Core degradation modeling of CANDU severe accident code, CAISER

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1. Introduction

Recently, the acceptable standard of fission product release is definitely defined in the severe accident legislation. That is, in the analysis of PSA, the accident frequency that the cesium-137 release rate reaches 100 TBq 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.

In the case of PWR, there are several famous severe accident codes in the world, such as MAAP, MELCOR, CINEMA, RELAP-SCDAP, 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(1)-CANDU [1], MAAP-ISAAC [2]. 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 with 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 last year with 5 years plan.

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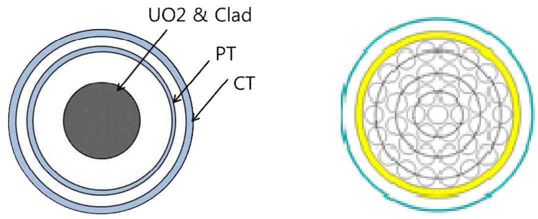
(1) MAAP is an Electric Power Institute (EPRI) software program that performs severe accident analysis for nuclear power plants including assessments of core damage and radiological transport. A valid license to MAAP4 and/or MAAP5 from EPRI is required.

This paper is aimed 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 existing codes. 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, the important severe accident phenomena in a fuel channel is difficult to model. 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 temperature of each ring is constant. And it results the distortion of hydrogen generation and the core degradation process in a fuel channel. Moreover, in the case of these node systems, it is difficult to model the fuel rod melt & relocation because the mass in each ring is also constant. And, the local fuel channel failure cannot be modeled because the pressure tube and calandria tube is modeled with a single node.



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

Fig. 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, 2-dimensional Cartesian coordinate node system is applied. Since it has 1-dimensional node for a flow direction, a fuel channel is modeled with 3-dimensional node system. The pressure tube and calandria tube has 1-dimensional nodal system in an azimuthal direction, which enable to model the local thermal failure of fuel channel.

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.

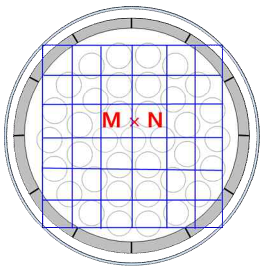


Fig. 2 Node system for a fuel channel in CAISER

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

$$\frac{dm^{clad}_{m,n,k}}{dt} = \varepsilon \frac{dm^{Zr,ox}_{m,n,k}}{dt} + w^{Zr,in}_{m,n,k} - w^{Zr,\mathrm{out}}_{m,n,k} + w^{ZrO2,in}_{m,n,k} - w^{ZrO2,\mathrm{out}}_{m,n,k} + \frac{dm^{clad,sagging}_{m,n+1,k}}{dt} - \frac{dm^{clad,sagging}_{m,n,k}}{dt}$$

Cladding energy conservation

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

Fuel mass conservation

$$\frac{dm^{fuel}_{m,n,k}}{dt} = w^{\mathrm{fuel},in}_{m,n,k} - w^{\mathrm{fuel,out}}_{m,n,k} + \frac{dm^{\mathrm{fuel},sagging}_{m,n+1,k}}{dt} - \frac{dm^{\mathrm{fuel},sagging}_{m,n,k}}{dt}$$

Fuel energy conservation

$$\frac{d(m^{fuel}_{m,n,k} h^{fuel}_{m,n,k})}{dt} = q^{dh}_{m,n,k} - q^{f-c}_{m,n,k} - q^{s,fuel}_{m,n,k} + q^{fuel,axi}_{m,n,k} + q^{fuel,vert}_{m,n,k} + q^{fuel,horiz}_{m,n,k} - q^{fuel,ext}_{m,n,k} + (w^{\mathrm{fuel},in}_{m,n,k} - w^{\mathrm{fuel,out}}_{m,n,k}) h^{melt}_{UO2} + \frac{d(mh)^{\mathrm{fuel},sagging}_{m,n+1,k}}{dt} - \frac{d(mh)^{\mathrm{fuel},sagging}_{m,n,k}}{dt}$$

In the above equations,

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

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

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

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

$q^{dh}_{m,n,k} = q'''^{dh}_{m,n,k} V^{fuel}_{m,n,k}$ is the nodal decay heat power,

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

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

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

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

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

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

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

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

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

$\frac{dm^{Zr,ox}_{m,n,k}}{dt}$ 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.

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

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

$w^{Zr,in}_{m,n,k}$ 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,

$w_{m,n,k}^{ZrO2,in}$ is the mass flow rate of molten Zirc oxide from node (m,n+1,k) to node-(m,n,k)

$w_{m,n,k}^{ZrO2,out}$ is the mass flow rate of molten Zirc oxide from node-(m,n,k) to node (m,n-1,k)

$h_{ZrO2}^{melt} = c_p^{ZrO2} T_{ZrO2}^{melt} + \lambda_{ZrO2}$ 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. The modeling for the pressure tube and calandria tube is developing in this stage.

2.3 Core degradation modeling in a Calandria tank

It is noted that the fuel channel integrity is closely related with a moderator water level as well as the thermal state inside a fuel channel. And, the mass & energy transport caused by a fuel channel failure is important in a calandria tank module. Hence, CAISER has nodalized the calandria tank with 3-dimensional node system in Cartesian coordinate, as shown in Figure 3. The calandria tank wall also has 3-dimensional node system in azimuthal, radial, axial direction, to simulate calandria tank failure.

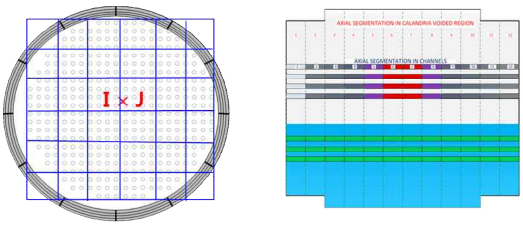
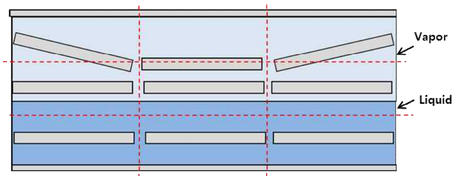
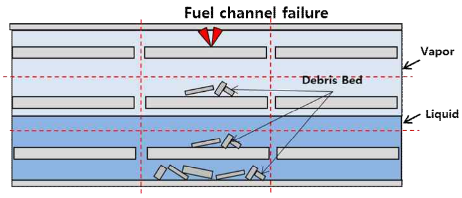


Fig. 3 Node system for a calandria tank in CAISER

For each node of calandria tank, the information of fuel channel, such as calandria tube temperature, fuel channel integrity, is given by the fuel channel module. On the other hand, the information of calandria tank, such as the moderator water level, the mechanical load on a fuel channel which is caused by a mass relocation of above fuel channel, is transferred to the fuel channel module. As shown in Figure 4, the fuel channel mass relocation is mainly happened by the sagging of a fuel channel, a fuel channel failure in the form of debris bed.



(a) Sagging of a fuel channel



(b) Fuel channel failure & debris bed formation

Fig. 4 Core degradation for a calandria tank in CAISER

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.

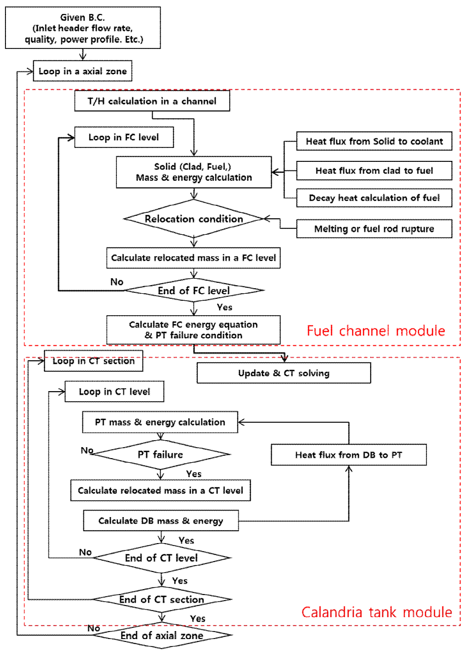


Fig. 5 Logic diagram for core degradation in CAISER

The modeling of a stratified flow in a fuel channel and thermal-hydraulics of moderator is important in the core degradation modeling, which are omitted in this paper. As shown in the logic diagram of figure 5, CAISER mainly consist of the fuel channel module and the calandria tank module, which interact each other every time step.

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 calandria tank module includes the sagging of a fuel channel, debris bed formation caused by a fuel channel failure, the molten pool formation and the calandria tank wall failure. The detailed modeling and the numerical results is developing in this stage and will be presented in the future.

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