Investigation on Core Downward Flow by a Passive Residual Heat Removal System of Research Reactor

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Abstract. Most of existing research reactors has been designed with Active Residual Heat Removal System (ARHRS) to remove decay heat of reactor core when the primary cooling pump stops. However, ARHRS takes much cost and is hard to design. As an alternate system, Lee et al. [1] proposed a Passive Residual Heat Removal System (PRHRS) of research reactor. PRHRS consists of three main components, a flywheel linked to the primary cooling pump, Gravity Core Cooling Tank (GCCT), and flap valves. For the PRHRS, a research is needed to verify the safety system can be applied to design of research reactor. In this paper, the verification was focused on performance of the GCCT in terms of hydraulics, specifically mass flow rate. An experimental facility was manufactured replicating a research reactor with GCCT in small scale and experiment was conducted. Furthermore, a theoretical formulation and computational fluid dynamics (CFD) model were developed to provide a better understanding of fluid flow characteristics of GCCT. The maximum mass flow rate of two models was about 50% higher than experimental results. It is because the pressure loss of experimental facility is bigger than that of two models. Considering this reason of difference, theoretical and CFD models were improved to follow the experimental results by adjusting diameter of DPP. As a result, the difference of maximum mass flow rate decreased below 17%. To apply these models to real scale research reactors, the models must be verified through further experiments in many different conditions including heat transfer aspects.

1. Introduction

Preparing for an accident that the Primary Cooling Pump (PCP) is malfunctioned, a safety system is required to remove decay heat of a reactor core. Active Residual Heat Removal System (ARHRS) has applied in most research reactors. However, ARHRS has some difficulties in designing the system and the cost. It is not easy to design its pump system because the operating point of secondary cooling pump is changed a lot along with the operating conditions of the primary cooling pump. Furthermore, because the system is affected by radiation, all component of the system should have high safety classification for enduring radiation effect, which is costly to manufacture.

Lee et al. [1] recently proposed a new concept of Passive Residual Heat Removal System (PRHRS) that can solve above-stated problems. A conceptual diagram of the PRHRS with GCCT is depicted in *FIG. 1* [2]. This passive system mainly consists of the three parts; a flywheel (350) linked to the primary cooling pump maintains core downward flow even though the pump stops; Gravity Core Cooling Tank (GCCT) (200) makes flows continuously directed downward; and flap valves (370) change the direction of the core flow to upward. This system is more economical and easy to design than the ARHRS. Lee et al. [1] explained the system mechanism and presented a mathematical analysis of hydraulic performance of PRHRS. On normal operation, the coolant is circulated throughout the loop by primary cooling pump (PCP), which makes pressure drop of the reactor core. Due to this pressure drop, the water in the GCCT moves to the reactor pool. In other word, differential head between reactor pool and GCCT is created. If the PCP stops, the PRHRS is operated following below sequences;

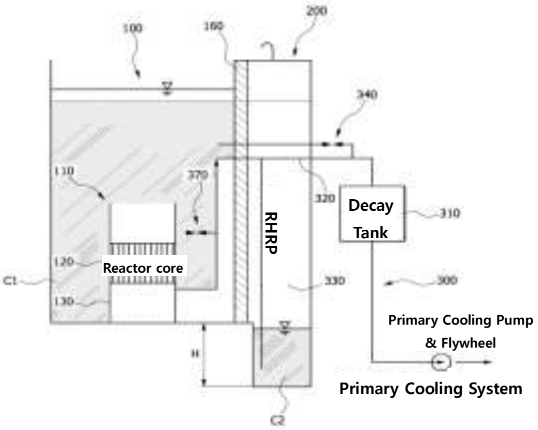

FIG. 1. Conceptual drawings of PRHRS [2]

Step 1) The flywheel makes the pump rotate continually by inertia so that the flow in the core is maintained downward direction for several ten seconds.

Step 2) As the flywheel stops, pressure difference through the core decreases. Simultaneously, the water in the reactor pool moves back to GCCT, so flow keeps going downward for a few minutes.

Step 3) When a natural convection flow can remove the lowered core decay heat sufficiently, flap valve opens to make the natural circulation happen.

Although previous researchers presented the mathematical analysis and the system mechanism [1], the real experiment is needed to verify the PRHRS can be applied to research reactor as a safety system. Therefore, the first objective of this research is to manufacture a downscaled experimental facility and collect experimental data. The second objective is to develop a theoretical model and a computational fluid dynamics (CFD) model which can predict the hydraulic performance of the PRHRS.

2. Methodology

In order to verify that the PRHRS can be applied to real research reactor, three methods were used: Experimental, Theoretical, and Computational Fluid Dynamics (CFD) analysis.

2.1 Experiment

A downscaled experimental facility was manufactured, replicating a research reactor with GCCT. The detail drawing of experimental facility is depicted in *FIG. 2*. The highest part of facility is the top of GCCT being about 2.3 m tall. The total width is about 2.1 m. The diameter of the reactor pool and GCCT are 700 mm, 150 mm respectively, in which surface velocity of water in the reactor pool is negligible, compared to that of GCCT.
FIG. 3 shows how the facility actually looks like. The reactor pool is simplified by cutting unnecessary below part. A thin horizontal pipe located in center of the facility was named as Differential Pressure Pipe (DPP), which takes a role of making pressure drop, like what real reactor core do. The pressure drop makes the water in the GCCT move to the reactor pool until the hydraulic pressure between two components become equal to the pressure drop occurred by DPP. In addition, an inverter pump and globe valve are installed on the system so

that adjust the initial differential head by changing mass flow rate on normal operation.

The facility was filled with water up to 2 m high. If the pump turns on, a water level of the reactor pool increase less than 100 mm according to mass flow rate of the pump. After the water level becomes stable, the experiment can be started by stopping the pump. The important results of this experiment are mass flow rate and duration time of core downward flow when the pump turns off.

There are several instrumentations in the facility. Each ruler is attached on the reactor pool and GCCT respectively to measure the height of water. A Pressure sensor on bottom of the GCCT is installed to measure mass flow rate of water flowing into the GCCT. The data of hydraulic pressure was converted to terms of pressure head as seen in *FIG. 4*. As you can see, the pressure head of GCCT is recovered from 0.85 m to 2 m on 1.21 m initial condition of differential head. On each side of DPP, a differential pressure sensor was installed to measure the amount of pressure drop. The data of differential pressure of DPP on time can be seen in *FIG. 5*. Independent variables of experiment are a size of DPP and initial differential head between reactor pool and GCCT. The DPP is replaced with a different diameter (3/4", 1") so that the results in two cases are compared.

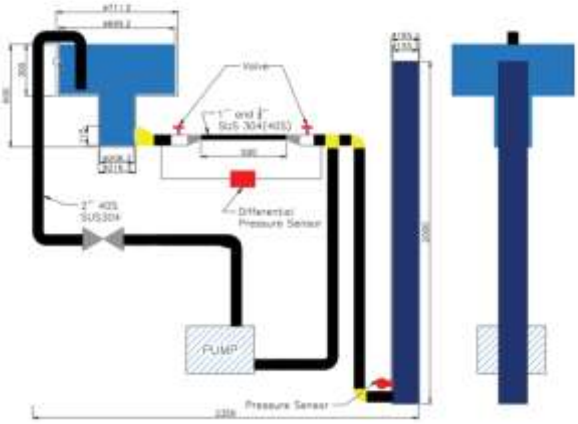

FIG. 2. Detail drawing of experimental facility

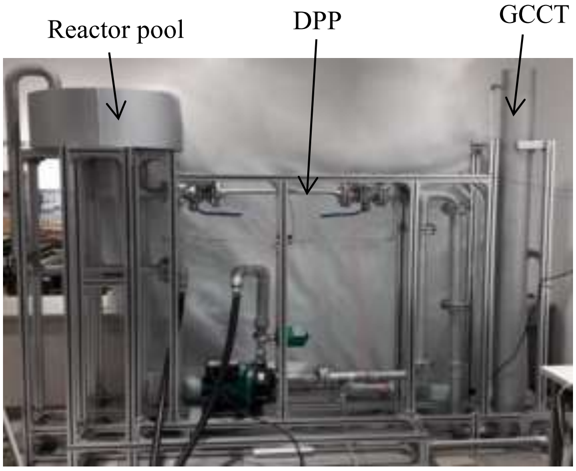

FIG. 3. Experimental facility

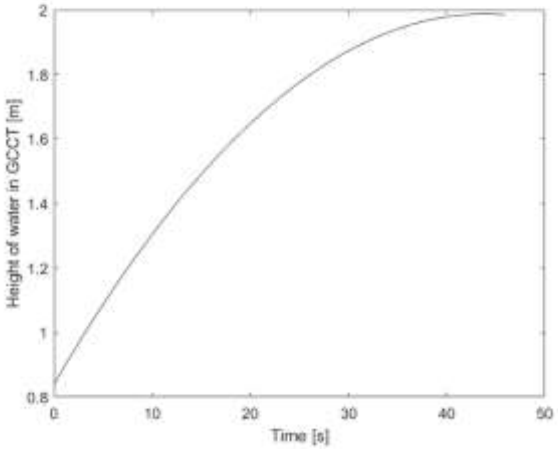

FIG. 4. Pressure head of GCCT

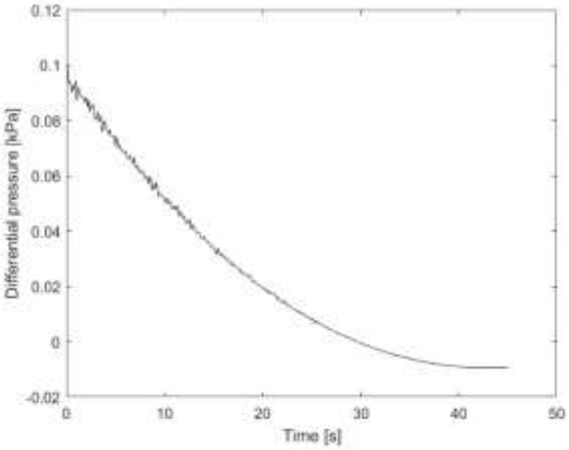

FIG. 5. Differential pressure of DPP

2.2 Theoretical analysis

Lee et al. [1] presented mathematical formulations of the entire PRHRS. Among them, the equation for the velocity at the inlet pipe of GCCT, called Residual Heat Removal Pipe (RHRP), was modified as follows;

$$V_p = \sqrt{\frac{2g(H_1 - H_2)}{(\frac{A_p}{A_2})^2 + K_{12}}} \tag{1}$$

, where top surface of the reactor pool is point 1 and that of GCCT is point 2. K_{12} stands for sum of all the pressure loss coefficients from point 1 to point 2. The K values were calculated based on CRANE technical paper [3]. This formulation was derived from Bernoulli equation under some assumptions; it deals with a situation that the pump is off, the atmospheric pressure of both reactor pool and GCCT is same as 1atm, and the water velocity of reactor pool is negligible. It also needs to be noticed that the Bernoulli equation used to derive equation (1) is for a case of steady state flow. However, because the flow in PRHRS is transient, the model has some error especially in first few seconds.

The mass flow rate at GCCT was calculated with following equations [1]:

$$\dot{m} = \rho A_{RHRP} V_p \tag{2}$$

$$H_1 = H_{RX} - \int \frac{\dot{m}(t)}{\rho A_{RX}} dt \tag{3}$$

$$H_2 = H_{GCCT} + \int \frac{\dot{m}(t)}{\rho A_{GCCT}} dt \tag{4}$$

An equation of the mass flow rate was obtained by solving those equations;

$$\dot{m} = -\frac{(\frac{1}{\rho A_{RX}} + \frac{1}{\rho A_{GCCT}}) \times (\rho A_p)^2 g}{(\frac{A_p}{A_{GCCT}})^2 + K_{12}} t + \dot{m}_{ini} \tag{5}$$

The previous model and modified model that are applied to real scale of research reactor were compared as seen in *FIG. 6*. The modified model has higher mass flow rate than previous model. It suggests that GCCT actually has better performance of core downward flow than what the previous model predicted.

Taking into account the shape and dimension of experimental facility, theoretical values of mass flow rate and duration time of core downward flow were obtained from above equation and compared to experimental data.

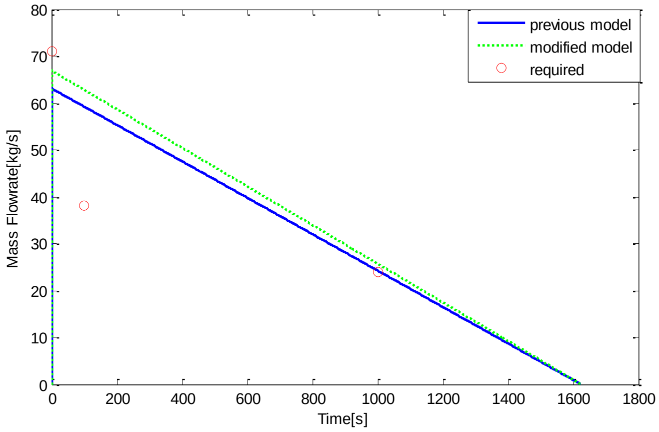

FIG. 6. Comparison between previous model and modified model [1], [4]

2.3 CFD Analysis

Computational geometry of the experimental facility of PRHRS has been created using SolidWorks 2016. What was analyzed through this CFD study is the core downward flow to the GCCT when the pump is off. Thus, leaving out the rest of parts, 3D modeling just includes reactor pool, main pipe with DPP, and GCCT.

The computational code of ANSYS fluent was adapted for meshing and solver. Owing to a flow condition of each part of geometry, the meshing process was broken down into smaller 5 sections. The mesh model is shown in *FIG.7*. Different mesh models and base size of elements for each part were used to capture the flow characteristic properly. For the upper part of reactor pool and GCCT, coarse mesh of hexahedral elements were adapted to secure the visibility of water level change and reduce the solving time. Due to uniform flow direction, hexahedral meshes were generated for the main pipe including DPP from reactor pool to GCCT as well. On the other hand, some parts adjacent to pipe joints were filled with fine mesh of tetrahedral elements to take into account the effect of vortex of flow. Although it has risk of high skewness and divergence when calculate the equation, those approach can calculate more efficiently and make animation of calculation more clearly. By conducting the simulation with tetrahedral fine meshes to all parts and combination of coarse and fine meshes, the grid sensibility of the mesh models was checked. According to that grid test, it shows very similar result on the duration time of downward flow within 1.5%. Thereby, the combination mesh model was adopted.

The system has a fluid region of which boundary is set up as a normal wall from reactor pool to GCCT. Because the fluid flow is caused by only gravity force, there is no inlet boundary, but the upper surfaces of reactor pool and GCCT have boundary type of pressure outlet. The surfaces open to the air and volume fraction of air backflow is 1, which means empty space of the volume is filled with air.

As the objective of CFD study is checking downward flow on time, transient model was chosen rather than steady-state. VOF / Multi-phase method was used to assign the region of each material and divide the region of air and water precisely. Also, k-ϵ turbulent model was used because the flow in the experimental facility is estimated as it has characteristic of turbulent flow at those narrow pipes. In order to obtain more stable results and fast calculation process, Pressure Implicit with Splitting of Operator (PISO scheme) was applied as a solution method. In addition, as a relaxation factors of the chosen method, Gradient - (Least Squares cell based), pressure - (Presto), Momentum - (Second order upwind), volume fraction - (geo-reconstruct), turbulent kinetic energy - (first order upwind), turbulent dissipation rate - (first order upwind), Transient formulation – (first order implicit) options are adopted.

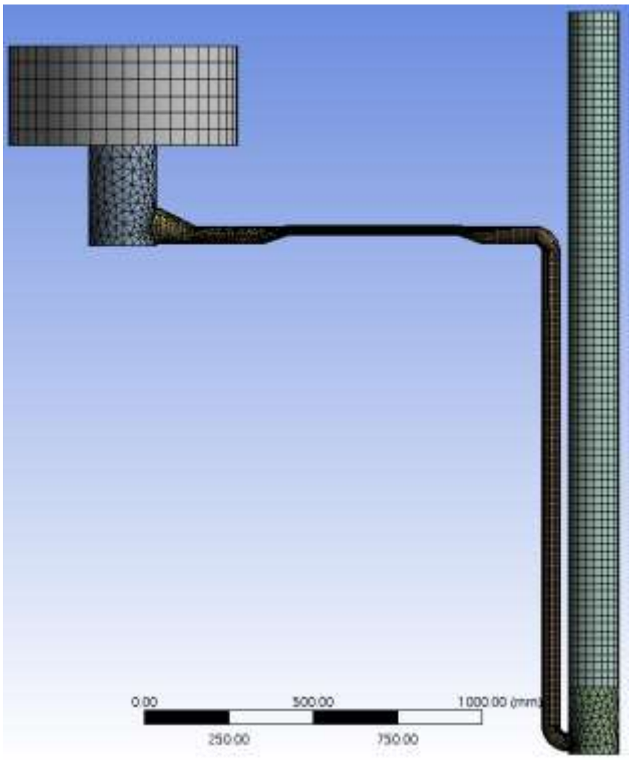

FIG. 7. A mesh model of PRHRS

3. Results and discussion

The initial conditions are all same among three analysis methods. The initial height of water in reactor pool and GCCT are 2.06 m and 0.26 m respectively, which has 1.8 m differential head. At the conditions, the water flowing from reactor pool to GCCT, the mass flow rate and duration time of core downward flow was obtained for each analysis methods and compared each other.

The comparison between measurements and predictions of the first models for 1 inch DPP case can be seen in *FIG.8* and Table I. The maximum mass flow rate from theory and CFD are approximately 54.5% and 44.7 % higher, respectively, than the experimental value. It suggests that there is more effect of friction loss on experiment than prediction models. This is because there are minor losses of such as flanges and fittings that are not considered in the models.

Taking into account the minor losses by finely adjusting the diameter of DPP, the second models were developed to make models closely follow the experiment results. The diameter of DPP was reduced by 10% for theoretical model and 20% for CFD model. Consequently, the comparison between measurements and predictions of second models for 3/4 and 1 inch DPP case can be seen in *FIG. 9* and Table II. The largest percentage difference is 16.8%, which is recorded for the duration time for the case of 3/4 inch DPP. However, it is important that the three results have very similar slope shape, especially between CFD model and experiment.

In order that these models have reliability for applying to the real scale research reactor, more data comparison should be done for different size of DPP. If a tendency of pressure loss coefficient K can be found according to DPP size, it will be acceptable to apply these models to real research reactor.

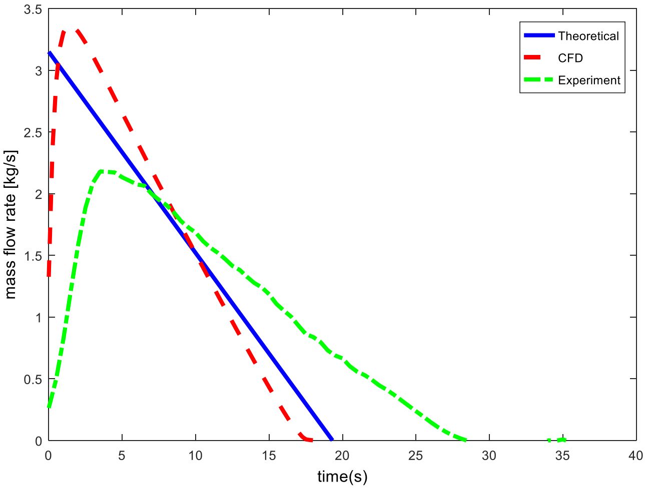

FIG. 8. Core downward flow of the first model (1inch DPP)

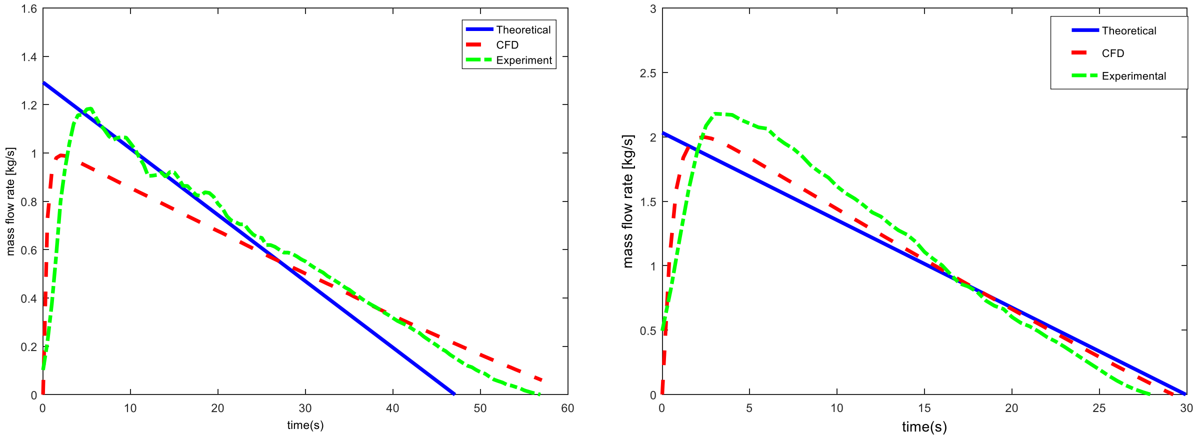

FIG. 9. Core downward flow of the second models ***(left :*** *3/4" DPP,* ***right :*** *1" DPP)*

TABLE I: Core downward flow of the first model (1 inch DPP)

		Experiment	CFD	Theory
Maximum mass flow rate	Value (kg/s)	2.176	3.361	3.149
	% difference	0	54.5	44.7
Duration time	Value (s)	28.0	18	19.3
	% difference	0	-35.7	-31.1

TABLE II: Core downward flow of the second models

		Experiment		CFD		Theory	
		3/4 inch	1 inch	3/4 inch	1 inch	3/4 inch	1 inch
Maximum mass flow rate	Value (kg/s)	1.184	2.176	0.9902	1.999	1.292	2.033
	% difference	0	0	16.4	8.13	-9.12	6.5
Duration time	Value (s)	56.5	28.0	60.0	29.2	47.0	29.9
	% difference	0	0	-6.19	-4.29	16.8	-6.79

4. Conclusion

An investigation of PRHRS for research reactor, which had been proposed recently as an alternative safety system was conducted by experimental and analytical methods. In current study, the investigation was focused on the GCCT of PRHRS which makes core downward flow when the pump is malfunctioned. For this study, downscaled experimental facility was manufactured and mass flow rate and duration time of core downward flow were measured. Based on experiment results, theoretical and CFD models were developed for predicting core downward flow of the system. In terms of maximum mass flow rate, the first models have largest difference over 50% with measurement values from experiment. The models were improved by taking into account minor losses by finely adjusting diameter of DPP. The largest difference decreased below 17%.

For the future research, analysis on more cases of DPP size should be conducted to make the models more reliable. Furthermore, the models that take into account the decay heat of reactor core have to be developed to verify that PRHRS with GCCT can be applied to real research reactor as a safety system.

5. Reference

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