Feasibility analysis of flooding safety system of ATOM during early phase of accident by using MELCOR code

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1. Introduction

Recently small modular reactor (SMR) has been highlighted with its advantages such as enhanced safety and flexibility to the grids [1]. Because the SMR systems are modularized, simplified, and integrated with key components, the possibility of loss of coolant accident (LOCA) which is a representative design basis accident (DBA) can be reduced significantly. In addition, owing to the lower thermal power and smaller pressure drop compared to large commercial reactors, more aggressive passive safety systems can be deployed for the SMR. Consequently, the safety of the SMRs are expected to be enhanced significantly by securing long-term safety without any active systems or with only minimum active systems.

NuScale Power Module (NPM), the representative SMR, proposed an outstanding passive safety system achieving an indefinite grace period [2]. To control the flammability of hydrogen and to prevent the heat loss from the reactor pressure vessel (RPV), weakly vacuumed containment vessel (CNV) is adopted for the NPM. 12 NPM modules are designed to be submerged in a common pool (CP) acting as an ultimate heat sink during an accident. During loss of coolant accident (LOCA), reactor vent valves (RVVs) installed on the top of the RPV are operated to depressurize the RPV. Subsequently, the released steam is condensed on the inner wall of the CNV. When the sufficient condensate is accumulated in the CNV, the condensate water can be resupplied into the core through recirculation valves on the RPV. By using this emergency core cooling system (ECCS), the decay heat in the RPV can be removed through the water in the CP. During non-LOCA accidents, decay heat removal system (DHRS) connected to steam generators (SG) is actuated. The DHRS transfers the heat from SGs to heat exchangers installed in the CP. Consequently, the decay heat from the reactor module is transferred to the coolant in the CP under postulated accidents. The water is expected to be depleted by boiling on the CNV wall after 30 days since reactor shutdown for the thermal power of 160 MWt [2]. Nonetheless, the core integrity can be secured because the decay heat decreases less than 0.4 MWt, which is sufficiently low to be removed by air-cooling.

Despite innovative concept of the NPM passive safety system, however, several limitations such as more heat loss due to the radiative heat transfer [3], difficult approach for management, and inadvertent interfering effects of an accidental module to other reactor modules are expected under submerged condition in a CP even during the normal operation. Moreover, large inventory of the CP is required for SMRs with higher thermal power SMRs such as mPower (530 MWt) [4], WSMR (800 MWt) [5], and ATOM (450 MWt) [6], to mention a few. Larger emergency coolant inventory results in more difficult maintenance of reactor modules and higher initial costs. Thus, further requirements suggested below could contribute to improving the NuScale's safety system.

- ✓ Maintaining reactor module cavities as separate and dry during the normal operation but can be flooded during an accident.
- ✓ Securing an additional passive safety system to sustain the long-term coolability.

Recently, a research team of Hanyang University and KAIST proposed a flooding safety system (FSS) shown in Fig 1, which can achieve the requirements mentioned above for development of an advanced design of SMR [7]. Emergency coolant is stored in the centralized CP and separate cavities are maintained dry during normal operation. During the postulated LOCA and accidents with overpressure of the RPV, the emergency coolant is supplied from the CP into the cavity through flooding valves which can be operated both passively and actively. Power and opening signal of the flooding valves are supplied by DC batteries. In addition, fail-safe concept is adopted to the flooding valves that makes the valves to be opened at the failure of the valves. During the accidents induced by insufficient cooling capability of secondary system, passive residual heat removal system (PRHRS) is actuated and the heat from the SGs is transferred to the auxiliary pool working as an emergency cooldown tank (ECT). As the heat is transferred from the reactor modules during an accident, the coolant is boiled on the CNV and on the heat exchangers in the auxiliary pool. To sustain the coolability, the vaporized coolant is condensed by the condenser installed on the ceiling of the plant building and re-collected into the CP or auxiliary pools. The re-collected coolant is resupplied into the module cavities or to the auxiliary pools. To investigate the described heat transfer mechanism and especially the coolability of the FSS, a lumped analysis was carried out to assess the long term coolability. As shown in Fig. 2, the longer grace period can be achieved with higher condensate re-collection. In the previous study, an immediate flooding was assumed to work. If the flooding is not performed promptly, however, the core damage may not be avoided due to the insufficient coolability.

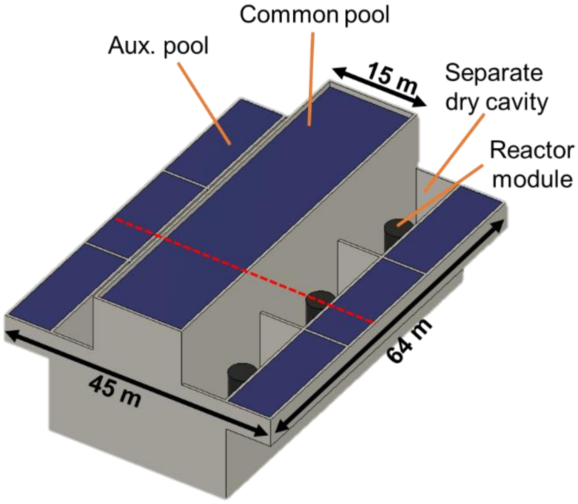

Fig. 1. A schematic of FSS

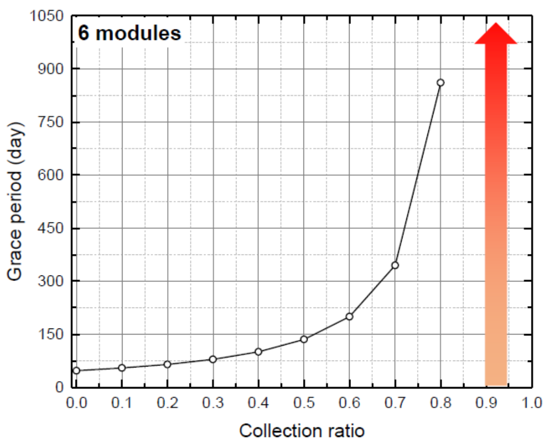

Fig. 2. Effect of recollection ratio on the grace period [7].

The objective of this study is to investigate the requirements of the flooding paths which can supply sufficient emergency coolant into the reactor module cavities before the core damage. The required time to submerge the reactor module with flow path conditions and time to core uncovery during LOCA were investigated by numerical analysis with MELCOR code. Consequently, the requirements for the flow paths were determined by comparing the grace periods.

2. Methodology

2.1. Reference reactor

A reference reactor chosen for this study is an Autonomous, Transportable, On-demand, and Modularization (ATOM). ATOM is an innovative SMR, whose thermal power under initial development stage was 330 MWt [8]. Recently, the power rating of the ATOM has been increased by as much as 450 MWt. The major components such as reactor core, 8 helical SGs, 4 reactor coolant pumps, and a pressurizer are integrated in a reactor module. 6 reactor modules are envisioned to be installed in a plant building. Similar to the recent SMR designs, a CNV is employed to confine the RPV. The diameters of the RPV and CNV are set as 4.6 m and 4.9 m, respectively. Automatic depressurization system (ADS) is installed on the top region of the RPV for depressurization of the RPV. ADS is actuated when RPV pressure exceeds 17.4 MPa. In addition, recirculation valve installed on the RPV connects the CNV and RPV.

2.2. Flooding Safety System (FSS)

Figure 3 shows the configuration of the FSS. The FSS consists of the centralized CP, 6 separate dry cavities, flooding valves, condenser above the CP, and auxiliary pools containing the emergency cooldown tank (ECT) of the PRHRS. The CP is a large inventory of emergency coolant. The CP also plays a role of the spent fuel pool, the total water level was set as 12 m from the bottom of the CP. Thus, the water level for the spent fuel pool should be higher than 2 m due to the length of the fuel rods. To fill 6 separate cavities, the available volume of water in the CP was set as 6 times the cavity. The volume of each cavity is 1,568 m^3. In case of the LOCA of several reactor modules, emergency coolant in the CP is supplied into the cavities as the integrated circuit (IC) logics to operate the flooding valves. As the coolant in the cavity is evaporated due to the transferred heat from the reactor, the steam is condensed on the condenser installed on the ceiling of the plant building. Therefore, condensed coolant can be recollected into the CP or auxiliary pools again. To ensure sufficient condensation performance, the heat transfer area of the condenser was set as 260 m^2.

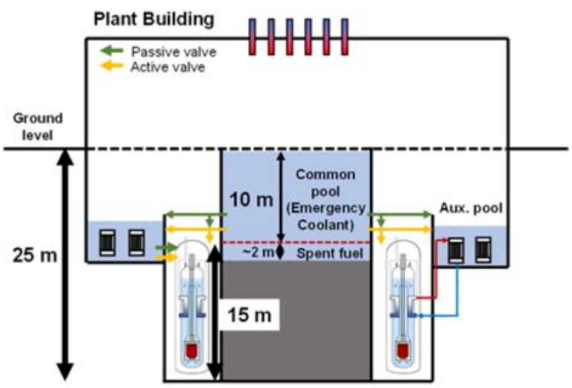

Fig. 3. A conceptual schematic of FSS

2.3. MELCOR model of reference reactor and flooding safety system

MELCOR input model of 330 MWt SMR and FSS was used for the flooding time investigation. Figs. 4 and 5 show the MELCOR nodalization of 330 MWt SMR and FSS modeling, respectively. Main components of the model are as follows, core channel (CV200), upper plenum (CV260), steam generator primary side (CV1~40), downcomer (CV160), pressurizer (CV300), and steam generator secondary side (CV 41~80). The model includes 4 SGs. Components of primary and secondary side SGs are divided into 10 volumes along the flow path direction. ADS ventilation valve connects the top section of the pressurizer and CNV volume. The flow area of the ADS ventilation valve was modeled to be 1.0134×10^{-4} m^2. CV900 represents the CP, CV995 a single cavity, and CV910 the combined volume of other cavities. Thus, the volume of CV910 is five times larger than the volume of CV995. CV910 is connected to the CP through 5 valves while CV995 is connected to the CP through single valve. In 6 cavities flooding case, both the CV995 and CV910 are flooded. In this study, every simulation cases assume flooding of all 6 cavities. Form loss coefficient of each valve was set as 1.5. Loss coefficient at pipe entrance from large pool reservoir and exit of pipe are 0.5 and 1.0, respectively. The valve was assumed to have short and simply straight, a pipe-like structure.

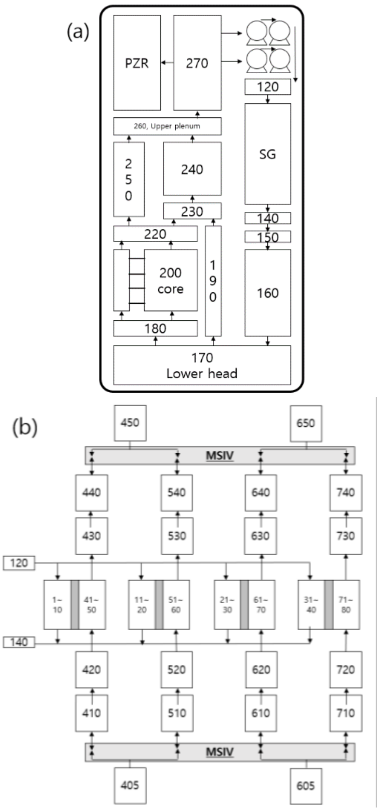

Fig. 4. MELCOR nodalization of SMR (a) primary system, (b) secondary system

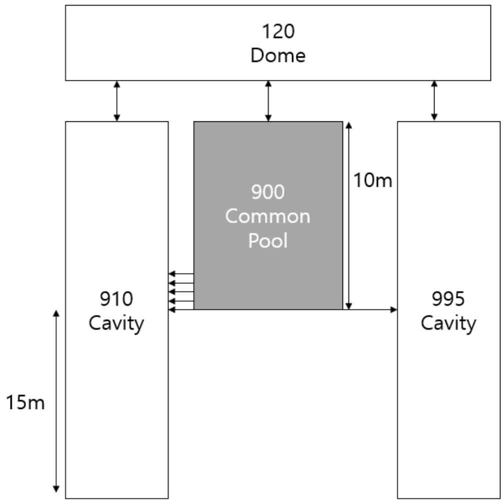

Fig. 5. MELCOR nodalization of FSS

2.4. Accident scenario and simulation matrix

Malfunction of the ADS accident, whose accident sequence is similar to the LOCA, was postulated as the accident scenario. In the scenario, ADS ventilation valve was accidently opened during normal operation. As the steam was released into the CNV through the ADS ventilation valve, RPV pressure rapidly decreased. As soon as the accident occurred, the reactor was shut down due to the reactor low pressure signal. Subsequently, reactor coolant pumps and feed water pumps stopped and forced coolant flow disappeared. To depressurize the RPV in a short time, the recirculation valve was opened as soon as the accident occurred. Other safety systems such as the PRHRS were excluded for conservative approach. The time when the coolant level of the core started to decrease was regarded as core uncovery time.

To evaluate the performance of the flooding valve, flow area and the number of the valves were set as shown in Table 1. The flooding times until the water level reached the 15 m with the conditions were investigated. Apparently the flow area affects the flooding time due to the coolant flow rate and pressure drop. To ensure multiplicity, multiple valves were envisioned to be installed in the CP. Accordingly, the effect of multiple valves on flooding time was also assessed. To confirm the effect of the flow area, single valve for each cavity was set. To confirm the effect of the number of valves, flow area of each valve was set to be 0.02 m^2. Time of the simulation was set for 10,000 seconds (2.778 hours).

Table 1. MELCOR simulation matrix

Flow area (m^2)	0.02	0.04	0.06	0.08	0.1
Number of valves	1	2	3	4	5

3. Results and discussion

3.1. Core uncovery time

To investigate the time to core uncovery, ADS malfunction accident was postulated as the accident scenario. As soon as the ADS ventilation valve and recirculation valve were opened, the coolant in the RPV was released into the CNV. Accordingly, the primary system pressure decreased rapidly as shown in Fig. 6. As the RPV was depressurized, the primary coolant started to boil. Consequently, the water level of the core decreased. As shown in Fig. 7, it took approximately 1 hour to the uncovery. Thus, to prevent core uncovery, the flooding needed to be completed within an hour since reactor shutdown.

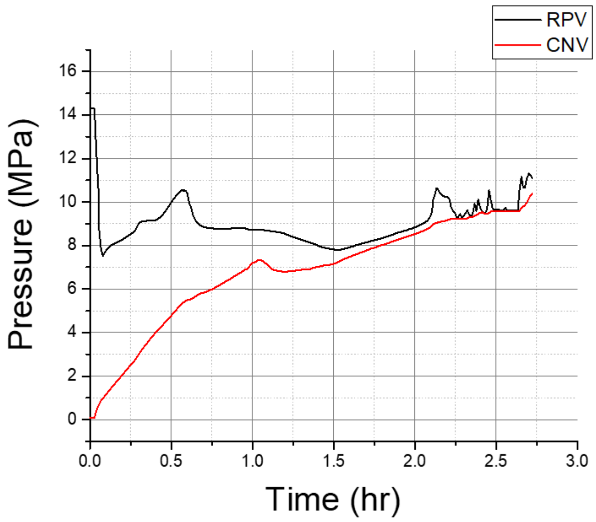

Fig. 6. Pressure of the RPV and CNV

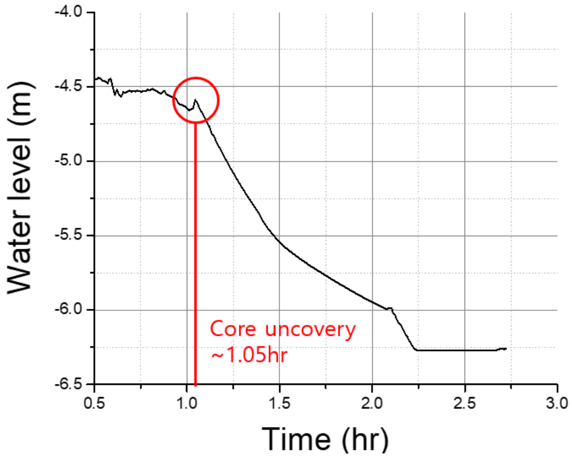

Fig. 7. Core channel water level

3.2. Cavity flooding time with valve parameters

The water level of the CP decreased as the water was supplied from the CP into the cavities. Accordingly, the flow rate was also reduced due to the reduced hydrostatic head by the water level change over time. As the flow rate became extremely low after the water level exceeded 14.9 m, which is 99.3% of the cavity depth, the flooding was assumed to be completed when the coolant level reached 14.9 m.

Table 2 and Figure 8 show the time to flooding the cavities with different flow areas of the emergency coolant supply line from the CP. The case of the larger flow area showed the shorter flooding time. The driving force of the flow was induced by the pressure difference between the inlet and outlet of the flow path. In other words, the driving force per unit flow area was determined by the water level. In addition, larger flow area exhibited the lower flow resistance induced by frictional head loss due to the larger flow diameter. Thus, large flow area could supply emergency coolant faster than small area due to the higher driving force and less pressure drop. The simulation results showed that flow area 0.02 m^2 and 0.04 m^2 completed the flooding after the core uncover. However, flow area with 0.08 m^2 and 0.1 m^2 completed the flooding before the core uncovery. The flooding completion time of the flow area 0.06 m^2 case was later than the core uncovery. However, the water level of the cavity was 14.7 m at the core uncovery time. The sufficient coolability was expected due to the 98% submerged CNV. Nonetheless, more detailed analysis on the heat transfer is required.

Table 2. Flooding time results along the flow area of the valve

Flow area (m^2)	0.02	0.04	0.06	0.08	0.1
Flooding time (hr)	NA	1.68	1.11	0.83	0.67

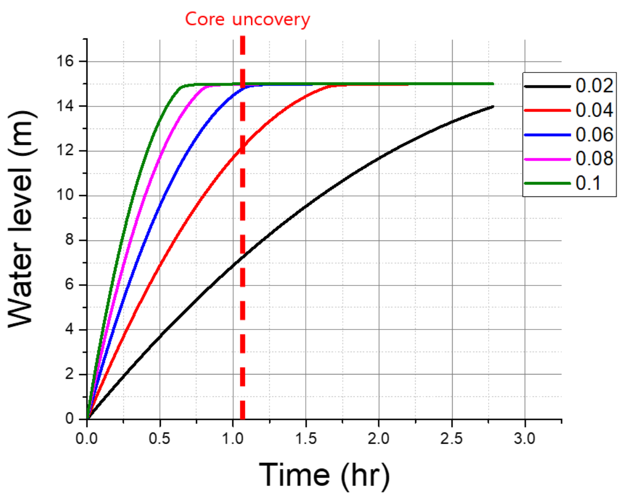

Fig. 8. Cavity water level with the flow area of the valve

Table 3 and Figure 9 show the time to flooding the cavities and flooding time delay by the multiple valves according to the different number of the coolant supply lines. Flooding time of the multiple valves was delayed approximately by 0.01 hr from a large valve with identical total flow area. The reason of the delay is extra head loss due to the smaller flow area. However, the flooding time difference from the head loss did not show significant change. Consequently, multiple valves can be recognized to have the same effect with a valve having same total flow area.

Table 3. Flooding time results along the number of the valves

Number of valves	1	2	3	4	5
Flooding time (hr)	NA	1.69	1.12	0.84	0.68
Flooding time delay (hr)	NA	0.012	0.011	0.011	0.01

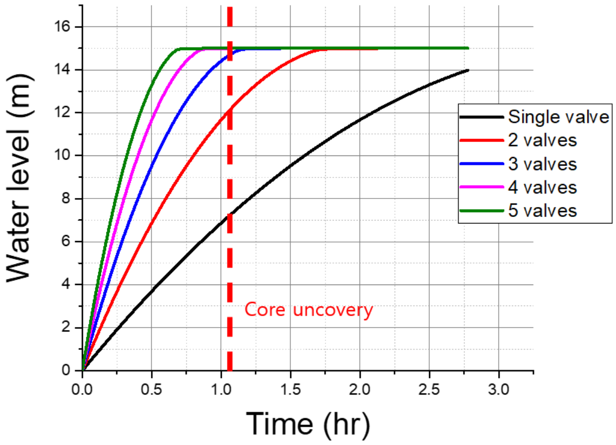

Fig. 9. Cavity water level with the number of valves

4. Conclusion

In this study, required flooding time of FSS to sustain core integrity was investigated by LOCA analysis of the 330 MWt SMR (ATOM) by using MELCOR code. Core uncovery was used as an indicator of the flooding time limit to prevent severe accident. With the result of the accident analysis, requirements of the flooding valves of the CP to complete the flooding before the time limit was derived. Two valve parameters, flow area, and the number of the valves, were selected as the sensitivity parameters. The results of the study are summarized below.

- ✓ As soon as the ADS ventilation valve opened, RPV pressure showed rapid decrease. After 1.05 hr of the accident, the coolant level of the core started to decrease (start of core uncover).

- ✓ Flooding time of the flooding valve was insufficient when the flow area of the valve was 0.02 m^2 and 0.04 m^2. On the other hand, flooding time of the valve with flow area 0.08 m^2 and 0.1 m^2 could avoid the core uncovery.

- ✓ Flooding valve having flow area 0.06 m^2 completed the flooding after 1.11 hr, which can be considered as a close failure. However, at the core uncovery time, coolant level of the cavity was 14.7 m, at which sufficient coolability was expected.

- ✓ Despite the more frictional head loss, multiple valves showed ignorable flooding time delay.

Acknowledgments

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