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Comparison of large LWR to SMR under LOCA for future development of autonomous operation algorithm

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1. Introduction

Recently, the development of a small modular reactor (SMR), which can be manufactured in a factory and installed and operated in multi-unit is receiving global attention. However, human error will have a larger consequence than the large nuclear power plant and therefore there is a strong need to reduce the human error if the SMRs were to operate in multi-unit with small number of operators per reactor. Thus, to decrease human error probability and increase safety and economic feasibility of SMRs, the development of autonomous operation system is necessary. The center of autonomous small modular reactor research (CASMRR) in Republic of Korea is now developing an autonomous transportable on-demand reactor module (ATOM) [1]. As a part of development of autonomous operation for ATOM, the authors propose to study the applicability of autonomous operation of the SMR compared to the existing large PWR.

In this paper, the authors will use the system thermal-hydraulic (STH) code to track the accident initiator of a large water-cooled nuclear power plant and discuss how this method can be useful for the multi-unit operation of SMRs that can be potentially staffed by a smaller number of operators per unit. Accident initiator tracker is simply obtaining the initial condition (i.e. root cause of the accident or transient) with given behavior of the system. Further details will be discussed below.

2. Accident Initiator Tracking Problem

The authors have used a loss of coolant accident (LOCA) in the pressurized water reactor system as the first sample problem to show the usefulness and implication of developing the intelligent autonomous operation system of large NPPs and SMRs.

In this paper, as the first attempt to develop an initial condition tracking system, only the break size is first searched. In other words, the system is formulated such that the code has to determine the break size when the code "knows" the followings:

1. Break location
2. Nodalization (in other words numerical representation of the real system)
3. The initial condition of the PWR

In order to verify the relationship between the measurement information and the initial condition of the accident, the authors used the measurement information of the primary system under the accident situation (i.e. pressurizer pressure trend in accident progress time).

2.1 Problem Definition

To test the accident initiator tracking system for LOCA of large NPP, Korea Standard Nuclear Power (KSNP, i.e. OPR1000) reactor is selected as the reference reactor. MARS-KS nodalization of the reactor input is shown in Figure 1.

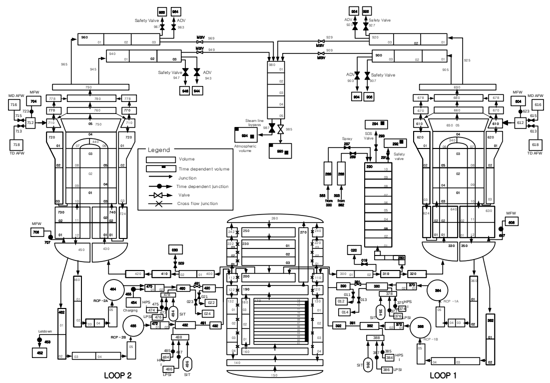

Fig. 1. Nodalization of KSNP for LBLOCA analysis.

The authors developed a separate SMR input deck based on the available information of the open literature for this study. MARS-KS nodalization of the SMR is shown in Figure 2. The selected reference accident scenario is a break at the pressurizer safety valve line. Location is highlighted by red circle in Figure 2. Break condition is set to be the same to KSNP LOCA analysis.

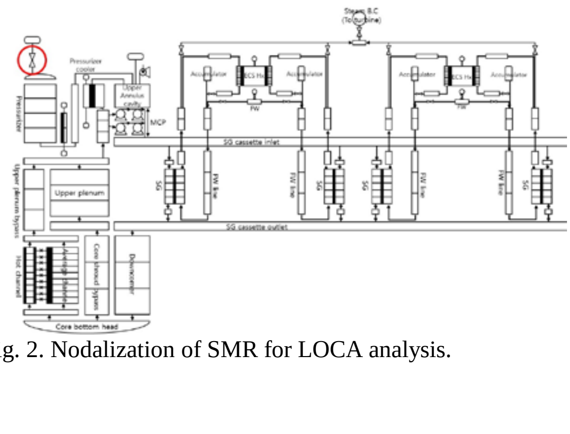

Fig. 2. Nodalization of SMR for LOCA analysis.

In this study, the correct break area size of LOCA by initial condition tracking system is searched by comparing the reference primary system measurement variables (i.e. a large break at the cold leg in front of the pump discharge in loop 1) to the newly calculated primary system measurement variables from the assumed break size. Peak cladding temperature (PCT), which is one of most important variables in LWR safety criteria is used as a search variable. Figure 3 shows the algorithm for initial condition tracking system.

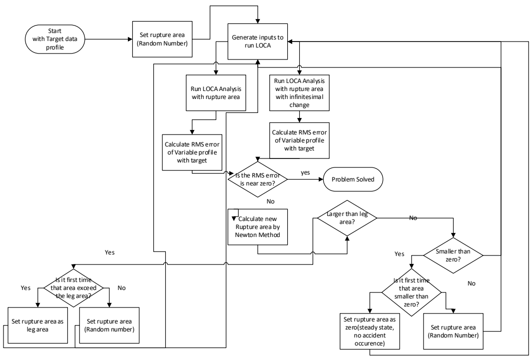

Fig. 3. Algorithm for Initial Condition Tracking System.

2.2 Preliminary Results

The first results are from the case of cold leg complete double guillotine break. From the industrial and regulatory point of view, this case is one of the most severe design basis accidents and it is often analyzed to test the success of the emergency core cooling system (ECCS) design. Numerically since the break size is the upper extreme of the physically possible break size, it was thought that the calculation will be much more straightforward than the smaller break size. It was also thought that the large break LOCA (LBLOCA) can be first used as a testing case for identifying any logical or programmatic flaws in the constructed in-house code.

Figure 4 shows history of how the in-house code is searching for the target reference break area. From the upper left corner of the figure, the result of tracking through core inlet temperature, core outlet temperature, PCT and pressurizer pressure are shown respectively. As mentioned earlier, the code “knows” the initial steady state and the break location of the reference case. The in-house code needs to find a break size that matches the reference variable profile. In this case, the initial condition tracking program finds target area with less than 10 iterations for each case.

For the second test case, the break size is now reduced to 0.15m^2, which is a randomly selected break area to test the robustness of the current algorithm. Figure 6 shows the calculation results. From Figure 5, it is clearly shown that the iteration started from much larger break size than the target break size and this caused significant fluctuation in the guessed break size estimation during the iteration. In this case, unlike a guillotine break LOCA, more than a dozen iterations were required for initial condition tracking.

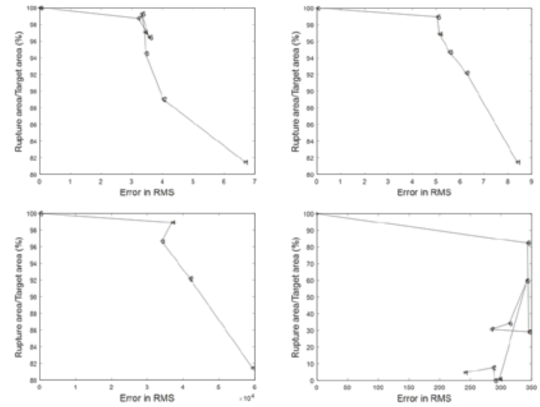

Fig. 4. Iteration history of LBLOCA in PWR

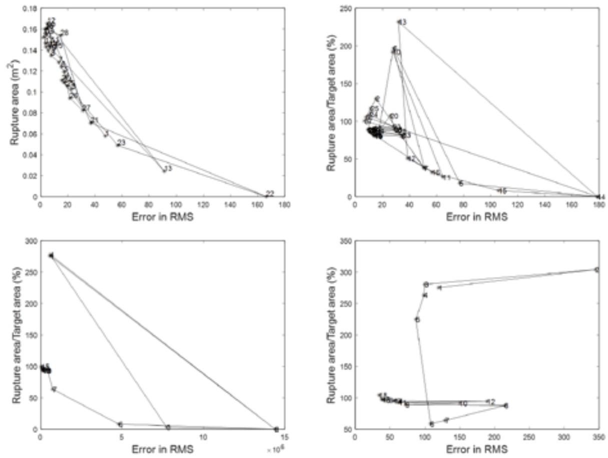

Fig. 5. Iteration history of LOCA with smaller break size in PWR.

Next, results of SMR case are presented and these are obtained from the case of pressurizer safety valve break. For the SMR case, calculations were performed for three different break sizes. For the first test case for SMR, the break size is set to 0.001m^2. Figure 6 shows the calculation results with comparison of pressurizer pressure. In this case, the initial condition tracking program finds target area relatively quickly with less iteration numbers compared to the large PWR case. Also, calculations were done for break size 0.0005 m^2 and 0.002 m^2. Figures 7, 8 and 9 show the results for break size 0.0005 m^2, 0.001 m^2 and 0.002 m^2 respectively. From the upper left corner of the figure, the result of tracking with core inlet temperature, core outlet temperature, PCT and pressurizer pressure are shown, respectively. In this case, the initial condition tracking program finds the target area with less than 10 iterations for each case. In the SMR case, the initial condition tracking program finds target area quickly regardless of the break size. This is because the sensitivities of SMR calculations for break size have more linear characteristics than the sensitivities of large PWR calculations.

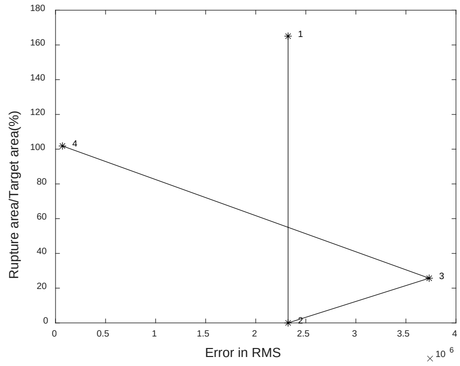

Fig. 6. Iteration history of SBLOCA in SMR with break size $0.001 m^2$ – pressurizer pressure comparison.

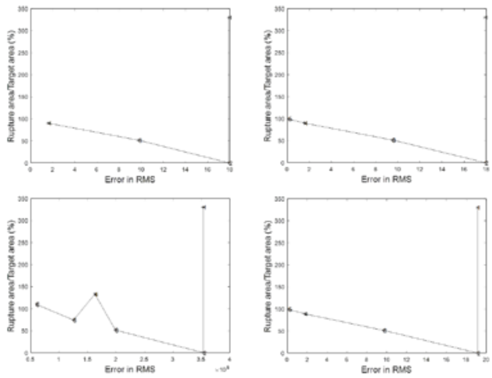

Fig. 7. Iteration history of SBLOCA in SMR with break size $0.0005\ m^2$ – Core inlet/outlet temperature, peak cladding temperature and pressurizer pressure.

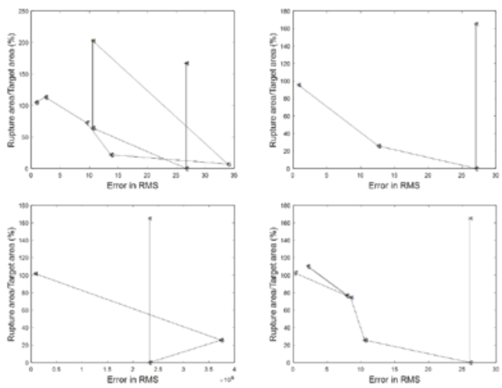

Fig. 8. Iteration history of SBLOCA in SMR with break size $0.001\ m^2$ – Core inlet/outlet temperature, peak cladding temperature and pressurizer pressure.

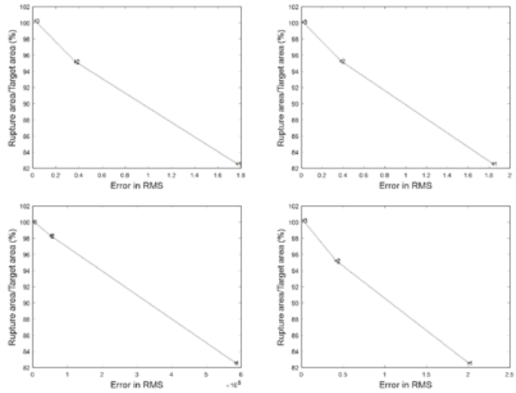

Fig. 9. Iteration history of SBLOCA in SMR with break size $0.002\ m^2$ – Core inlet/outlet temperature, peak cladding temperature and pressurizer pressure.

2.3 Discussion

The first to be discussed is the relationship between the break size and the maximum PCT. In general, it is often taken for granted that as the break size area increases the maximum PCT during the event will become higher. However, in Figure 10, it can be seen that there is a large nonlinearity between the calculated results when the break size is small. If the break size cases around the $0.05 m^2$ break are studied closer, the non-linearity of the calculation is more clearly shown.

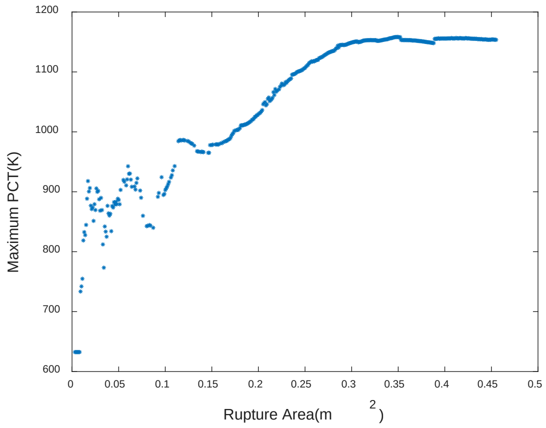

Fig. 10. Highest PCT for different break size – Large PWR.

Another interesting issue that can be identified from Figure 11 is that the maximum PCT does not occur at the largest break instead it occurred at around 90% break of the total cold leg cross-sectional area. Figure 11 compared the 100% break case to the 90% break case. From Figure 11 it is clearly shown that the 90% break blowdown peak is about 2 K higher (90% break is 1157.3 K while 100% break is 1155.3 K) than the 100% break case PCT. However, the reflood peak (the second peak) is more important for the nuclear fuel integrity from the practical point of view and the 100% case definitely has higher reflood peak than the 90% break case.

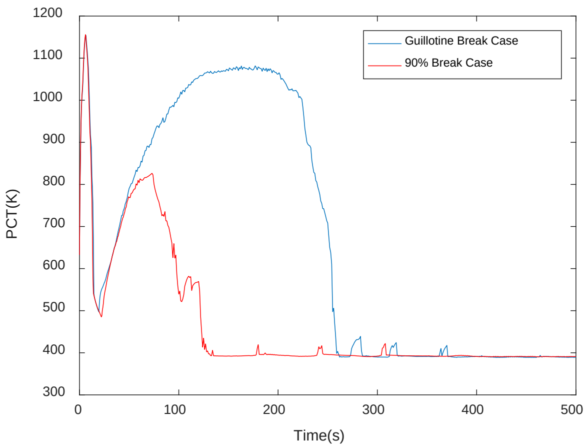

Fig. 11. PCT Profile for selected break size areas in large PWR calculation.

In case of SMR, the maximum PCT was increased as the break size decreased. And when the break size is larger than 0.0011 m^2, the maximum PCT does not exceed the maximum cladding temperature of normal operation. This is shown in Figure 12.

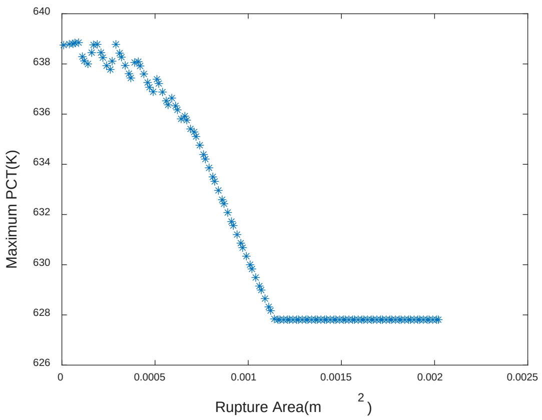

Fig. 12. Highest PCT for different break size – SMR.

To explain the reason why tracking the break size under SMR conditions was faster (in other words why SMR case shows more linear characteristic in accident initial tracking problem), the minimum coolant inventory to reactor power during problem time of two reactors are plotted in Figure 13 and Figure 14. For the large PWR case, the minimum coolant inventory to reactor power during problem time shows a steep slope change under 0.25 m^2 rupture area. Oscillation is shown between guillotine break and 0.25 m^2 rupture area. However, in SMR case, the minimum coolant inventory to reactor power during problem time shows a linear change under 0.0006 m^2. It is similar to the maximum PCT for different break size trends, a large PWR case shows more nonlinearity in Figure 10.

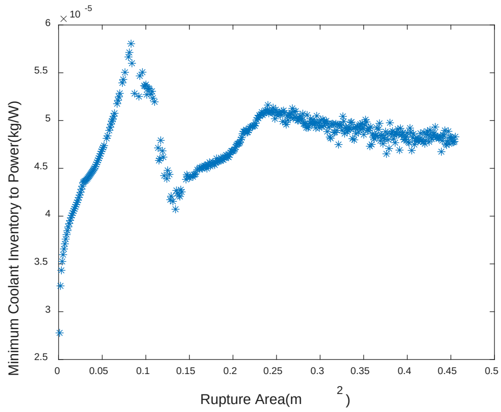

Fig. 13. The minimum coolant inventory to reactor power during problem time – Large PWR

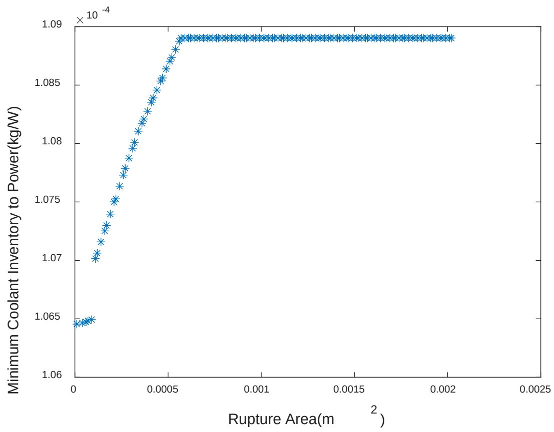

Fig. 14. The minimum coolant inventory to reactor power during problem time – SMR

3. Summary

The results showed some success of correctly identifying the break size when the break location is given with large PWR and SMR conditions. New phenomena, such as nonlinearity issue can be identified with large PWR conditions. On the contrary, high linear characteristics are shown for SMR conditions. For this reason, tracking the break size under SMR conditions was faster with the suggested algorithm. Since the sensitivity and response of SMR are more linear than those of a large PWR, the number of training sets can be reduced in case of using machine learning method for autonomous operation later.

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