

Study of an Integrated Passive Safety System for a Research Reactor

K.Y. Lee¹, H.G. Yoon²

- 1) Department of Mechanical and Control Engineering, Handong Global University, Pohang 37554, Korea
- 2) Korea Atomic Energy Research Institute, 111 Daedeok-daero, Yuseong-gu, Daejeon, 34057, Korea

Corresponding author: kylee@handong.edu

Abstract. An integrated passive safety system for a research reactor was suggested to improve the safety of the research reactor. This integrated system has three roles in a facility as a decay tank, siphon breaker, and long-term cooling tank. To design and optimize the decay tank and the siphon breaker of the integrated passive safety system, CATIA program was used to design 3D model, and flow fields were simulated by ANSYS Fluent. From the simulation result we could satisfy the design requirement of the decay tank, that is 60s minimum flow residence time. Also, the performance of new type siphon breaker was tested. An 18-inch diameter size siphon breaker was designed at the roof of decay tank's 3rd section, and we could observe siphon breaking phenomena that can prevent a severe accident of the research reactor. By locating siphon breaker at 3rd section of decay tank, we could also use the coolant of the front three sections for a long-term cooling of the research reactor.

1. Introduction

Research reactor is a nuclear facility to produce neutron transmutation doping (NTD) and radioisotope (RI) and to research using neutron in the reactor, such as neutron radiography (NR). The safety related devices in a research reactor are decay tank and siphon breaker. Decay tank is the device to provide sufficient flow residence time to decrease N-16 activity in the primary coolant passing the reactor core. N-16 has the most high-strength γ -rays among many kinds of radionuclides in the primary coolant. The N-16 dose rate at the inlet of the decay tank is much larger than those of other radionuclides. Fortunately, its half-life is very short, only 7.13 second, and the dose rate of N-16 decreases as flow residence time increases dramatically. Therefore, it could be helpful to design other equipment, such as pumps, heat exchangers, valves, etc., in primary cooling system of the research reactor if the coolant is delayed in the decay tank to reduce the radiation level of N-16 sufficiently in normal operation of research reactor. Also, siphon breaker is a safety device to prevent a severe accident in a loss of coolant accident (LOCA) in research reactors. In the event of an accident such as a pipe rupture, all the cooling water inside the decay tank will be leaked out by siphon phenomenon caused by the pressure difference. Then, the water level of the reactor pool becomes lowered and the core located at the bottom of the reactor pool is exposed to the air. As the possibility of secondary damage due to overheating of the core increases, the siphon breaker is operated rapidly after accident and an inrush of air through siphon breaker can prevent water efflux by siphon phenomenon. So that, the level of the reactor pool is maintained at an appropriate level to prevent overheating of the core.

Jeong et al.[1] estimated flow residence time using a computational fluid dynamics (CFD) code, ANSYS-CFX, in a decay tank that consists of a cylinder and two elliptic hemi-spheres with three perforated plates. Also, Jeong et al.[2] studied the decay tank using another CFD code, FLUENT, to check the relationship between the fluid distribution along the residence time and the total dose rate. The flow residence time was estimated by the particle tracking method, such as the discrete phase model (DPM) in FLUENT.

To investigate the siphon breaker, Kang et al.[3][4] performed real-scale verification experiments by using a large-sized pipe. Its results could be applied to the actual siphon breaker design in JRTR. Lee et al.[5][6] developed a theoretical model and the siphon breaker simulation program to utilize the established model to predict the progress and the result of the siphon breaking phenomenon well.

Also, long-term cooling after reactor shutdown in an accident should be considered for high thermal power research reactor. So, Lee et al.[7] suggested a new design for long-term cooling of research reactor with a dam and small pipes between the reactor pool and the service pool. Combining the functions of all devices mentioned above, the new concept of integrated passive safety facility for research reactor was developed. This system can play three roles of decay tank that reduces the radioactivity by delaying the passing time of the coolant in normal operation of the research reactor, siphon breaker that prevents the coolant loss when a LOCA occurs, and long-term cooling tank that can remove the decay heat of the core by supplying the coolant to the reactor pool passively.

At first, the decay tank were examined to optimize and design the proposed facility in 15MWt size research reactor. The simple maintenance of the decay tank is essential since the internal part of decay tank will naturally be radio-activated. For this reason, the internal part of the decay tank model in this research is much simpler than that of the existing decay tank design. Here, to determine if the decay tank is properly designed, we used particle tracking method to determine whether the fastest particles would take more than 60 seconds to pass through the decay tank. Also, we tried to confirm that the siphon phenomenon is cut off properly when the siphon breaker is operated in a new safety facility.

2. System Description of Integrated Passive Safety System

A new safety system for a research reactor, which integrated decay tank, siphon breaker, and long-term cooling tank as single facility, is suggested as shown in Figure 1 to improve the space efficiency and the simplicity of manufacture and maintenance. The number and size of Sections of the facility could be decided by the amount of evaporated water during long-term cooling and the flow residence time.

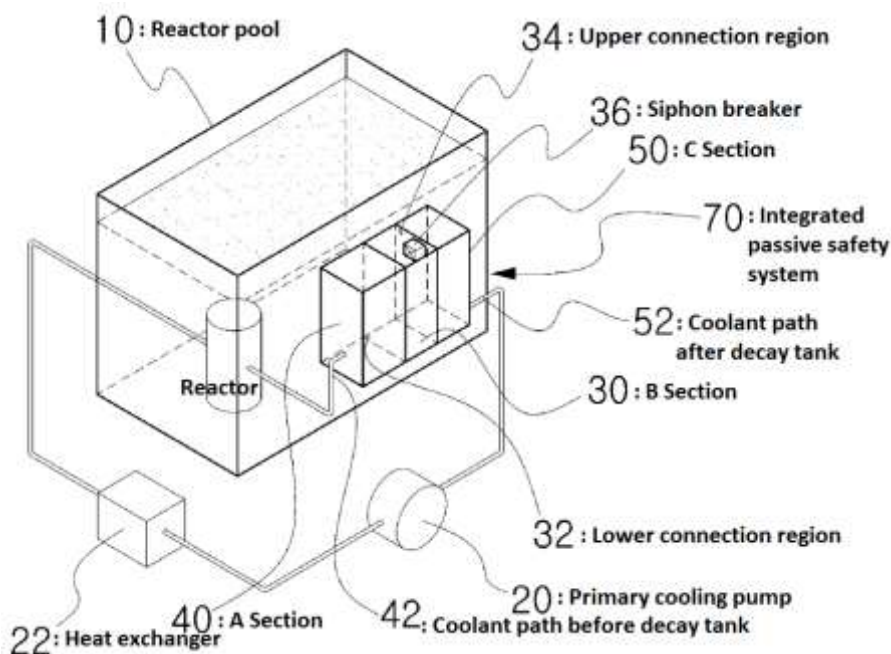


FIG. 1. Schematic diagram of integrated passive safety system

In normal operation of the research reactor, the coolant passing the reactor core is containing N-16, that has high radioactivity, but short half-life. So, the decay tank in a primary cooling system should be able to contain the coolant for enough time to satisfy the design requirement of delaying flow. The maintenance of existing decay tank designs using perforated plates or using internal vertical baffles inside a hemi-spherical cylinder is difficult because of complicated internal parts. Therefore, the internal parts of decay tank should be simplified for the convenience of maintenance and manufacture. The internal part of the suggested decay tank model in this research is much simpler than that of the existing decay tank designs. The Sections A, B, and C have a role of the decay tank in normal operation. As shown in Figure 2(a), the coolant flown into the Section A will stay inside Section A for enough flow residence time. After that, it will flow into the Section B through the connection region at the bottom of Section B. Then, the coolant will flow into the Section C through the connection region at the top of Section C and to outside through the main pipe of primary cooling system (PCS) at the bottom of Section C. Therefore, the simpler model than the existing design ensures the flow residence time and is convenient to keep the maintenance.

In research reactor, the reactor core is cooled by natural circulation through the flap valves to the reactor pool after the Primary Cooling Pump (PCP) is turned off. The pool water itself is the ultimate heat sink of the core decay heat. Thus, it is very important to guarantee that the pool water level be higher than the minimum level from a safety point of view. When a postulated pipe break occurs at below the reactor core position, the pool water can be drained below the core by siphon phenomena, and the core cannot be cooled by natural circulation. Therefore, siphon breakers are installed in the PCS to limit the pool water drain during and after all postulated initiating events. In this study, a new type of siphon breaker was suggested. It consists of siphon breaking shut-off valves and a differential pressure transmitter in Section B of Figure 1. At the roof of Section B, the air will pour in by opening siphon breaking shut-off valves when siphon occurs. The air will fill the Section B until the connection region at the top and stop siphon phenomenon by shutting the coolant flow off as shown in Figure 2(b).

In addition, high power research reactors can have some components of the PCS installed below the core level because of special restrictions, even though they have upward core flows. At that time siphon breaking pipe will be installed on the top of the section B. Water level in the siphon breaking pipe is self-regulated by operating static pressure. In this case, this new type of siphon breaker can be used without the siphon breaking shut-off valves and a differential pressure transmitter. It means that this safety system can be operated as a perfectly passive system.

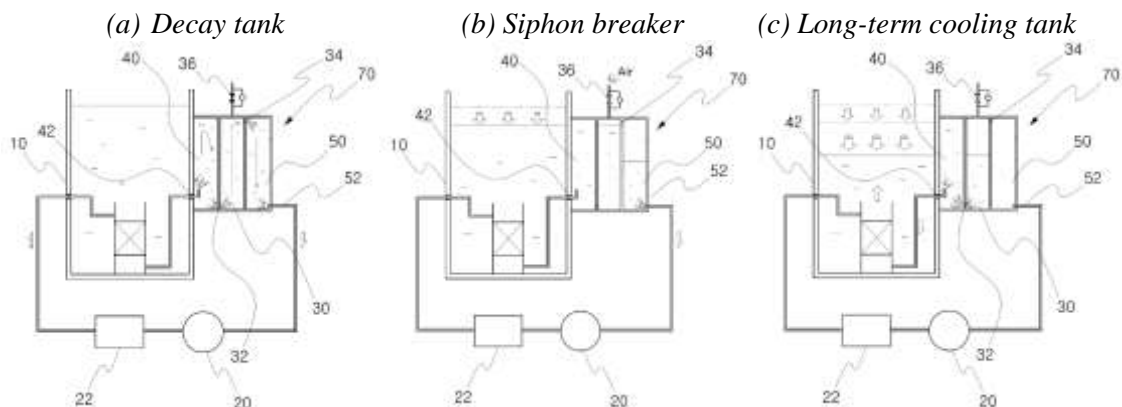


FIG. 2. Operation modes of integrated passive safety system

On stopping siphon breaking phenomenon, the rapid loss of coolant will shut off in the reactor as shown in Figure 2(b). At the moment, the water level of Section B and the research pool are the same. However, the siphon breaking phenomenon lasts only for several minutes while the core long-term cooling takes several days. Therefore, as soon as the siphon breaking phenomenon stops, the water evaporates for days due to remaining core decay heat. The enough coolant need to be filled. The Section A and Section B will act as long-term cooling tank and compensate for the evaporated water in the reactor pool as shown in Figure 2(c).

3. CFD for Decay tank

Two types of mesh are used for the numerical simulation. One is tetrahedron shape mesh and the other is hexahedron shape mesh. Number of mesh of final model was 300,000 based on the grid dependency test. Simulation results of the flow residence time are almost same with larger mesh numbers.

Two types of turbulence stress model; k- ϵ realizable model and the transition shear stress transport (SST) model are used to simulate the flow field and flow residence time. There isn't significant difference between k- ϵ realizable model and SST model in this research because flow fields are simple. Flow fields of the decay tank are almost same with the internal duct flow. k- ϵ realizable model was selected to calculate flow residence time because simulation results of this new system doesn't show strong swirl flow and internal flow fields are almost straight flow at each section of the decay tank. In this test, automatic wall treatment model was used as wall function.

Final decay tank model and its mesh model are shown in Figure 3. We did not use auto-mesh method which makes tetrahedron shape mesh for all Sections. The tetrahedron shape mesh was used the part where swirling and flow complexity was expected, the hexahedron shape mesh was used for the remaining body, and the sweepable method was used for the pipe. Number of mesh size is determined based on the grid dependency test and computational limit.

Minimum 60 seconds of flow residence time is given as the design requirement for decay tank. This residence time is selected based on the required dose rate at the decay tank outlet. Jeong et al.[2] showed that the dose rate by N-16 becomes smaller than that by the other radionuclides when the flow residence time is greater than 60 seconds. It is very conservative requirement comparing with the suggested residence time by the radiation design. It is mentioned on the previous research that the required minimum flow residence time is only 16 seconds.

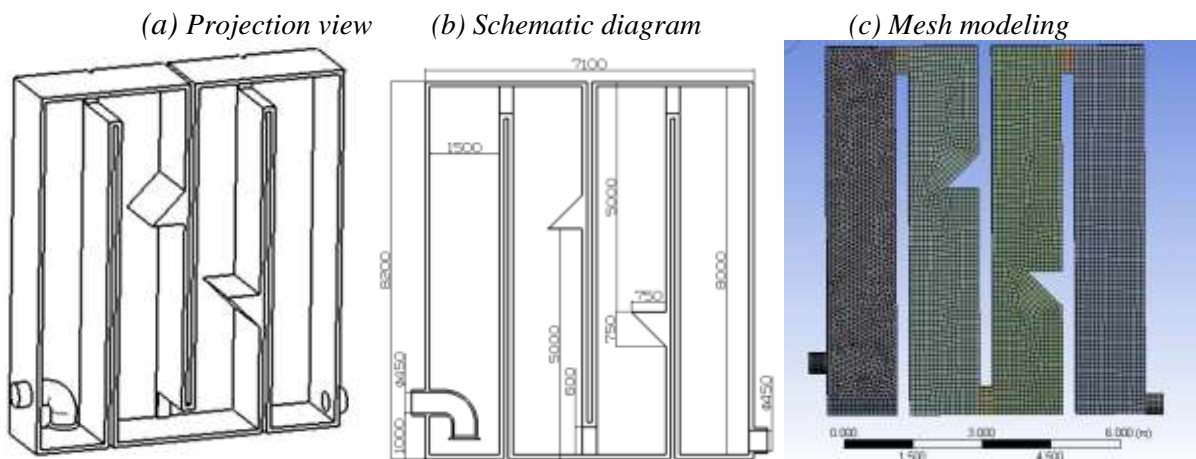


FIG. 3. Final decay tank model

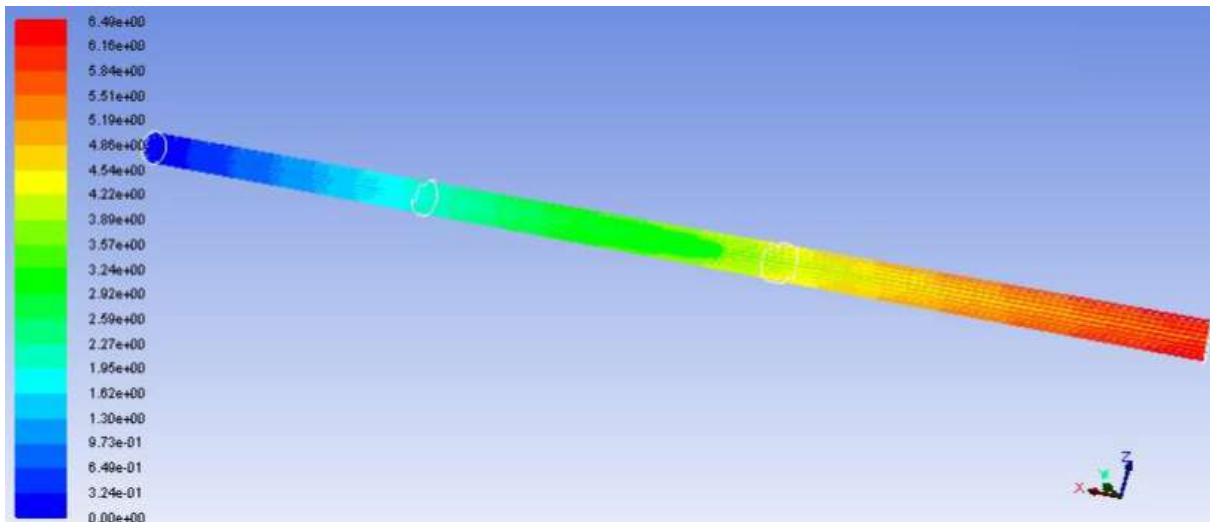


FIG. 4. Process to verify DPM meth

Discrete phase model (DPM) function was used for particle tracking method to calculate whether minimum flow residence time is longer than 60 seconds in the decay tank. 1,000 floating particles are used in this calculation which have same density as water. In order to verify the validity of the DPM function, flow field was calculated along the pipe. Calculated result of the inner pipe flow rate are compared to the theoretical result. Geometrical conditions of the pipe are 0.05m of diameter and 1.5m of length. Flow condition is 0.5kg/s mass flow rate. It is 0.255m/s based on water density. The theoretical flow residence time is 5.88 second with the mean velocity. The calculated flow residence time by DPM function is 5.42 second. Accumulated residence time calculated by DPM method is shown in Figure 4. Flow field is developed from the uniform flow at the inlet to the fully developed pipe flow. It makes the slight difference of the residence time between the calculation and theoretical results.

Figure 5 shows velocity profile and particle distribution of final decay tank model. In this study, 2m/s legend was unified to compare the flow velocity. The velocity does not exceed 1m/s in any section other than the pipe. Also, particle distribution is shown in Figure 6. It has been conservatively designed, and it has been confirmed that the target average flowable particle exceeds 60 seconds or more and the minimum time exceeds 60 seconds, and 70% of the particles stay within 60 to 100 seconds.

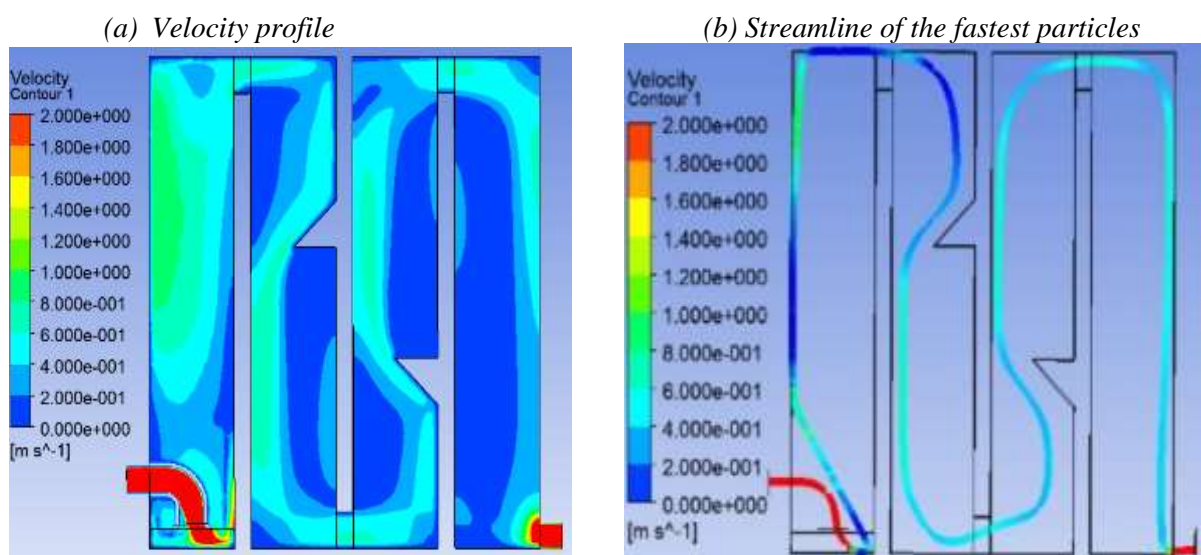


FIG. 5. CFD results for decay tank

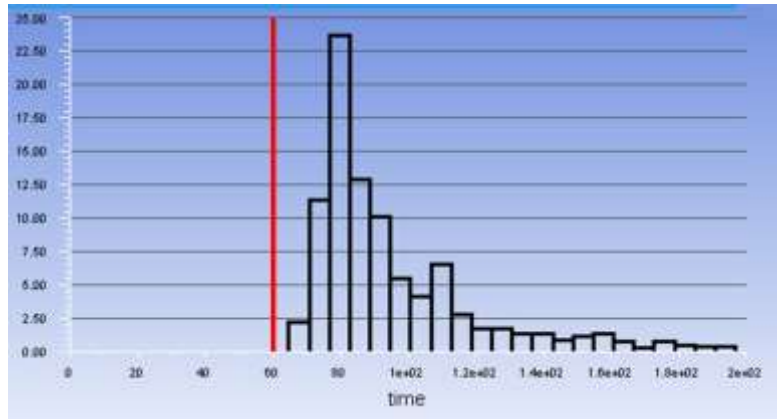


FIG. 6. Particle distribution

4. CFD of Siphon Breaker

Geometrical and mesh model are explained on Figure 7. Final decay tank model is used to simulate the siphon breaking phenomenon. Reactor pool, siphon breaker and connected pipe lines are added for the numerical simulation. Mesh size of reactor pool is relatively coarse because flow rate of reactor pool region is slow and there are no complex flow field. In addition, the fine mesh are used at the region where siphon breaker and the connection part between 3rd and 4th Section because two phase flow of the water and air are generated at that region. Siphon valve with 18 inch is used in this calculation.

VOF model is used to simulate the physical phenomena of water-air phase. Transient calculation method is used to observe the two-phase flow filed according to time change. Accurate calculation result is available when time step is small. In transient method, courant number controls time step. Time step of 0.01~ 0.05sec are used in this calculation. Courant number of 1 is used in this simulation in consideration of the velocity field at the region of the siphon breaker and computation resource.

The siphon breaking phenomenon is simulated with the 18-inch siphon breaking valve as shown in Figure 8. The decay tank is disconnected between the 3rd and 4th section because of the siphon breaking. Therefore, reactor pool is filled with the water after finishing the siphon phenomenon. Siphon is broken in about 5 seconds in this calculation.

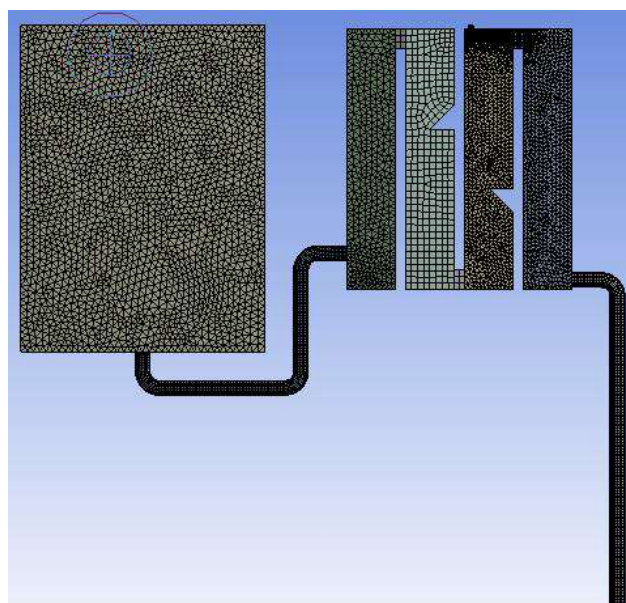


FIG. 7. Mesh modeling for siphon breaker

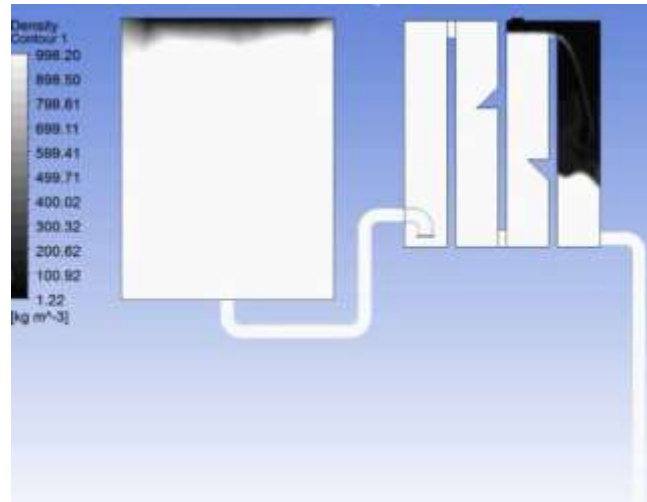


FIG. 8. Simulation result of siphon breaking phenomenon

5. Conclusions

The validity of the Integrated Passive Safety System of Research Reactor idea is verified through CFD. The decay tank was conservatively designed with the minimum residence time of 60 seconds. Flow residence time is at least 67 seconds and more than 70% of particles have the residence time between 60 and 100 seconds by using the DPM function. Also, validity by DPM function are checked by comparing the simulation and theoretical results in the simple piping flow. Idea about the siphon breaking phenomenon are simulated and verified that the siphon phenomenon was blocked by installing an 18-inch diameter valve in the 3rd Section of the decay tank.

Existing papers have been studied for decay tanks using perforated plates and siphon breaker with complex two-phase flow regime. This new integrated safety system has three roles of decay tank, siphon breaker and long-term cooling tank. So that, the space can be efficiently used through one structure. Since the structure of the facility is simple, it is easy to maintain and reduce the construction cost, so it will be easier to secure safety of research reactors.

6. References

- [1] JEONG, N.G., et al., “Estimation of flow residence time in a decay tank for a pool type research reactor using CFD”, *Nuclear Engineering and Design* **255** (2013) 162-168.
- [2] JEONG, N.G., et al., “Design evaluation of decay tank for a pool-type research reactor from the required minimum flow residual time point of view”, *Journal of Nuclear Science and Technology* **51** (2014) 1064-1072.
- [3] KANG, S.H., et al., “Experimental study of siphon breaking phenomenon in the real-scaled research reactor pool”, *Nuclear Engineering and Design* **255** (2013) 28-37.
- [4] KANG, S.H., et al., “Investigation on effects of enlarged pipe rupture size and air penetration timing in real-scale experiment of siphon breaker”, *Nuclear Engineering and Technology* **46** (2014) 817-824.
- [5] LEE, K.Y., et al., “Theoretical study on loss of coolant accident of a research reactor”, *Nuclear Engineering and Design* **309** (2016) 151-160.
- [6] LEE, K.Y., et al., “Development of siphon breaker simulation program for investing loss of coolant accident of a research reactor”, *Annals of Nuclear Energy* **101** (2017) 49-57.
- [7] LEE, K.Y., et al., “A long-term cooling method for a research reactor”, in *Proceedings of the International Group on Research Reactor (IGORR 15)*, Daejeon, South Korea (2013).