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

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1. Introduction

1.1 Research Background

Active residual heat removal system is applied in most research reactors to remove decay heat which is continually generated after the primary cooling system stops. However, there are difficulties to design the active system. It requires additional cooling system as well as primary cooling system. Also, the additional system should have safety grade devices, and it is costly to design and manufacture. Moreover, it is not easy to design its pump system because the pump's operating point is changed a lot along with the operating conditions of the primary cooling pump.

Lee et al. [1][2] proposed a new concept of passive residual heat removal system(PRHRS) that solves stated problems above. This passive system mainly consists of the three parts; a flywheel linked to the primary cooling pump maintains core downward flow even though the pump stops; Gravity Core Cooling Tank (GCCT) makes flows continuously directed downward; and flap valves change the direction of the core flow to upward. This system is more economical and easy to design than the active system. Furthermore, it promptly works when pumps of the primary cooling system are malfunctioned. Therefore, it ensures the safety of the research reactor by maintaining core downward flow for sufficient time and removing residual heat in passive way.

Although previous researchers presented a simple theoretical model and an explanation of the system mechanism [1], the validation of the passive system through simulation, experiments, and theoretical analysis is required for applying the system to a real research reactor.

1.2 Model Description

The conceptual diagram of the PRHRS with GCCT is presented in Figure 1. Main parts are the core (120) which is the source of heat, reactor pool (100), residual heat removal pipe (RHRP, 330), fly wheel (350), GCCT (200), and flap valve (370).

In normal operation of the reactor, the primary cooling system eliminates heat emitted by nuclear reaction in the core. At this time, pressure drop occurs from top to bottom of the core because downward flow goes through narrow path between several plate fuels. Due to this pressure drop the water height of GCCT is lower than that of the reactor pool.

If the primary cooling pumps fail, nuclear fuels may be damaged because the core decay heat would not be removed. To avoid this accident, the PRHRS is operated following below sequences:

① The flywheel maintains its rotation by inertia so that the flow in the core is maintained downward direction for several ten seconds.

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

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

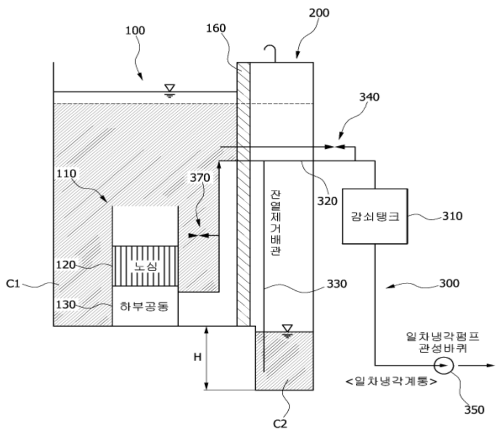


Figure 1. Conceptual diagram of the passive residual heat removal system

2. Methods

The following are theoretical, computational fluid dynamics (CFD), and experimental methods used to verify the performance of GCCT for core downward flow.

2.1 Design of Experimental facility

We designed the experimental facility by reducing the size of actual research reactor. Figure 2 shows the schematic diagram of experimental facility. Here, (a) is a front view of the experimental facility and (b) is a side view. The maximum height of the facility is about 2.3 m (reactor pool) and the width is about 1.9 m. The main components of the experimental facility are a reactor pool, GCCT, Differential Pressure Pipe (DPP), and so on.

2.1.1 Reactor Pool

In Figure 1, the tank shown at the top left is the reactor pool. The initial water level is 1.9 m. Because the water level change is only about 10 cm during pump operation, the lower unnecessary part of the reactor pool could be cut. As we consider the water level, the height of the reactor pool is designed to be 2.1 m. The diameter of the reactor pool is 700 mm. In that size of diameter, the water velocity of the reactor pool is negligible compared to that of GCCT during the test.

2.1.2 Gravity Core Cooling Tank (GCCT)

As we consider that the water level of GCCT varies from 0.2 m to 1.9 m, the height of the GCCT is designed to be 2 m. The area of the GCCT has a great influence on the duration of the core downward flow. In order to facilitate the measurement and comparison of the experimental results, the diameter of the GCCT was determined to be 150 mm so that the reactor downward flow last at least 15 seconds.

2.1.3 Differential Pressure Pipe (DPP)

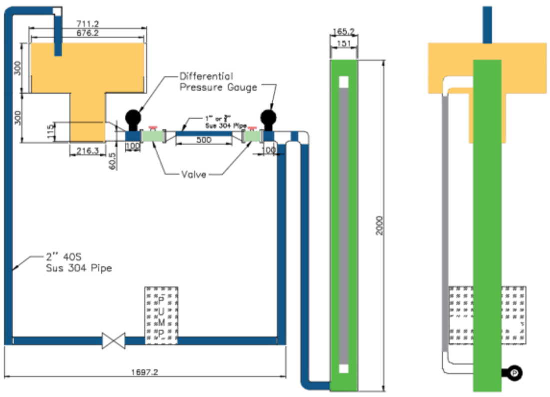
We named the thin pipe horizontally passing through the center of the experiment facility as Differential Pressure Pipe (DPP). In order to make differential pressure as a core pressure drop of real research reactor, the diameter of the DPP was designed to be smaller than that of the main pipe.

As a parameter of the experiment, DPP can be replaced with a different diameter (3/4 ", 1") so that the experimental results is compared.

2.1.4 Instruments and Visualization

On the side of GCCT, a transparent tube was installed to visually confirm the water level of the tank. A pressure sensor is also installed the lower end. By simply calculating the hydraulic head pressure data, the mass flow rate of the cooling water moving to the GCCT can be obtained.

A differential pressure sensor was installed at both ends of DPP to measure the pressure loss value. By comparing this value with the actual water level difference, the hydrodynamic movement of the water can be grasped.



(a) (b)

Figure 1. Experimental facility design

2.2 Theoretical analysis

We obtained the mass flow rate and duration time of core downward flow by making a theoretical model for the experimental facility that we designed. Based on the theoretical model that Lee et al.[1] suggested, we improved some theoretical calculation.

At the Figure 1, by setting the water surface of the reactor pool as point 1 and that of the GCCT as point 2, we could build the equation (1) from the Bernoulli's equation.

$$\mathrm{H}_1 + \frac{P_1}{\rho g} + \frac{V_1^2}{2g} + \Delta h_p = \mathrm{H}_2 + \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + \Delta h_f + \Delta h_m \quad (1)$$

In addition, here are some conditions of our facility design, (2), (3), (4).

$$\Delta h_p = 0 \quad (2)$$

$$\mathrm{P}_1 = \mathrm{P}_2 = 1\,\mathrm{atm} \quad (3)$$

$$\frac{V_1^2}{2g} \cong 0, \quad (\because \mathrm{V}_1 << \mathrm{V}_2) \quad (4)$$

We deal with a situation that the pump is off (2). We assume that the atmospheric pressure of both tank is same as 1atm (3). The water velocity of reactor pool is negligible, because we designed the area of reactor pool to be much larger than that of GCCT (4).

As we give the conditions in the equation (1), equation (5) could be made.

$$\mathrm{H}_1 = \mathrm{H}_2 + \frac{V_2^2}{2g} + \Delta h_f + \Delta h_m \quad (5)$$

Also, the law of the conservation of mass should be satisfied,

$$A_2 V_2 = A_p V_p \quad (6)$$

After setting K12 as the sum of pressure loss factor from point 1 to 2, following is the equation (7) which means the velocity of RHRP.

$$V_p = \sqrt{\frac{2g(H_1 - H_2)}{(\frac{A_p}{A_2})^2 + K_{12}}} \qquad (7)$$

The equation (7) is the improved equation from theoretical model that Lee et al.[1] suggested. Moreover, the mass flow rate at RHRP and height of reactor pool and GCCT are could be represented like following equations (8), (9), and (10);

$$\dot{m} = \rho A_{RHRP} V_p \qquad (8)$$

$$H_1 = H_{RX} - \int \frac{\dot{m}(t)}{\rho A_{RX}} dt \qquad (9)$$

$$H_2 = H_{GCCT} + \int \frac{\dot{m}(t)}{\rho A_{GCCT}} dt \qquad (10)$$

If we put the equations (9) and (10) to the equation (7), and put that result equation to the equation (8), we could get a mass flow rate from equation (11).

$$\dot{m}(t) = -\frac{(\frac{1}{\rho A_{RX}} + \frac{1}{\rho A_{GCCT}}) \times (\rho A_p)^2 g}{(\frac{A_p}{A_{GCCT}})^2 + K_{12}} t + \dot{m}(0) \qquad (11)$$

From this, we could know the duration time of downward flow at core by calculating the time that mass flow rate is going to be 0.

2.3 CFD Analysis

In part of CFD analysis, we inserted mesh separately on each part. To secure the visibility of water level changes, hexahedral meshes are used on the water tank. On the same way, due to the uniform flow direction from reactor tank to GCCT, hexahedral meshes are used to capture those flow characteristics. However, in some parts which have a hole like pipe joints, tetrahedral meshes are inserted densely to satisfy the quality and capture the vortex at their part.

Next, Volume of Fluid and Realizable k-epsilon models, PISO solution method are used to calculate and verify our systems. Although, in this analysis, standard wall function is used to conduct basic calculation, we will change those options to match with the results of experimental data.

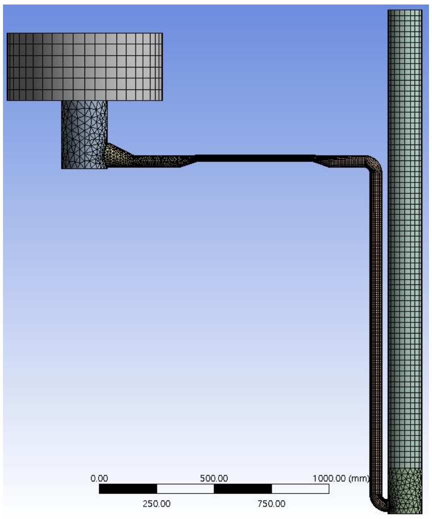


Figure 3. CFD mesh model

3. Results

We will set the diameter of the differential pressure pipe to a variable and set it to a 3/4 " and 1 ". If the diameter of the differential pressure pipe is changed, it is possible to analyze the experimental data in different conditions. Figures 3 and 4, and Tables 1 and 2 are comparing the results of theoretical study and CFD model when the DPP are 3/4 " and 1 ".

The theoretical values on the tables were obtained from the equation (8) in two cases. In the CFD model, data was different depending on measuring position, because CFD analysis even contain the sloshing and inertia of the fluid. Therefore, we obtained data from center of the DPP where the actual removal is happened.

The theoretical and CFD values have some different, because the loss coefficient of theoretical model is larger than that of CFD. Moreover, the Bernoulli's equation require a steady-state flow condition, but our experimental flow condition is a transient.

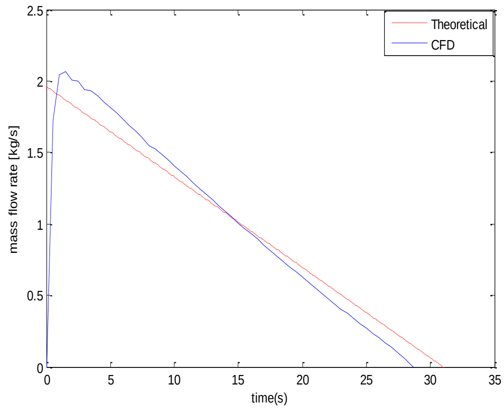


Figure 4. Mass flow rate & duration time in 3/4" DPP

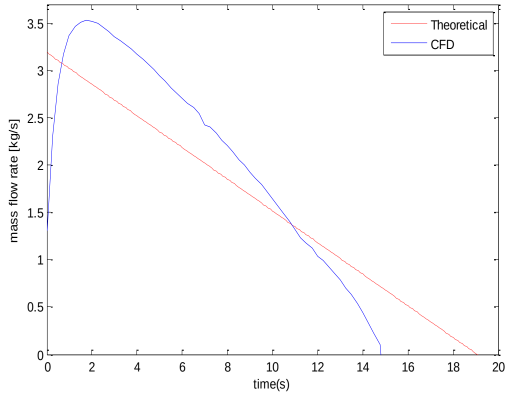


Figure 5. Mass flow rate & duration time in 1" DPP

Table I : Results in 3/4" DPP

	Theoretical	CFD	Error
Initial mass flow rate	1.96 (kg/s)	2.07 (kg/s)	4.99%
Duration time	30.9 (s)	28.5 (s)	8.42%

Table II : Results in 1" DPP

	Theoretical	CFD	Error
Initial mass flow rate	3.19 (kg/s)	3.53 (kg/s)	9.52%
Duration time	19.0 (s)	15.0 (s)	26.6%

4. Conclusion

In order to verify the downward flow performance of PRHRS, we designed an experimental facility. Also, we developed a theoretical model and conducted CFD analysis for the facility. The results of theoretical and CFD analysis show 4.99 % error of initial mass flow rate and 8.42 % error of duration time in case of 3/4 " DPP. The error in case of 1" DPP grew to 9.52 % and 26.6 %, which was about two and three times larger. It is because the difference of loss coefficient between theoretical and CFD model affect more dominantly the value of 1" DPP case. The Duration time in case of 1" seem to have too big error, but it is because the value is too small.

In the future, we will perform experiment and use the data to improve the theoretical model and CFD analysis. We expect that improved theoretical and CFD model will be adapted to real size research reactor.

REFERENCES

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[2] K.Y. Lee, S.H. Kim, and J.H. Yoon, Passive Residual Heat Removal System in Research Reactor with Gravity Core Cooling Tank, Registered patent 10-1407129, 2014