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Concept Design of a Gravity Core Cooling Tank as a Passive Residual Heat Removal System for a Research Reactor

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1. Introduction

In an open-pool type research reactor, the decay heat of the core is transferred into the reactor pool by a natural circulation through the flap valves after the Primary Cooling Pump (PCP) is turned off. That is, the flap valves installed on the pipe of the Primary Cooling System (PCS) inside the reactor pool are designed to be passively opened, when the flowrate of the PCS is reduced below the design limit. Recently, a core downward flow is considered to use a plate type fuel because it is benefit to install the fuel in the core. If a flow inversion from a downward to upward flow in the core by a natural circulation is introduced within a high heat flux region of residual heat, the fuel fails instantly due to zero flow. Therefore, the core downward flow should be sufficiently maintained until the residual heat is in a low heat flux region.

In a small power research reactor, inertia generated by a flywheel of the PCP can maintain a downward flow shortly and resolve the problem of a flow inversion. However, a high power research reactor more than 10 MW should have an additional method to have a longer downward flow until a low heat flux. Usually, other research reactors have selected an active residual heat removal system as a safety class. But, an active safety system is difficult to design and expensive to construct.

2. System Design

A passive residual heat removal system for an open-pool type research reactor was developed using a Gravity Core Cooling Tank (GCCT), as shown in Figure 1. The GCCT beside a reactor pool is a small tank opened to the air with atmospheric pressure. A Residual Heat Removal Pipe (RHRP) is connected to a lower plenum of the Reactor Structure Assembly (RSA) and bottom of the GCCT. Thus, cooling water passing the core can flow to the GCCT through the RHRP to remove core decay heat. Additionally, a Pool Water Cooling and Purification System (PWCPS) was designed to improve the safety and usability of the research reactor. A PWCPS consists of a pump, a flow control valve, a heat exchanger, a filter, an ion exchanger, and related pipes. A Decay Wall (DW) is installed to separate a discharge area from the RHRP and a suction area of the pump because cooling water passing the core has a very high radiation level. Namely, cooling water discharged from the RHRP stays for a sufficiently long time inside the GCCT before entering the PWCPS to decay out N-16, which has a high radiation level but short half-life time. As a result, cooling water inside the PWCPS has a low radiation level, and the design of PWCPS is easy and cheap.

Here, the reactor pool, GCCT, and RHRP shall be designed as the safety class, but the PWCPS will be a non-safety class because it is not related with reactor safety directly.

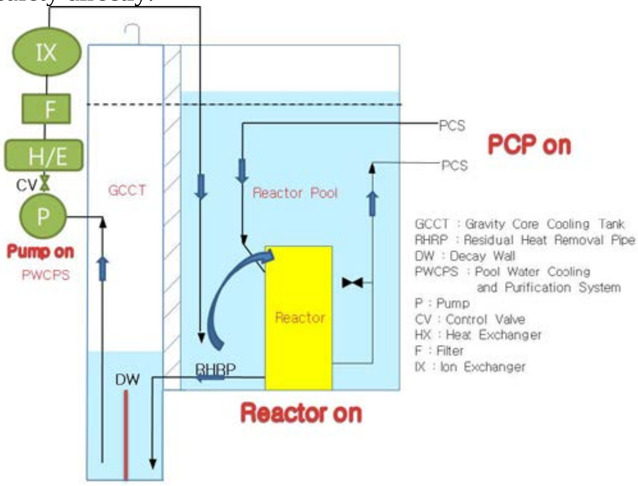

Fig. 1. PRHRS for Research Reactor using GCCT

3. Operation

When the reactor is off, the reactor pool and GCCT have the same pool water levels because cooling water can move freely through the RHRP between the two pools.

After the PCP is turned on, the water level of the GCCT gradually decreases because some water moves from the GCCT to the reactor pool through the RHRP. An increase of the reactor pool water level is small because the surface area of the reactor pool is much larger than that of GCCT. Finally, two pools have a water level difference and the flow of cooling water through the RHRP is stopped. Here, the hydrostatic head by the water level difference is the same as the pressure drop through the core. PWCPS is turned on after the PCS, reactor pool, and GCCT are in stable operation conditions. Cooling water flows in the PWCPS from the GCCT, and is discharged into the reactor pool after passing the pump, heat exchanger, filter, and ion exchanger of the PWCPS. Some reactor pool water is suctioned into the reactor through the top opening of the RSA, mixed with PCS water, and passed the core. Some of the heated cooling water at the lower plenum of the RSA moves into the GCCT through RHRP. After PWCPS is stable with the balanced mass flowrates, the reactor shall start a power operation. A flow diagram is shown in Figure 1 for normal power operation conditions. When PCS water is discharged into the RSA, some PCS water will be released into the reactor pool through the top opening of the RSA due to collisions between flows and structures. It will generate some flow in the upper section of the reactor pool above the reactor, and this flow will make the radiation material moved on the surface of the reactor pool. However, the suction flow of the reactor pool water through the top opening of the RSA blocks the released PCS flow, and the pool top surface radiation level is low. In addition, an extra purification system for a PCS is not required because the purified water from a PWCPS is mixed with PCS water.

Under reactor accident conditions, the reactor is shut-down, and the PCP is quickly turned off. Even though PWCPS can remove the core decay heat, this system shall be neglected for the safety analysis because it is a non-safety class. The water level difference between the reactor pool and GCCT maintains core downward flow naturally and the flow stops when two pool levels are equal. Then, a flap valve on the PCS pipe inside the reactor pool is automatically opened by gravity force. The decay heat is removed by natural circulation through the flap valve, lower plenum, and the core to the pool.

4. GCCT sizing

An open-pool research reactor was preliminarily designed in this paper. It has 15 MW of thermal power, a 20 m^2 reactor pool area, a 30 m^2 service pool area, and 11 m water levels under normal power operation conditions. Normally, the pool gate between the reactor pool and service pool was opened. The flowrate of PCS was 550 kg/s, and the pressure drop through the core was 110 kPa. During reactor normal operation, the rector pool and service pool therefore had an 11 m water level, and the GCCT had a 0 m water level.

After the reactor shut-down, 8% of full power was considered as a decay heat of the core, and was 1200 kW. To consider the hot channel effect, we assumed that the required heat removal capacity was double, i.e., 2400 kW. In addition, we assumed that the inlet coolant temperature was 40 ℃, and it was heated as saturated liquid at the outlet of the core with 120 ℃. The specific heat was assumed to be 4.2 kJ/kg• ℃. Then, the required flowrate was 7.14 kg/s from the heat balance. The decay heat was decreased to 4% and 2% of full power after about 200 and 2000 seconds, respectively. Of course, the required flowrate was 1.78 kg/s for 2% decay heat removal. A natural circulation flow can be removed at this level of decay heat, and the flow reversal from downward to upward at the core may then be permitted. From the Bernoulli equation, the velocity at the RHRP was dependent on the root of the water level difference, and the flowrate through the RHRP was the pipe diameter multiplied with the velocity. The reactor pool water level gradually decreased and the GCCT water level increased. The flow disappeared when the two water levels were the same. Figure 2 shows the flowrate from the reactor pool to the GCCT along with their water levels. The flowrate was decreased linearly, but it was higher than 1.78 kg/s until 1990 seconds. The flow stopped at 2200 seconds, and the final water levels were identically 10.6 m. The GCCT may be capable of applying an intermediate cooling method.

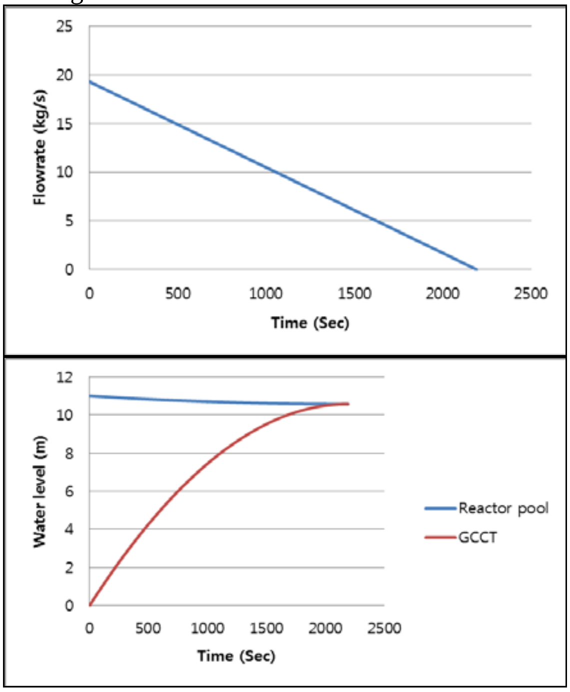

Fig. 2. RHRP flowrate and pool water levels during accidents

4. Conclusions

A Gravity Core Cooling Tank (GCCT) beside the reactor pool with a Residual Heat Removal Pipe connecting two pools was developed and designed preliminarily as a passive residual heat removal system for an open-pool type research reactor. It is very simple to design and cheap to construct. Additionally, a non-safety, but active residual heat removal system is applied with the GCCT. It is a Pool Water Cooling and Purification System. It can improve the usability of the research reactor by removing the thermal waves, and purify the reactor pool, the Primary Cooling System, and the GCCT. Moreover, it can reduce the pool top radiation level.

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