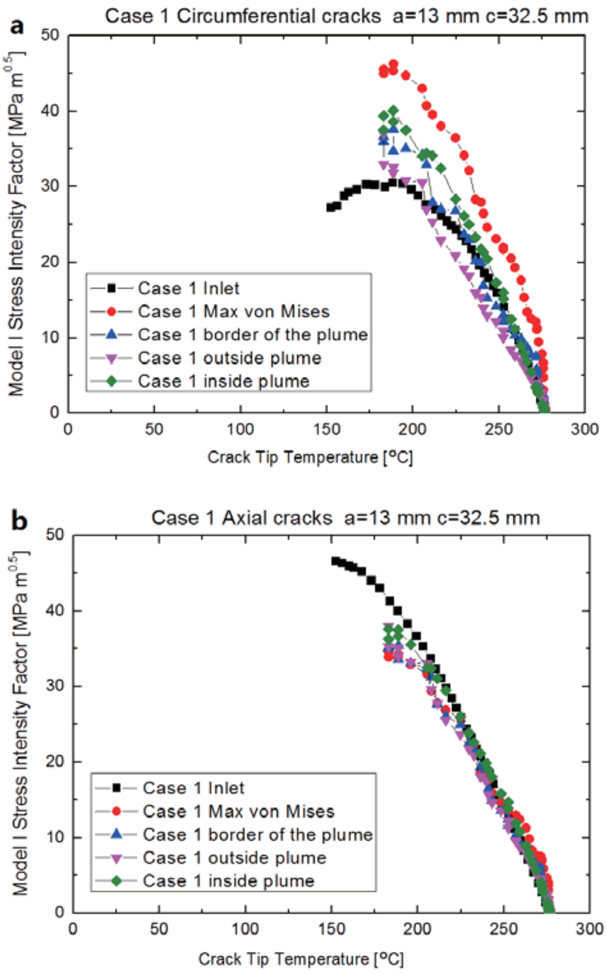

Fig.16 Case 1. SIF comparison at each crack location: (a) circumferential cracks (b) axial cracks

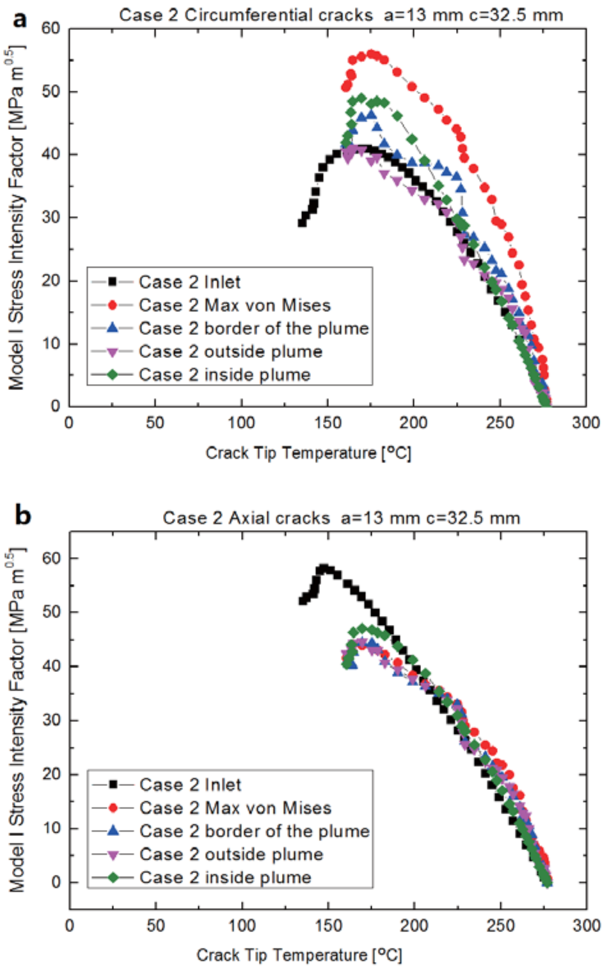

Fig.17 Case 2. SIF comparison at each crack location: (a) circumferential cracks (b) axial cracks

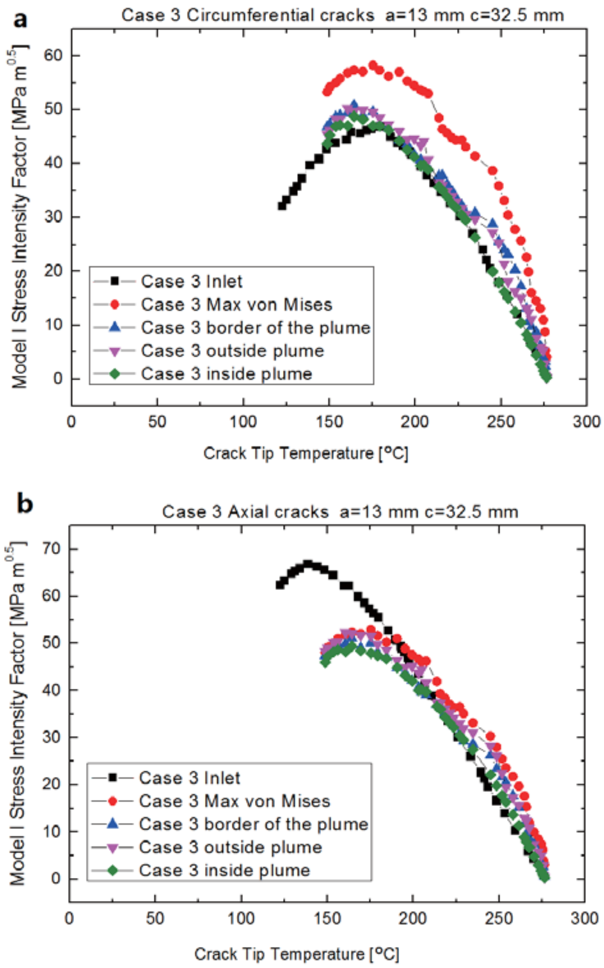

Fig.18 Case 3. SIF comparison at each crack location: (a) circumferential cracks (b) axial cracks

The comparison for K_I at the deepest crack point for each cases, in each locations are shown in Fig.16 for the Case 1 (Fig.16(a) for the circumferential cracks and in Fig.16(b) for the Axial cracks), in Fig.17 for the Case 2 (Fig.17(a) for the circumferential cracks and in Fig.17(b) for the Axial cracks), and in Fig.18 for the Case 1 (Fig.18(a) for the circumferential cracks and in Fig.18(b) for the Axial cracks).

5. Conclusions

One-dimensional analysis is not conservative for the thermal loads for the fracture mechanics analysis in the RPV during PTS events. We assumed 3D-CFD simulations and fracture mechanics analysis of the RPV subjected to PTS loading. Analysis of the most dangerous region such as the regions are the inlet, the location of maximum von Mises stresses, inside, outside and border of the cooling plume in core region. Because of the high irradiation, Cracks inside the plume in the core region, consider this point as the most dangerous. And comparison for K_I at the deepest crack point for each locations when the SIP flow changes. It revealed the dependence of cooling conditions for SIF occurred to the cracks.

References

[1] Odette, G.R., Lucas, G.E., "Irradiation embrittlement of

reactor pressure vessel steels: mechanisms, models and data correlations, radiation embrittlement of reactor pressure vessel steels—an international review L.E. Steele (Ed.) ", ASTM STP 909, ASTM International, West Conshohocken, PA, USA , 1986, pp. 206-241.

[2] Sharabi, M., Freixa, J., "Analysis of the ISP-50 direct vessel injection SBLOCA in the ATLAS facility with the RELAP5/MOD3.3 Code", Nucl. Eng. Technol., 44 (7), 2012, pp. 709-718.

[3] González-Albuixech V.F., Qian G.., "Coupled RELAP5, 3D CFD and FEM analysis of postulated cracks in RPVs subjected to PTS loading", Nuclear Engineering and Design, Vol.297, 2016, pp.111-122.

[4] JSME, "Rules on fitness-for-service for nuclear power plants", The Japan Society of Mechanical Engineers, JSME S NA1-2012, Tokyo; 2012.

[5] González-Albuixech V.F., Qian G.., "Comparison of PTS analyses of RPVs based on 3D-CFD and RELAP5", Nuclear Engineering and Design, Vol.291, 2015, pp.168-178.

[6] Sharabi, M., González-Albuixech V.F., "Computational fluid dynamics study of pressurized thermal shock phenomena in the reactor pressure vessel", Nuclear Engineering and Design, Vol.299, 2016, pp.136-145.