SEVERE ACCIDENT SIMULATION OF CS28 EXPERIMENT BY USING CAISER CODE

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ABSTRACT

From the demands about accurate and realistic severe accident codes in the PHWR safety analysis, a new integrated severe accident code called CAISER has been developing at KAERI for a support of Korean regulatory body. The core degradation phenomena in a fuel channel, which is treated in CAISER, includes all kinds of heat transfer, steam-Zr oxidation, a fuel rod slumping (fuel rod movement below because of the weakness of spacer, bearing pad in high temperature condition), melting & relocation of main components and thermal interaction of relocated mass with pressure tube. And, the main phenomena in a calandria tank treated in CAISER include all kinds of heat transfer, sagging of a fuel channel, debris bed formation caused by a fuel channel failure, the molten pool formation and the calandria tank wall failure, which is modeled with the ablation of wall by molten corium, creep rupture failure mechanism.

KEYWORDS
Severe Accident, CANDU, Code, Analysis

1. INTRODUCTION

After Fukushima accident, the regulation for the severe accident mitigation has been strengthened in Korea. One of the regulatory actions which are applied in Korea is to make legislation for the severe accident management in order to guarantee the safety even in the severe accident situation. In line with the action, the acceptable standard of fission product release is definitely defined in the severe accident legislation. That is, in the analysis of PSA (Probabilistic Safety Analysis), the accident frequency that the cesium-137 release rate reaches 100TBq should be less than 10^{-6}. And, the operator of NPP (Nuclear Power Plant) is forced to submit the AMP (Accident Management Plan) to the regulation body until the June, 2019, which contains the severe accident analysis results which show that the current operating power plant satisfy the criterion of fission product release which is defined in the law.

In the case of PWR, there are several famous severe accident codes in the world, such as MAAP[1], MELCOR[2], CINEMA[3], RELAP-SCDAP[4], etc. Hence, the regulation body can review the AMP report by using the separate code which is different from the utility's code, which makes the independent review of regulation body to be possible.

On the other hand, in the case of PHWR, there are limited severe accident codes in the world, such as MAAP-CANDU [5], MAAP-ISAAC [6]. Both of them have similar features because they were developed based on MAAP code which is a fast-running code. Moreover, they use very simple model to simulate CANDU severe accident phenomena. Hence, it is very difficult to calculate the accurate severe accident criterion, such as Cs-137 < 100TBq, defined in AMP.

Moreover, it is also difficult to perform separate code to code comparison since all the CANDU severe accident codes were developed based on MAAP code. Hence, for the perspective of a regulation body, it is difficult to review the AMP report by using the separate severe accident code with high accuracy.

Although the MAAP-ISAAC code is developed in Korea based on MAAP code, through the recent deputy for the ownership of ISAAC code, the ownership of MAAP-ISAAC code is decided to belong to EPRI, which developed MAAP code, because the MAAP-ISAAC code was considered as one of the derivatives of MAAP code.

From the above mentioned background, the necessity for the development of CANDU severe accident code with high accuracy is raised. Hence, KAERI started the project to develop the detailed CANDU severe accident code from 2017 with 5 years plan. At the current stage, we have completed the modelling for the fuel channel module and are modelling for the calandria tank module, together with the code integration with the thermal-hydraulic code. The actual severe accident calculation for CANDU reactor is expected to perform for the next 3 years.

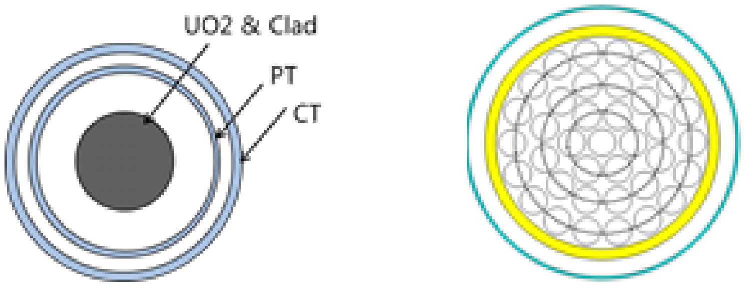
This paper aims to introduce the detailed CANDU severe accident code, named as CAISER (Candu Advanced Integrated SEveRe code). In this paper, the node system of a fuel channel and calandria tank, the main core degradation mechanism is described.

2. NUMERICAL METHODS

2.1. Nodalization

Figure 1 shows the node system for a fuel channel of the reference codes which is used in the industry. The cross-section of a fuel channel is modeled by a single node for MAAP-ISAAC or a 1-dimensional concentric node for MAAP-CANDU. Although these node systems are easy to model and well predict the fuel rod temperature distribution in the normal operation condition by using the ring power distribution in a fuel bundle. However, in a severe accident condition, the fuel rod is progressively uncovered by the loss of coolant in a fuel channel, which results that the fuel rod temperature is not only the function of ring power distribution, but it also depends on the severe accident progression, such as the coolant water lever, oxidation reaction.

Hence, the concentric node system of reference code has the limitation in the modeling of important severe accident phenomena in a fuel channel. For example, in a core uncovering process, the uncovered upper region of a fuel channel has high temperature, and the covered lower region of a fuel channel has relatively low temperature. However, in a concentric node system, the temperature difference between the upper and lower region of a fuel channel cannot be model because the upper and lower part of each ring has the same temperature. It brings to the distortion of hydrogen generation and the core degradation process in a fuel channel. And, in a concentric node system, it is difficult to model the fuel rod melt & relocation process because the mass relocation is evolved in the vertical direction. Moreover, in the reference codes, the local fuel channel failure cannot be modeled because the pressure tube and calandria tube is modeled with a single node. Actually, because of the limitation of nodal system, the reference codes are not considering the above-mentioned phenomena which are important in the severe accident condition.



(a) MAAP-ISAAC (b) MAAP-CANDU

Figure. 1. Node system of the existing overseas code

Figure 2 shows the node system for a fuel channel in CAISER. For a cross-section of fuel channel, the generalized 2-dimensional Cartesian coordinate node system is applied. Since it has 1-dimensional node for a flow direction, a fuel channel is modeled with the generalized 3-dimensional node system. The numbers of node in a horizontal, vertical and flow directions, which are denoted as

M, N, K in equations, respectively, are given by users. And, the pressure tube and calandria tube has 1-dimensional nodal system in an azimuthal direction, together with 1-dimensional node for a flow direction, which makes to enable the modeling of the local thermal failure in a fuel channel.

The initial nodal mass of fuel and cladding is secured as

$$m_{0,m,n,k}^{clad} = \sum_{i=1}^{4} \rho \cdot \left[\pi \left(\left(d^{rod} \right)^2 - \left(d^{fuel} \right)^2 \right) / 4 \right] \cdot L_k \cdot N_{i,m,n}^{rod} \tag{1}$$

$$m_{0,m,n,k}^{fuel} = \sum_{i=1}^{4} \rho \cdot \left[\pi \left(d^{fuel} \right)^2 / 4 \right] \cdot L_k \cdot N_{i,m,n}^{rod} \tag{2}$$

where d^{rod}, d^{fuel} is the diameter of fuel rod, fuel pellet, respectively. For all the ring number of i (i = 1~4), the number of fuel rods in each node of (m, n), $N_{i,m,n}^{rod}$, is given by user input. The number of fuel rods is given for each ring number of i, in order to consider the ring power distribution for the initial nodal power. As shown in figure.2, the number of fuel rod in each node has a real value, instead of integer. The mass and energy of each node is derived from a representative fuel rod, and the number of fuel rods in each node is reflected on mass and energy equations.

For the normal operating condition of CANDU reactor, the rod temperature is largely dependent on the ring number. However, in the severe accident condition, the rod temperature depends on the water level in a fuel channel. And the component melting & relocation is important phenomena in the severe accident condition. Although the modeling of fuel channel with the Cartesian coordinate is difficult because the geometric configuration of a fuel channel is circular, it has many merits in the severe accident condition, such as the consideration of water level in a fuel channel, the melt & relocation process in a fuel channel, and the local thermal failure of a fuel channel.

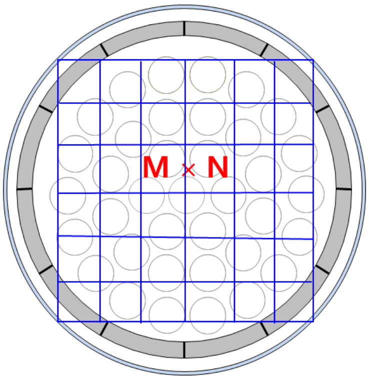


Figure. 2. Node system for a fuel channel in CAISER

2.2. Core Degradation Modeling in a Fuel Channel

The governing equations for the main components in a fuel channel of CAISER are as follows:

Cladding mass conservation

$$\frac{dm_{m,n,k}^{clad}}{dt} = \varepsilon \frac{dm_{m,n,k}^{Zr,ox}}{dt} + w_{m,n,k}^{Zr,in} - w_{m,n,k}^{Zr,\text{out}} + w_{m,n,k}^{ZrO2,in} - w_{m,n,k}^{ZrO2,\text{out}} + \frac{dm_{m,n+1,k}^{clad,sagging}}{dt} - \frac{dm_{m,n,k}^{clad,sagging}}{dt} \tag{3}$$

Cladding energy conservation

$$\frac{d(m_{m,n,k}^{clad}h_{m,n,k}^{clad})}{dt} = q_{m,n,k}^{OX} + q_{m,n,k}^{f-c} - q_{m,n,k}^{s,clad} + q_{m,n,k}^{clad,axi} + q_{m,n,k}^{clad,vert} + q_{m,n,k}^{clad,horiz} - q_{m,n,k}^{clad-ext}$$
$$+ (w_{m,n,k}^{Zr,in} - w_{m,n,k}^{Zr,\mathrm{out}})h_{Zr}^{melt} + (w_{m,n,k}^{ZrO2,in} - w_{m,n,k}^{ZrO2,\mathrm{out}})h_{ZrO2}^{melt} + \frac{d(mh)_{m,n+1,k}^{clad,sagging}}{dt} - \frac{d(mh)_{m,n,k}^{clad,sagging}}{dt} \quad (4)$$

Fuel mass conservation

$$\frac{dm_{m,n,k}^{fuel}}{dt} = w_{m,n,k}^{\mathrm{fuel},in} - w_{m,n,k}^{\mathrm{fuel,out}} + \frac{dm_{m,n+1,k}^{\mathrm{fuel},sagging}}{dt} - \frac{dm_{m,n,k}^{\mathrm{fuel},sagging}}{dt} \quad (5)$$

Fuel energy conservation

$$\frac{d(m_{m,n,k}^{fuel}h_{m,n,k}^{fuel})}{dt} = q_{m,n,k}^{dh} - q_{m,n,k}^{f-c} - q_{m,n,k}^{s,fuel} + q_{m,n,k}^{fuel,axi} + q_{m,n,k}^{fuel,vert} + q_{m,n,k}^{fuel,horiz} - q_{m,n,k}^{fuel,ext} + (w_{m,n,k}^{\mathrm{fuel},in} - w_{m,n,k}^{\mathrm{fuel,out}})h_{UO2}^{melt}$$
$$+ \frac{d(mh)_{m,n+1,k}^{\mathrm{fuel},sagging}}{dt} - \frac{d(mh)_{m,n,k}^{\mathrm{fuel},sagging}}{dt} \quad (6)$$

In the above equations,

$m_{m,n,k}^{clad}$ is the nodal mass of cladding,

$m_{m,n,k}^{fuel}$ is the nodal mass of fuel,

$h_{m,n,k}^{clad}$ is the nodal enthalpy of cladding,

$h_{m,n,k}^{fuel}$ is the nodal enthalpy of fuel,

$q_{m,n,k}^{dh} = q_{m,n,k}^{'''dh} \cdot V_{m,n,k}^{fuel}$ is the nodal decay heat power,

$q_{m,n,k}^{f-c} = q_{m,n,k}^{''f-c} \cdot As_{m,n,k}^{fuel}$ is the nodal heat transfer rate between the fuel and cladding, and $q_{m,n,k}^{''f-c}$ is the corresponding surface heat flux.

$q_{m,n,k}^{s,clad}$ is the convective heat transfer rate between the cladding and coolant.

$q_{m,n,k}^{s,fuel}$ is the convective heat transfer rate between the fuel and coolant.

$q_{m,n,k}^{OX}$ is the heat rate due to the exothermal oxidation reaction,

$q_{m,n,k}^{clad,axi}$, $q_{m,n,k}^{fuel,axi}$ is the conduction heat transfer along the axial direction (k-node) for cladding & fuel,

$q_{m,n,k}^{clad,vert}$, $q_{m,n,k}^{fuel,vert}$ is the radiation heat transfer in a vertical direction (n-node) for cladding & fuel,

$q_{m,n,k}^{clad,horiz}$, $q_{m,n,k}^{fuel,horiz}$ is the radiation heat transfer in a horizontal direction (m-node) for cladding & fuel,

$q_{m,n,k}^{clad,ext}$ is the nodal heat loss from the cladding materials to the surrounding structures

$q_{m,n,k}^{fuel,ext}$ is the nodal heat loss from the fuel to the surrounding structures

$\frac{dm_{m,n,k}^{Zr,ox}}{dt}$ is the Zircaloy oxidation rate in node-(m,n,k), and ε is the relative mass increase during the conversion of metallic Zircaloy to Zirc oxide.

$\frac{dm_{m,n,k}^{clad,sagging}}{dt}$ is the cladding mass relocation rate from node-(m,n,k) to the node below due to fuel rod sagging, and $\frac{d(mh)_{m,n,k}^{clad,sagging}}{dt}$ is the corresponding rate of energy transport

$\dfrac{dm_{m,n,k}^{fuel,sagging}}{dt}$ is the fuel mass relocation rate from node-(m,n,k) to the node below due to fuel rod sagging,

and $\dfrac{d(mh)_{m,n,k}^{fuel,sagging}}{dt}$ is the corresponding rate of energy transport

$w_{m,n,k}^{Zr,in}$ is the mass flow rate of molten Zircaloy from node (m,n+1,k) to node-(m,n,k)

$w_{m,n,k}^{Zr,out}$ is the mass flow rate of molten Zircaloy from node-(m,n,k) to node (m,n-1,k)

$h_{Zr}^{melt} = c_p^{Zr} T_{Zr}^{melt} + \lambda_{Zr}$ is the enthalpy of molten Zircaloy,

$w_{m,n,k}^{ZrO_2,in}$ is the mass flow rate of molten Zirc oxide from node (m,n+1,k) to node-(m,n,k)

$w_{m,n,k}^{ZrO_2,out}$ is the mass flow rate of molten Zirc oxide from node-(m,n,k) to node (m,n-1,k)

$h_{ZrO_2}^{melt} = c_p^{ZrO_2} T_{ZrO_2}^{melt} + \lambda_{ZrO_2}$ is the enthalpy of molten Zirc oxide,

$w_{m,n,k}^{fuel,in}$ is the mass flow rate of molten fuel from node (m,n+1,k) to node-(m,n,k)

$w_{m,n,k}^{fuel,out}$ is the mass flow rate of molten fuel from node-(m,n,k) to node (m,n-1,k)

$h_{fuel}^{melt} = c_p^{fuel} T_{fuel}^{melt} + \lambda_{fuel}$ is the enthalpy of molten fuel,

T_i^{melt} is the melting temperature of material-i ,

λ_i is the heat of fusion of material-i

The core degradation phenomena in a fuel channel, which is treated in CAISER, includes all kinds of heat transfer, steam-Zr oxidation, a fuel rod slumping (fuel rod movement below because of the weakness of spacer, bearing pad in high temperature condition), melting & relocation of main components and thermal interaction of relocated mass with pressure tube.

2.3. Validation of CAISER Code

With a purpose of verification of the CAISER code, the CS-28 experiment was calculated by using the CAISER code. The temperature distribution in fuel rods, a pressure tube and a calandria tube has secured and compared with the experimental data. The CS28-1 experiment [7] is one of the three experiments of the CS28-x series of experiments (CS28-1, CS28-2, and CS28-3) using a full scale horizontal fuel channel with a 28-element fuel bundle. Figure 3 illustrates the cross-section of test fuel channel in the CS28-1 experiment. The superheated steam at about 700 °C was injected into the inlet of the test section with a mass flow of 15 g/s. The test fuel channel is submerged in a water of 40°C, and the 28-element fuel bundle of 1.8m length is installed in the test fuel channel. The fuel bundle consists of three rings of FES (Fuel Element Simulator): 4 elements in the inner, 8 elements in the middle, and 16 elements in the outer ring. Since heater is installed inside FES, the power of test bundle was controlled with time in the experiment, which increases with time step by step, as shown in Fig. 4.

The surface temperature of the fuel element simulators (FES) is raised to have an oxidation reaction, which generates a hydrogen gas with the exothermal heat generation.

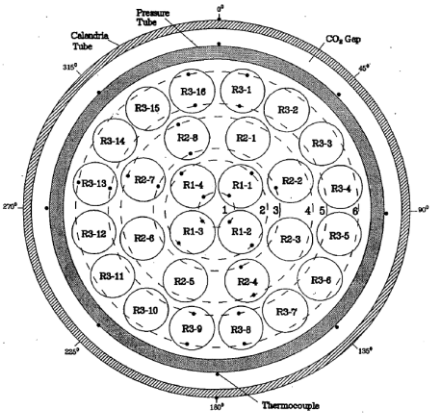


Figure. 3. Cross-sectional view of CS28-1 experimental test section.

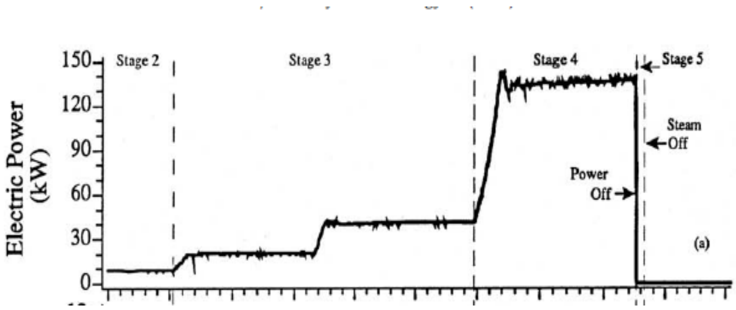


Figure. 4. Electric power to the heater in CS28-1 experiment

In order to simulate CS28-1 experiment, the cross-section of fuel channel has been nodalized with 3 by 6 node system, which is shown in Fig. 5. The pressure tube and calandria tube has also a number of azimuthal nodes. The fuel channel has 12 nodal numbers in a flow direction. The FES is modeled by the fuel and cladding in CAISER code, while the material property is corrected to reflect the electric heater in the experiment.

Figure 6 shows the comparison results between the experimental data and the numerical simulation results of CAISER code. The FES temperature is compared for the inner, middle and outer ring rods (Fig. 6(a)). The temperature is shown to increase with the increase of electric power, and it increases steeply by the exothermal oxidation reaction above 1200K. The FES temperature at inner ring has the highest temperature, while the FES temperature at outer ring has the lowest temperature, since the heat sink of fuel bundle is located at the outside of fuel channel, which is cold water surrounding the fuel channel. It is revealed that the FES temperature distribution which is calculated by CAISER is in line with the experimental data.

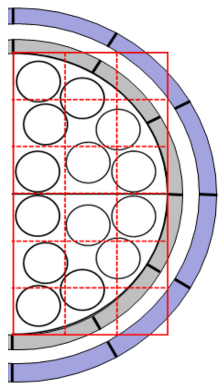
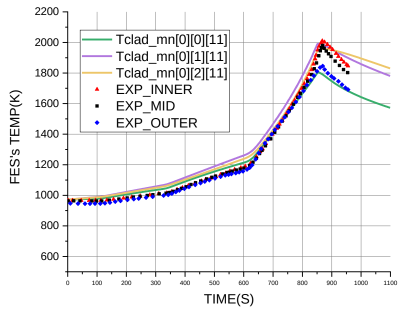
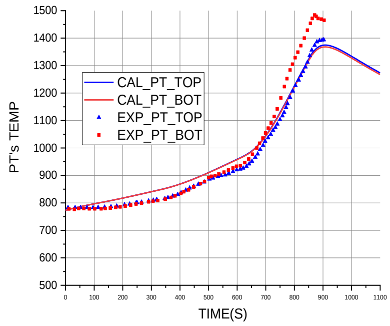


Figure. 5. CS28-1 nodal system in CAISER code

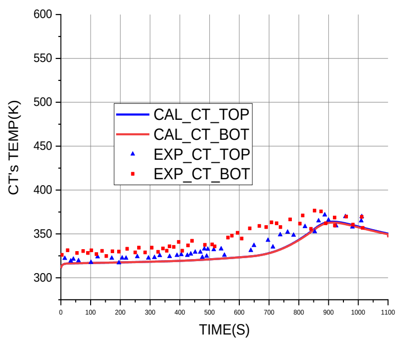
From the Fig. 6(b), it is shown that the pressure tube temperature of bottom region is higher than that of top region. Since the fuel rods experience the slumping in a high temperature condition, the fuel rods moves to the downward direction, which results the decrease of convective heat transfer from fuel rods, and the high coolant temperature in the bottom region, and it results to the high temperature of pressure tube in the bottom region.



(a) FESs temperature evolution



(b) A pressure tube temperature evolution



(c) A calandria tube temperature evolution

Figure. 6. Comparison of temperature distribution with the experimental data.

However, in the CAISER simulation, the coolant temperature has a temperature distribution only in a flow direction. That is, the coolant temperature is same on the cross-sectional plane. Hence, the pressure tube temperature is almost same between the top and bottom region. On the other hand, Figure 6(c) shows the calandria tube temperature is well predicted by the simulation of CAISER code.

3. CONCLUSIONS

From the necessity for the CANDU severe accident code having high accuracy to evaluate the allowable criterion on AMP, the detailed severe accident simulation code for CANDU reactor, CAISER has been developing in KAERI. The fuel channel module considers the water level change in a fuel channel, the melt & relocation process in a fuel channel, and the local thermal failure of a fuel channel by using 3-dimensional Cartesian coordinate node system. The CS28-1 experiment was simulated by using CAISER code, and compared with the experimental data. It is revealed that the FES temperature distribution is in line with the experimental data. However, the temperature distribution of the pressure tube shows little difference in an azimuthal direction, which is different with the experimental data, because the coolant temperature in CAISER code has 1-dimensional distribution in a flow direction. The effect of the local coolant temperature distribution on the cross-sectional section should be considered in a future.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (Ministry of Science, ICT, and Future Planning) (No. NRF-2017M2A8A4017283).

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