Three-dimensional Multi-Physics Analysis of an Unprotected LOCA in the CANDU6 System

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1. Introduction

The reactor power change in a transient is determined by the change in reactivity caused by the coolant temperature, density and the fuel temperature variation during the transient. Especially in the CANDU6 reactor system, it is well known that the positive coolant void reactivity may cause a drastic power increase in a LOCA (loss of coolant accident) situation, and it is obvious that this phenomenon needs to be analyzed in detail and very carefully. For an accurate analysis of the LOCA, an integrated multi-physics code system including a neutronic code and a thermal-hydraulic code is required so that the detailed reactor feedbacks can be considered during the simulation.

In this work, a neutronic code COREDAX-2 [1] based on the AFEN method and a thermal-hydraulic system code MARS-KS [2] was coupled for a multi-physics analysis of a CANDU reactor. As a preliminary study, a LOCA scenario was simulated by the coupled code system.

2. Coupled Code System

In MARS-KS, there is a framework for a coupling calculation with a neutronic code, MASTER [3], through the DLL (dynamic-link library) as shown in Fig 1. In this work, the MASTER code was simply substituted by the COREDAX-2 code with some additional modifications in MARS-KS for simulation of the CANDU6 system. In the coupling calculation, MARS-KS provides the whole-core thermal-hydraulic data to COREDAX-2, while COREDAX-2 performs a neutronic calculation based on the provided thermal-hydraulic conditions. Then, MARS-KS performs a thermal-hydraulic calculation based on the power distribution determined by COREDAX-2.

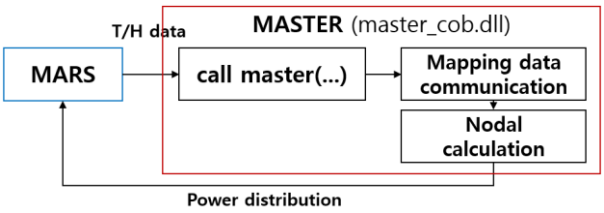

Fig. 1. MARS-MASTER coupling structure

2.1 Evaluation of CANDU-6 Cross Sections

The CANDU6 time-average model was used in the COREDAX-2 analysis. The bundle-wise time-average cross sections are generated by COREDAX-CANDU [4], which is a code system to generate the time-average model of the CANDU6 core. COREDAX-CANDU iteratively performs the COREDAX-2 calculation and the time-average calculation using a Windows batch script. On every time-average iteration, there are T/H corrections and also the equilibrium Xe/I correction on the bundle-wise cross sections. For the time-average calculation, the burnup-dependent cross sections and the incremental cross sections for the reactivity devices are required, and they are generated by CANDU6 lattice calculation using a Monte Carlo code Serpent2. [5]

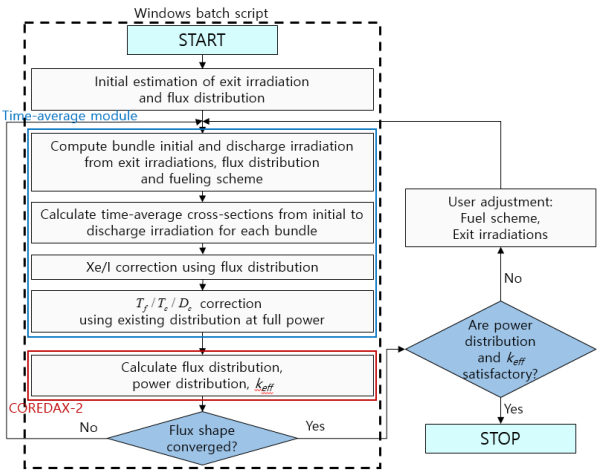

Fig. 2. Flowchart of COREDAX-CANDU

Above all, since the T/H feedbacks in the 3-D neutronic analysis are done based on the cross section change for the variation in the coolant temperature, density and the fuel temperature, the reliability of a multi-physics reactor analysis highly relies on the accuracy of the cross section derivatives, which means the change in the cross sections per unit change in each T/H condition. In this work, the cross sections derivatives were generated by Serpent2 branch calculations near the nominal conditions by which one can obtain the cross section derivatives on every burnup step. Using the burnup-wise derivatives, the bundle-wise derivatives were calculated in time-average sense also by COREDAX-CANDU.

2.2 Node Mapping

In COREDAX-2, the neutronic analysis was bundle-wisely performed with total 7560 nodes including the

reflector region. Meanwhile, in MARS-KS, total 380 channels of the CANDU core were divided into 4 large channels with considering the bi-directional flow of the coolant, and one of them was further divided into 7 small channels as shown in Fig. 3. Consequently, the CANDU whole core was modeled with total 10 channels in MARS-KS. Each channel consists of 12 nodes, so that the axial division of one channel is the same as in COREDAX-2.

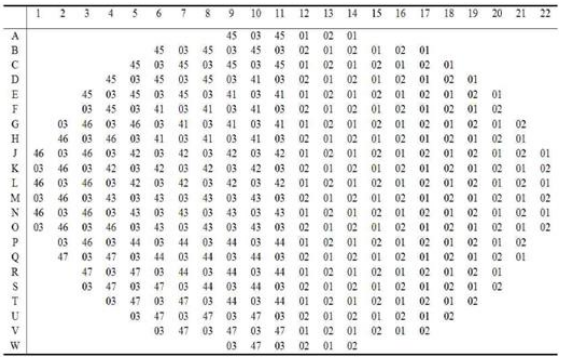

Fig. 3. Radial Mapping information

Since the node division of the whole core is not identical in two coupled codes, the node mapping data input needs to be provided. According to the mapping information in both codes, the whole-core mapping input for COREDAX-2 was appropriately prepared.

2.3 Transient Xe-135/Sm-149 treatment

Usually, the behavior of Xe/Sm concentration has not been considered during a short transient since it varies quite slowly. However, during such a transient with a drastic power increase cause by a LOCA, the effect of Xe/Sm on the power-increasing rate can be non-negligible. In this study, the effect of considering the Xe/Sm transient is also analyzed using an existing option regarding the transient Xe/Sm treatment in COREDAX-2.

If the transient Xe/Sm option is off, the equilibrium Xe/Sm macroscopic cross sections and derivatives are simply included in the bundle-wise cross sections and derivatives as if the Xe/Sm concentrations are fixed on equilibrium level during a transient analysis. Meanwhile, when the transient Xe/Sm option is on, the bundle-wise Xe/Sm concentrations are separately calculated at every time step, and the corresponding macroscopic cross sections and derivatives are added to the bundle-wise quantities.

3. Numerical Results

Basically, a steady-state analysis needs to be done prior to a transient analysis, so first a steady-state analysis was performed for initialization. From an initial neutronics state with initial guesses for the T/H conditions, the coupled analysis reached a steady state after about 210 coupled iterations. For the converged initial state, power distributions in 10 channels are compared with a reference profile in Table I, which is the relative power to the reference results. [6] It seems that the overall power distributions are quite close to the reference, while the error is relatively large near the vacuum boundary.

Table I-1: Relative power at the initial state (1)

Node #	Relative power (%)				
	Large channels			Small channels	
	1	2	3	4	5
1 (in)	100	102	98	93	93
2	101	101	98	93	94
3	99	100	97	92	94
4	98	99	96	91	94
5	97	97	95	89	94
6	97	98	96	90	94
7	97	98	96	90	94
8	97	98	96	90	94
9	98	99	97	91	94
10	100	99	98	92	94
11	102	101	100	92	94
12 (out)	103	100	101	91	92

Table I-2: Relative power at the initial state (2)

Node #	Relative power (%)				
	Small channels				
	6	7	8	9	10
1 (in)	95	100	100	100	111
2	96	100	99	100	110
3	96	100	94	97	108
4	95	99	93	96	108
5	97	98	91	95	107
6	96	99	92	96	108
7	96	99	92	96	108
8	97	98	92	95	107
9	96	99	93	96	109
10	96	100	93	97	109
11	96	100	97	100	111
12 (out)	95	99	98	101	111

With the restart files for each code generated by above steady-state analysis, an unprotected LOCA analysis was performed. In Fig. 4, the results were compared to the conventional results from a MARS stand-alone simulation that uses a pre-calculated time-dependent power distribution tables. In the LOCA simulation, it was assumed that 35% of reactor inlet header is broken at time 0. In the MARS stand-alone simulation, it was assumed that the reactor is properly tripped or shut down by the reactor protection system right after the LOCA occurs. However, in the current work, an unprotected LOCA situation was simulated by the MARS-COREDAX-coupled simulation. Regarding

the xenon model during the fast transient, two cases, with or without transient xenon modelling, were compared in this unprotected LOCA simulation.

From Fig. 4, one can note that the initial power excursion is rather similar for the two simulations although the excursion rate is even slightly lower in the new unprotected MARS-COREDAX analysis. It is noteworthy that the coupled simulation terminated at about 2.4 seconds after the LOCA since the MARS-KS system was broken due to the unusual T/H conditions in the CANDU6 system. Figure 4 clearly demonstrates that the reactor power can increase very quickly in an unprotected LOCA and the normalized power can be over 30 in only about 2.4 sec.

Meanwhile, due to the consideration of the transient neutron poisons, the power-increasing rate is increased. In such a power-increasing transient, the concentrations of Xe/Sm decrease since they burn faster than in a steady state, and it gives a positive reactivity to the reactor so that the power-increasing rate is amplified. Even though the T/H calculation was shutdown at only ~2.4sec, one can clearly observe a significant difference between the two different Xe considerations. The small difference at 2.4sec can be a lot larger after just few seconds since the power increases exponentially. Consequently, it seems that the impact of considering the transient neutron poisons is rather sizable and it should be correctly modelled for a better understanding on the LOCA in CANDU6.

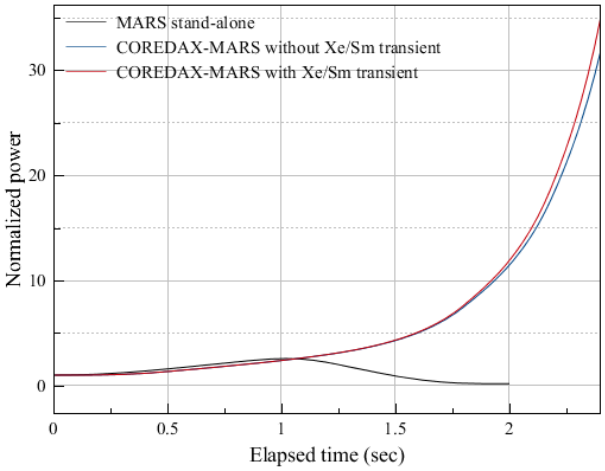

Fig. 4. LOCA analysis comparison

From Figs. 5 to 7, the detailed T/H conditions in each channel were plotted. In this LOCA analysis, the break occurs at inlet header of channel 4, which consists of 7 small channels. First, the maximum fuel centerline temperature of each channel is plotted in Fig. 5. It is observed that the maximum fuel centerline temperatures of all channels quickly increase following the channel power over the transient and it is expected that the centerline fuel temperature will reach UO_2 melting temperature in a few second in this unprotected LOCA. In channel 4, the boiling point of coolant is lowered in a moment due to the rapid depressurization, so there is a rapid boiling of the coolant, which is clearly observed in Fig. 7. At the same time, the maximum temperature of the coolant in the liquid state is slightly reduced due to the rapid depressurization. In other channels without the inlet header break, the maximum coolant temperatures simply increase as the power increases.

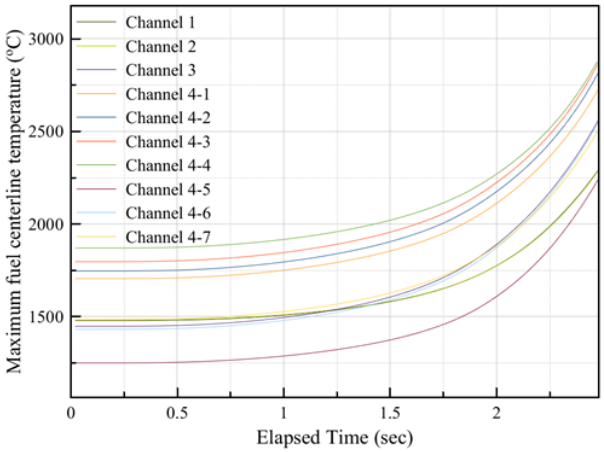

Fig. 5. Maximum fuel centerline temperature

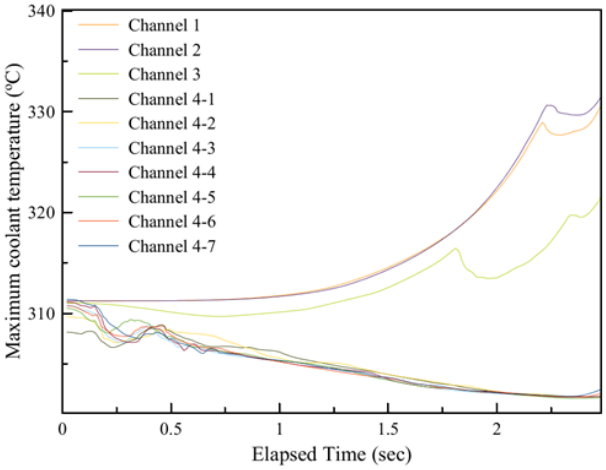

Fig. 6. Maximum coolant temperature (Liquid)

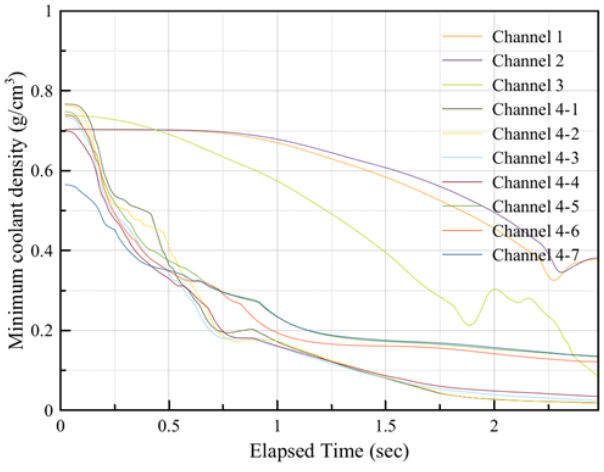

Fig. 7. Minimum coolant density

4. Conclusions

For accurate 3D multi-physics analysis of CANDU6 reactors, a neutronic code COREDAX-2 and a thermal-hydraulic code MARS-KS have been successfully coupled using the DLL scheme. For a deeper understanding of the unprotected LOCA in CANDU6, a LOCA transient analysis were performed using the coupled MARS-COREDAX code system, and it was shown that the coupled analysis can provide physical and reasonable results when compared with the conventional analysis. In the future, the coupled code system will be refined and extended for more accurate and realistic simulation of the unprotected LOCA situations.

ACKNOWLEDGMENTS

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