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A Numerical Study on the Effect of DVI Nozzle Location on the Thermal Mixing in RVDC

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Abstract

Direct safety injection into the reactor vessel downcomer annulus(DVI) is a fundamental feature of the KNGR(Korean Next Generation Reactor) four-train safety injection system. The numerical analysis of thermal mixing of ECC(Emergency Core Cooling) water through DVI with the water in the RVDC(Reactor Vessel Downcomer) annulus has been performed, in order to study the impact of nozzle location on the pressurized thermal shock and safety analysis. The results of this study show that the thermal mixing due to the natural circulation induced by the limiting accident conditions is sufficient to prevent temperature in the RVDC from dropping to the level of concern for PTS. When the DVI nozzle is located right above the cold leg, the temperature distribution at the outlet of flow field is most uniform. The tool used for numerical analysis is CFDS-FLOW3D.

1. Introduction

DVI concept is conservatively accepted as ECC of ALWR(Advanced Light Water Reactor) in USA to satisfy the licensing requirement of PTS[1]. However, the flow and temperature pattern during safety injection via DVI nozzle has not been investigated extensively, although there exist some analytical and experimented investigation[2][3][4]. If the fluid temperature around core beltline is dropped below RT_{NDT}(98 °F), reactor vessel has the possibility to be exposed to embrittle fracture. NSSS(Nuclear Steam Supply System) design requires that the temperature of core beltline should not be decreased abruptly when ECC coolant injects into reactor vessel. The temperature distribution in the RVDC is determined by the temperatures and the flow mixing between injected ECC coolant through DVI nozzle and circulated reactor coolant through cold leg. The temperatures of ECC coolant and reactor coolant depend on the plant characteristics. The degree of mixing will depend on the DVI nozzle location. The main purpose of this study is to recommend optimum DVI nozzle location which maximizes thermal mixing in RVDC. This report provides the result of numerical analysis on thermal mixing and evaluation of the PTS concerns based on PTS screening criteria of NRC(Nuclear Regulatory Commission)

2. Selection of Accidents to be Analyzed

It is thought that the RT_{NDT} of end of core life in KNGR doesn't exceed RT_{PTS} as defined in PTS criteria[1]. The events to be evaluated for thermal mixing is carefully chosen from those of lower than the range of AOO(Anticipated Operating Occurrence) in PWR operation experience. It is recommended that SBLOCA(Small Break Loss Of Coolant Accidents) and MSLB(Main Steam Line Break) are the most dangerous accident for PTS[5]. It is judged that the effect of MSLB is more severe than that of SBLOCA by engineering insight. The most conservative accident scenario in the MSLB about PTS is large RCS(Reactor Coolant System) pressure drop, low reactor coolant temperature, maximum ECC injection flowrate and minimum RCS circulation flow. During that accident, mixing of two coolant in the RVDC is expected minimum resulting in low temperature distribution in the core beltline. Since ECC injection flow increases RCS pressure drops, zero power operation is more conservative than full power operation. The loss of offsite power with RCP(Reactor Coolant Pump) stop is also a severe condition inducing poor mixing of ECC injection flow and reactor coolant circulation flow. Consequently, the most severe condition for PTS under MSLB is zero power operation, loss of offsite power, no circulation flow in the intact SG(Steam Generator) loop, and only natural circulation of low temperature coolant through the affected SG loop for 570~600 seconds after MSLB incident.

3. Method of Analysis

Three nozzle locations are carefully selected as shown in Fig. 1. The case 1 is selected as a reference which is proposed by ABB-CE System 80+ design. To check the effect of circumferential and axial shift from reference nozzle location, case 2 and case 3 are selected. The span is determined by considering interface concerns from component design of vessel. The DVI nozzle inside diameter of System 80+ is 8.5″. But DVI nozzle inside diameter in KNGR is increased to 10.125″ due to consideration of LBB(Leak Before Break) and BLPB(Branch Line Pipe Break) concerns. Based on the above, a half cylindrical geometry having hot leg, cold leg per each SG loop and two DVI nozzles is constructed. The cold leg and DVI nozzle are assumed a regular square for convenience of grid generation which will not affect flow and thermal pattern greatly. Figure 2 shows the grid for the numerical calculation simulating RVDC of KNGR reactor vessel system configuration. The data of reactor coolant massflow rate, fluid temperature in cold leg and ECC massflow rate are quoted from the result of safety analysis in the CESSAR-DC(Combustion Engineering Standard Safety Analysis Report-Document Certified). The temperature of ECC coolant is assumed 55 °F conservatively. The massflow of ECC coolant depends on the characteristic curve of ECC pump. The boundary condition of cold leg and DVI nozzle is a inlet using Dirichlet condition. So all transport quantity are specified. The RVDC outlet boundary condition is a massflow boundary that is Neumann condition. Adiabatic and no-slip condition are used at wall and symmetry condition is applied at 180° cut wall. Initial conditions, 570 second after MSLB quoted from safety analysis result, is core inlet temperature and RCS pressure.

4. Numerical Scheme

The flow is modeled by incompressible three dimensional Navior-Stokes equation with k-ε turbulence model. The core beltline temperature is calculated for 570~600 seconds after MSLB. The fixed time step and adaptive time step are alternatively used in the transient computation. User fortran USRBCS with inlet temperature and velocity is used to assign transient boundary condition. The time step of case 1 and case 2 is about 1×10^{-3} ~ 1×10^{-4} second, but that of case 3 is carefully selected to about 1×10^{-4} ~ 1×10^{-5} second because of poor convergence in enthalpy. In general, velocity, mass, k and ε except enthalpy are well converged for all cases. To get better convergence for enthalpy, under relaxation factor of enthalpy is decreased to 0.5 ~ 0.7 for all cases and the number of iteration for transport equations, minimum number of sweep for w-velocity and enthalpy are increased to 2 ~ 3 for case 3. The calculation stop when the normalized enthalpy residual becomes smaller than 1×10^{-5} ~ 1×10^{-6} for case 1 and case 2 and 1×10^{-4} ~ 1×10^{-5} for case 3. The number of grid is shown in the table 1. The grid spaces are uniform for all direction.

	I	J	K
Case 1	5	59	54
Case 2	6	49	64
Case 3	4	29	48

Table 1 Grid Number

5. Analysis Result

The surface temperature distribution and velocity vector in RVDC of case 1 at 600 seconds after MSLB are shown in Fig. 3 and Fig. 4, respectively. Since most of the ECC flow from the left DVI nozzle flows down to the left side of RVDC outlet, the low temperature distribution at the core beltline appears at the location of about 0° to 10° from the left symmetry plane(Fig. 6). The ECC flow from the right DVI nozzle severely affected by the RCS circulation flow from the cold leg B. Part of the flow moves upward and soon turns to the downward direction to join the rest of the flow and most of the DVI flow migrates to the symmetry planes where the fluid velocity maximum(Fig. 5). Flow from the cold leg B seems to behave as a flow barrier. Fig. 6 shows the circumferential temperature distribution at the core beltline. The lowest temperature also appears near the left symmetry plane due to the fluid velocity profile explained on the above. The non-uniform flow velocity and temperature distribution in Fig. 3 and 4, may cause large temperature difference locally resulting high thermal stress. However, PTS concern is not a problem in this case, since the lowest temperature is well above RT_{NDT} (98 °F). The core beltline temperature of other side (around 180°) is relatively stable. It means that ECC flow from the right DVI nozzle flows circumferential direction and fairly good mixing there. The temperature distribution and velocity vector for case 2 are shown in Fig. 9~11. The flow patterns are similar to those of case 1. However, Fig. 9 and Fig. 11 show that most of the water from the right DVI nozzle flows towards the other symmetry plane, and some rest of them flows down to the right side of cold leg B. In Fig. 7 the temperature gradient of core beltline at around 0° position shows more stiff than case 1(Fig. 6). The lowest temperature is much lower than that of case 1 because the fluid mixing is not so good. However, the PTS concern is not a problem in this case, too. Case 3(Fig. 12~14) shows that flow pattern and temperature distribution is significantly different from those of case 1 and case 2. Fig. 8 shows the core beltline temperature for the case 3. The temperature is quite uniform circumferentially. By comparing the temperature distribution between the top and bottom of core beltline, we can find that the flow from the right DVI nozzle moves to the other symmetry plane while mixing with RCS circulation flow. The temperature variance means that the fluid is not completely good mixing. Through the analysis, we may recommend the case 3 as an optimum nozzle location in view of thermal mixing. The final recommendation should be made by considering not only thermal mixing but also structure integrity, piping interface, etc.

Reference

1. ABB-CE Standard Safety Analysis Report for System 80+ Design Certification, ABB Combustion Engineering, 1993
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5. Y. S. Kim, "DVI Design Development for R&D for KNGR" KAERI internal Technical Report, Dec. 1994
6. CFDS-FLOW3D 3.3 User Guide, UKAEA

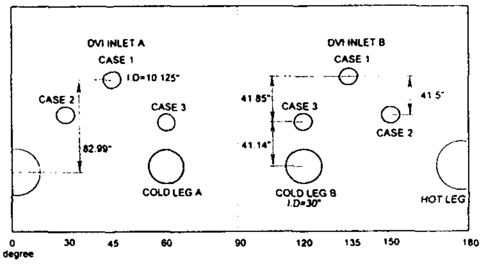

Fig. 1 DVI Nozzle Location

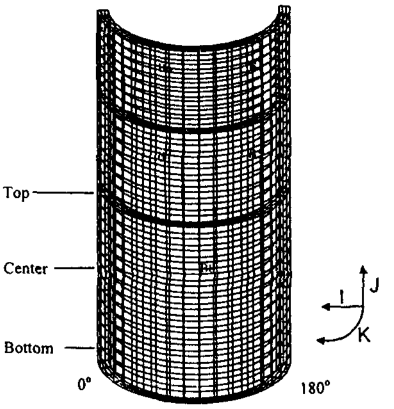

Fig. 2 Grid of RVDC

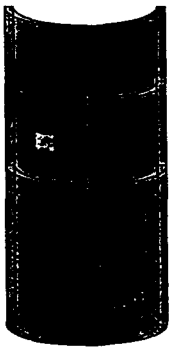

Fig. 3 Surface Temp. of RVDC (Case 1)

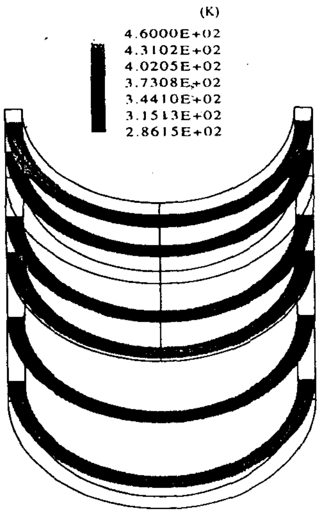

Fig. 4 J Plane Temp. of RVDC (Case 1)

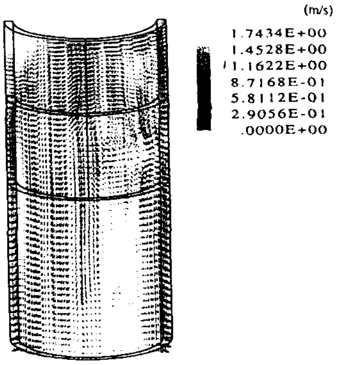

Fig. 5 Velocity Profile in RVDC (Case 1)

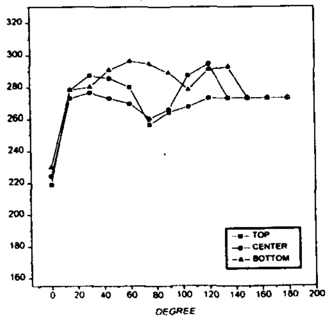

Fig. 6 Core Beltline Temp. (Case 1)

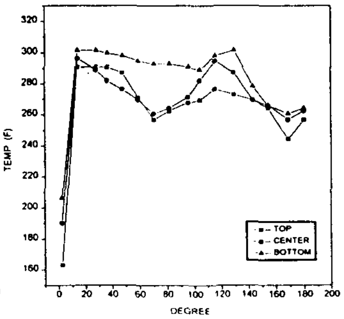

Fig. 7 Core Beltline Temp. (Case 2)

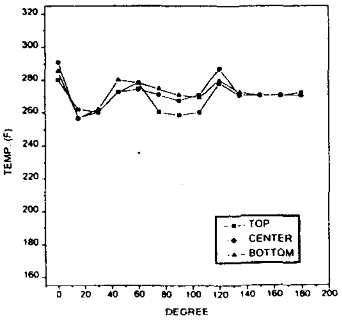

Fig. 8 Core Beltline Temp. (Case 3)

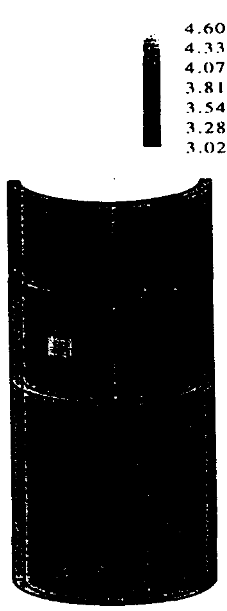

Fig. 9 Surface Temp. of RVDC (Case 2)

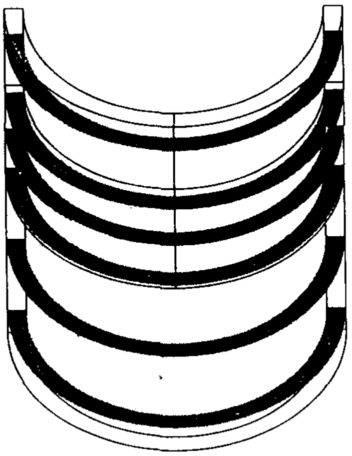

Fig. 10 J Plane Temp. of RVDC (Case 2)

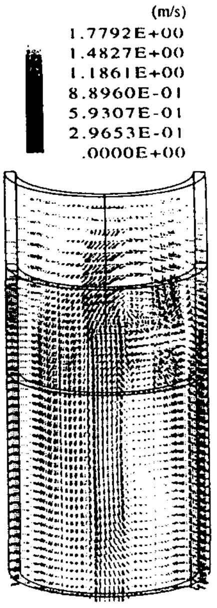

Fig. 11 Velocity Profile in RVDC (Case 2)

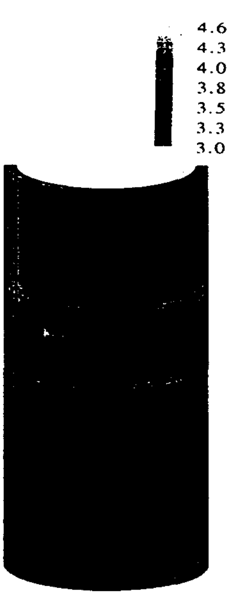

Fig. 12 Surface Temp. of RVDC (Case 3)

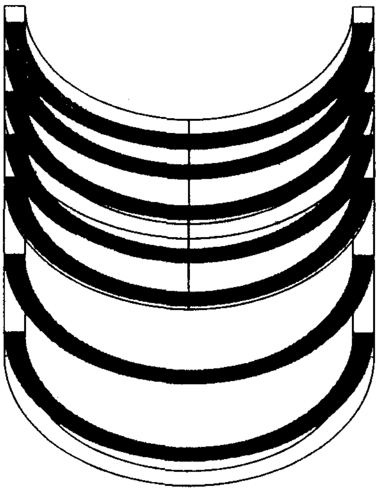

Fig. 13 J Plane Temp. of RVDC (Case 3)

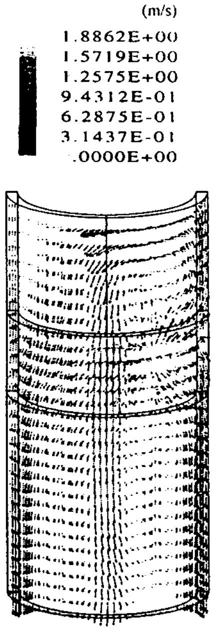

Fig. 14 Velocity Profile in RVDC (Case 3)