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NUMERICAL STUDY ON THE HEAT TRANSFER PHENOMENA IN WATER POOL TYPE REACTOR CAVITY COOLING SYSTEM OF VERY HIGH TEMPERATURE GAS-COOLED REACTOR

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ABSTRACT

Many studies have been performed on High Temperature Gas-cooled Reactor (HTGR) which is able to make a mass production of hydrogen with economy and efficiency. The HTGR is designed to remove heat using passive cooling system in order to have an inherent safety and high heat removal capacity during the accident. Therefore, Reactor Cavity Cooling System (RCCS), is installed between the reactor vessel and the containment in cavity, is considered to remove heat during normal operation and accidents. The cooling type of RCCS was divided by cooling method water-cooled and air-cooled type. The concept of the water pool type RCCS, which was proposed at Seoul National University, consists of a reactor vessel, water pool surrounding the vessel, upper tank, cooling pipes and air supply system. It was designed to overcome the disadvantage of both the weak cooling ability of air cooled type and the complex structures of water cooled type. In this study, preliminary numerical analysis for experimental facility was performed to evaluate the proposed RCCS design. CFX was used for modeling of experimental facility and the surface temperature of cooler calculated by RETRAN-3D/INT was used as a boundary condition. The calculation results from CFX and RETRAN-3D/INT show good agreements with each other and it is found that the proposed RCCS design has sufficient cooling capability

Keywords: HTGR, RCCS, Water-cooled Type, Air-cooled Type, Water Pool Type

1. INTRODUCTION

Recently, the demands of hydrogen energy have increased as an alternative energy resource to solve the energy and green house effect problems. Many studies have been performed on HTGR which is able to make a mass production of hydrogen with economy and efficiency [1]. The HTGR has average coolant temperatures above 900 ℃ and fuel temperatures above 1250 ℃. The concept of HTGR allows a wide range of process heat applications such as coal gasification, thermo-chemical hydrogen production. However, if accident such as a loss of coolant accident (LOCA) or a loss of forced convection (LOFC) accident occurs, the safety of reactor is threatened greatly since it has a high operation temperature. For this reason, the HTGR needs a different concept of cooling system to increase the safety in normal operation and accidents. The HTGR is designed to remove heat using passive cooling system for inherent safety and high heat removal capacity during the accident condition [2].

Reactor Cavity Cooling System (RCCS), is installed in cavity between the reactor vessel and the containment, is designed to remove decay heat during the accident. The function of the RCCS was to preserve the reactor vessel under the maximum temperature and to be able to protect the structure of reactor containment in the event of the failure of all active cooling systems.

The cooling type of RCCS is classified by cooling method such as water-cooled and air-cooled type. RCCS of all HTGR are tabulated in Table1. The water-cooled type has the limitations of the water tank volume since the cavity is located between reactor vessel and containment [2-6]. In addition, it has a possibility of increasing the pressure of water tank as the boiling and evaporation. In order to provide high reliability of RCCS, it needs to be equipped with the complex systems such as heat exchanger. However, it has a sufficient cooling capacity. In the other hand, the air-cooled type has low cooling capacity. That provides the natural circulation of air through the chimney and has the possibility of releasing radioactive materials from cavity to atmosphere. Due to the natural circulation of air, however, it has more passively system than water cooled type and has the simplicity of cooling system without additional devices. In addition, it is possible to offer the long term cooling without forced cooling system. For these reason, the concept of RCCS, named water pool type RCCS, was proposed at Seoul National University to overcome the disadvantage of both the poor cooling ability of air cooled type and the complex structure of water cooled type.

As a part of those studies, preliminary calculation for evaluation of the concept of the RCCS was carried out. Numerical calculation for code-to-code benchmark was conducted using CFX5.7 code and RETRAN-3D/INT system code. Also numerical calculation for the heat transfer phenomena in water pool type RCCS was performed. RETRAN-3D/INT system code computed a surface temperature of cooling pipe and water temperature of water storage. [7] The CFX5.7 calculated to obtain detail information such as velocity and temperature distribution in water pool without simulating forced convection heat transfer of cooling pipes. After the data were fitted in 5th polynomial expression, it was used as a boundary condition of pipe surface on CFX5.7 code.

Table 1. RCCS in the HTGR

Reactor	RCCS Coolant / Type	Secondary coolant / Type
HTTR	Water Forced Convection	Water Forced Convection
HTR-10	Water Natural Convection	Air Natural Convection
PBMR	Water Natural Convection	Air Natural Convection
GT-MHR	Water Natural Convection	Water Forced Convection
MHTGR	Air Natural Convection	No Secondary cooling

2. CONCEPT OF THE WATER POOL TYPE RCCS

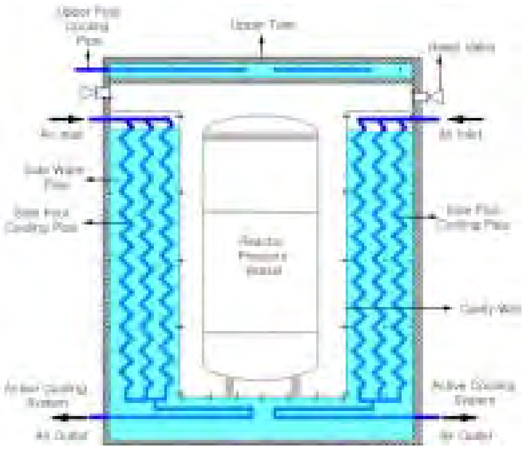
The water pool type RCCS was proposed to overcome the disadvantage of both the weak cooling ability of air cooled type RCCS and the complex structure of water cooled type RCCS. The schematic diagram of water pool type RCCS is shown in Fig. 1. This is different from water cooled type RCCS since water pools, between reactor vessel and containment, were used as heat sink during normal operation and the afterheat during the accident. The system of water pool type RCCS mainly consists of a reactor vessel, water pool surrounding the vessel, upper tank, cooling pipe which is installed in the water pool, and air supply system. In normal operations, the heat loss from the reactor vessel is transferred into the water pools via cavity. The heat is rejected to atmosphere by forced convection of air flowing through cooling pipe.

Under the LOFC accident conditions, the RCCS has to remove the entire core afterheat through a passive cooling method in the shutdown of all active cooling systems. The generated Steam during heat-up is released to the atmosphere. The maximum vessel temperature should satisfy the design criteria for 72 hours without any behaviors of operator. RCCS is designed to provide sufficient cooling capacity of the passive afterheat removal.

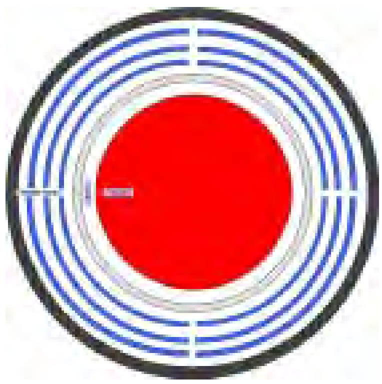
The water pool type RCCS is similar to the common water cooling systems but it is expected to be easier to design and analyze because of the simple geometry. It uses ambient air to reject the afterheat so additional cooling systems are not necessary. Poor cooling capability of air, however, may result in large capacity of the air supply system and the size of the water pool should be limited due to space of the cavity.

Due to this reason, we need to perform numerical studies to evaluate the feasibility of the water pool type RCCS as preliminary process of experiment. CFX code and RETRAN-3D/INT for numerical analysis used for the evaluation of the feasibility and optimization of the system. The experimental analysis for the validation of CFX code and RETRAN-3D/INT are planned to be performed.

In this paper, the numerical results were presented which were performed to investigate the heat transfer phenomena such as the natural convective heat transfer in the water pool and the forced convective heat transfer in the cooling pipe.



(a) Front View of Water Pool Type RCCS

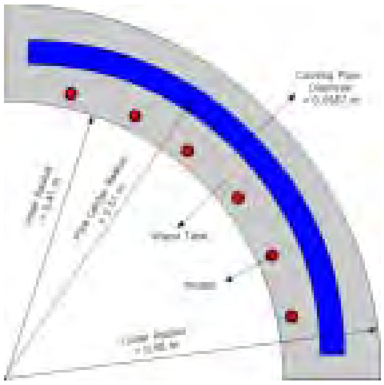


(b) Top View of Water Pool Type RCCS

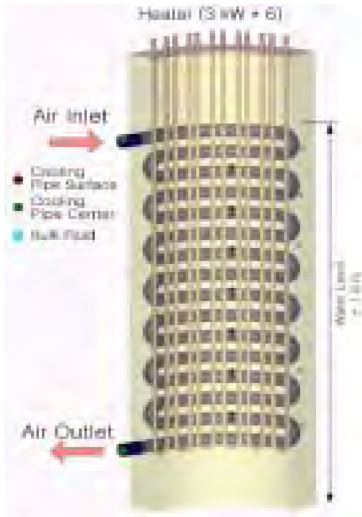
Figure 1. Concept of the Water Pool Type RCCS

3. TEST FACILITY FOR CODE EVALUATION

A test facility for code evaluation was constructed to investigate convective heat transfer between the water pool and cooling pipes during normal operation condition of the water pool type RCCS. The schematic diagram of the test facility is indicated in Fig. 2. The linear scaling methodology was adopted for the design of the test facility and was reduced to 1/10 length scale. The test section was designed for a 1/4 section of the water pool with the assumption of symmetric temperature distribution. The inner and outer wall of the test section represent cavity outer wall and containment respectively. As shown in Fig. 3, six U-bend heater rods were equipped at near the inner wall of the test section to reproduce the heat transfer from the reactor vessel to the water tank through the cavity. A cooling pipe with fifteen U-bends was installed in the water pool. The outlet of the cooling pipe is connected to the suction of a blower and ambient air flows through the inlet of cooling pipe.



(a) Top View of Separate Test Facility



(b) Front View of Separate Test Facility

Figure 2. Geometry of Test Facility for Calculation

4. NUMERICAL CALCULATION

CFX code and RETRAN-3D/INT system code was used as preliminary calculation for the evaluation of water pool type RCCS to investigate natural or convective heat transfer. When heat transfer phenomena from the water pool to the cooling pipe is considered in CFX calculation, additional nodes for conduction calculation are required and the nodalization for the pipe thickness may cause the problem during mesh generation since the thickness of the pipe is quite small compared with the whole domain size. Therefore, in order to reduce the computation time and the number of mesh, air forced convection heat transfer of cooling pipe was not calculated and the temperature distribution along the cooling pipe surface is used as a boundary condition which is calculated by RETRAN-3D/INT [7] code. RETRAN-3D/INT is one-dimensional system code based on the RETRAN-3D [8] and developed by Seoul National University for the analysis of nuclear marine reactor.

The nodalization for the analysis by RETRAN-3D/INT is shown in Fig. 3 and 4. The analysis model consists of 55 volumes and 74 junctions. It includes the 33 heat structures to conduct the heat transfer phenomena at heater and cooling pipe. In addition, there are cross flow junctions to consider the cross flow between heater region and cooler region in Fig. 4. The inlet of the cooling pipe is modeled using fill junction and the mass flow rate was given as a boundary condition. heat transfer coefficients of Zukauskas [9] and Mori-Nakayama [10] were used as heat transfer coefficients for shell and tube sides of cooling pipe, respectively.

The CFX calculation was carried out to investigate the heat transfer phenomena in the water pool using surface temperature distribution of RETRAN-3D/INT. In order to reduce the computation time and the number of mesh, the calculation geometry of RCCS is simplified like duct shape. The calculation geometry of air pipe is shown in Fig. 5. It is designed to have a same heat transfer area with the pipe and the air does not flow in duct. It has only a function of heat sink to remove the heat from heater to water pool. The RETRAN-3D/INT data of the cooling pipe surface temperature were implemented as boundary conditions. The k-ε model was used in the turbulent modeling and the initial temperature of water pool was 45 ^{o}C.

The cases of calculation are tabulated in Table2.

Table 2. The cases of Calculation

	Heat Power (kW)	Air Velocity (m/s)
CASE1	2.74 kW	32 m/s
		48 m/s
		58 m/s
CASE2	4.0 kW	32 m/s
		48 m/s
		58 m/s

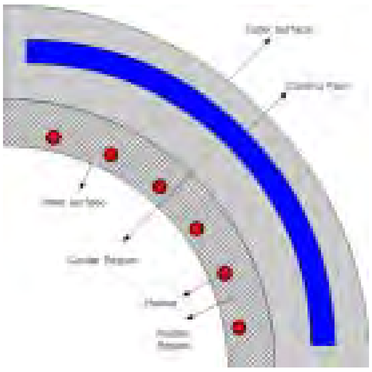


Figure 3. Region of Calculation

Figure 4. Nodalization of RETRAN-3D/INT

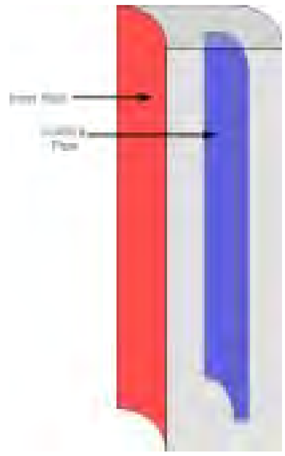


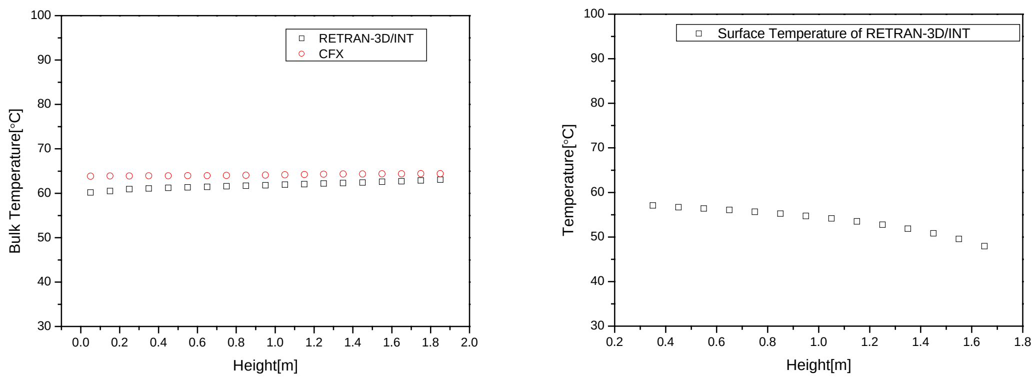
Figure 5. Domain of CFX calculation

5. RESULTS

Fig. 7 to 12 show the calculation results of the temperature distribution of water pool and cooling pipe surface. The surface temperature of cooling pipe gradually increases as going to the outlet. Helical coil model was used in the calculation geometry of cooling pipe of RETRAN-3D/INT to simulate the heat transfer of cooling pipe with the U-bends shape. Due to the difference of heat transfer coefficient between the helical coil model and the actual pipe, the inlet surface temperature was lower than other surface temperature. In addition, RETRAN-3D/INT is not able to accurately calculate the pressure drop in bend of cooling pipe since it have a lumped nodalization of cooling pipe as shown in Figure5.

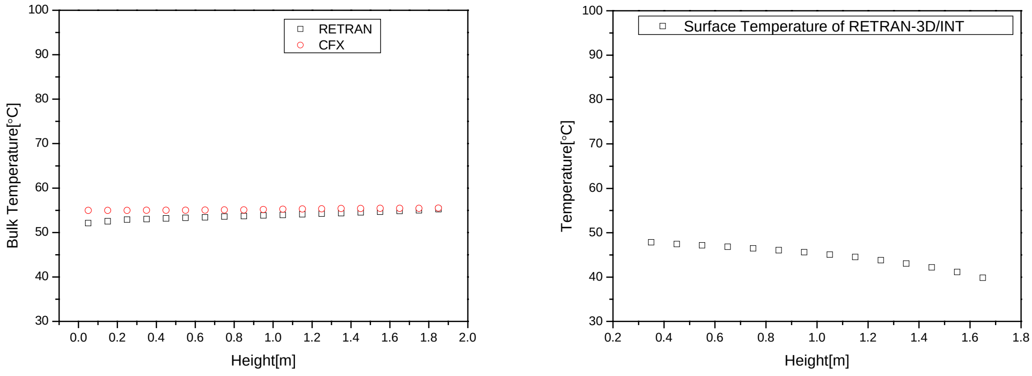
In the results of CASE1, the CFX code over-predicts the water pool temperature of bottom part by 3~4 ^{o}C than results of RETRAN-3D/INT since CFX code does not calculate natural circulation between bends. The natural convection of water pool happens between top part of cooling pipe and bottom part of cooling pipe due to the duct shape. Moreover, as the inlet velocity of air increases, the temperature difference between results of CFX code and those of RETRAN-3D/INT decreases. However, in the results of 4kW, RETRAN-3D/INT over-predicts the water pool temperature of top part by 3~4 ^{o}C than results of CFX code since the bulk temperature of water pool is influenced by fast inlet velocity. In other words, this means that heat transfer of top part of near inlet is not good.

The temperature difference between top of water pool and bottom of water pool is 2~3 ^{o}C. This means that the natural convection occurs in water pool. The velocity field in water pool is shown in the Fig. 13. Natural circulation was found as the upward flow in near the inner heating wall and downward flow in near the cooling pipe occur.



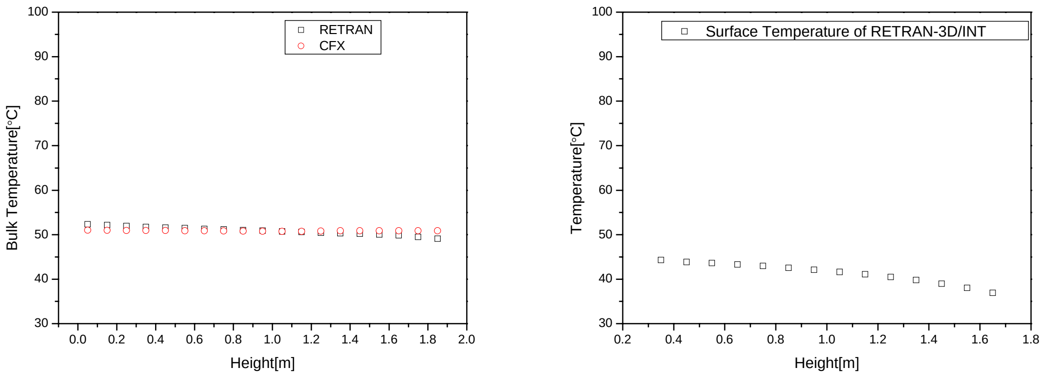
(a) Bulk Temperature of Water Pool (b) Surface Temperature of Cooling Pipe

Figure 6. Temperature distribution of Heat=2.74 kW and Velocity=33 m/s



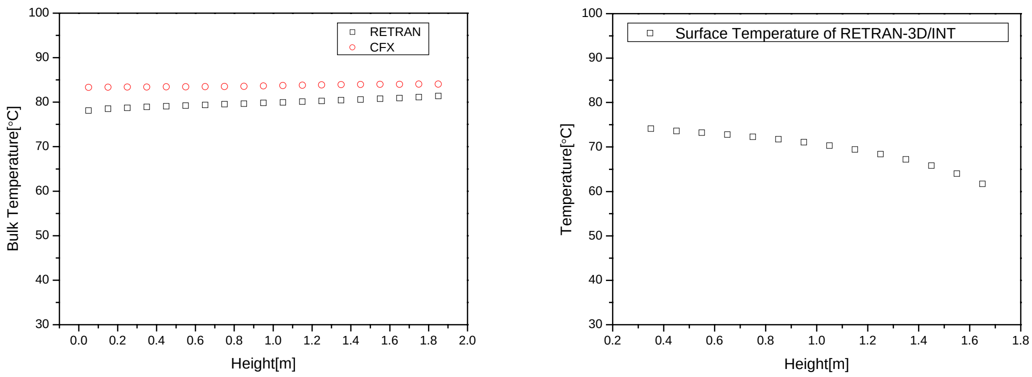
(a) Bulk Temperature of Water Pool (b) Surface Temperature of Cooling Pipe

Figure 7. Temperature distribution of Heat=2.74 kW and Velocity=48 m/s



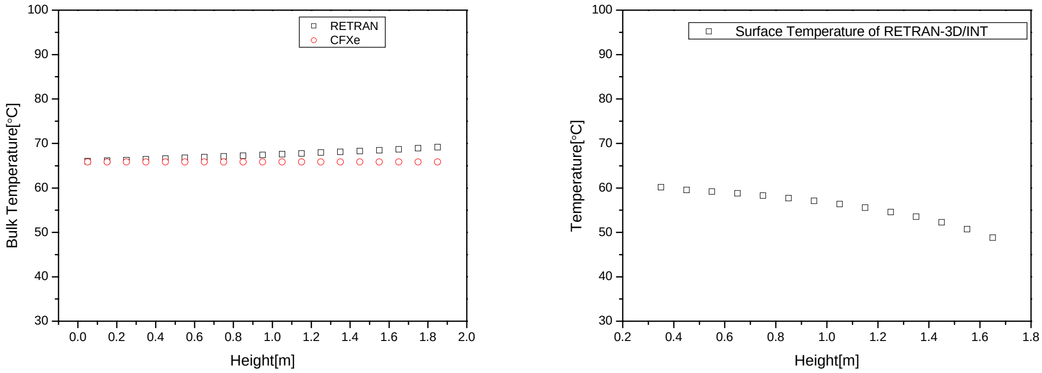
(a) Bulk Temperature of Water Pool (b) Surface Temperature of Cooling Pipe

Figure 8. Temperature distribution of Heat=2.74 kW and Velocity=58 m/s



a) Bulk Temperature of Water Pool (b) Surface Temperature of Cooling Pipe

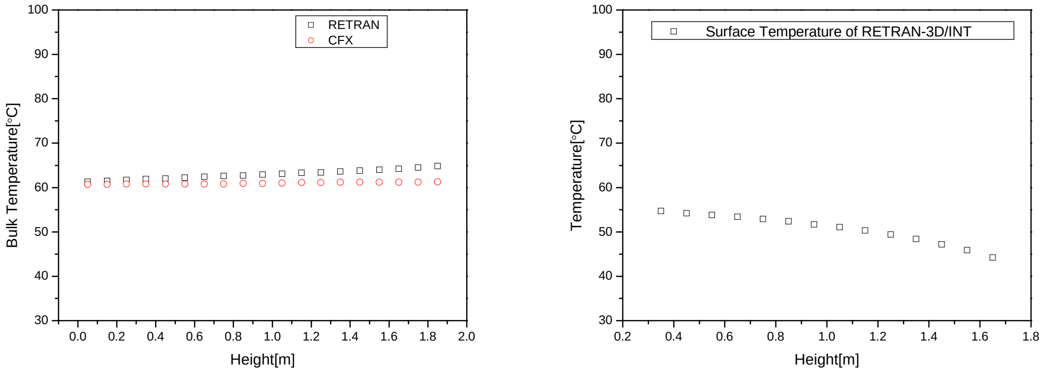
Figure 9. Temperature distribution of Heat=4.0 kW and Velocity=33 m/s



a) Bulk Temperature of Water Pool

(b) Surface Temperature of Cooling Pipe

Figure 10. Temperature distribution of Heat=4.0 kW and Velocity=48 m/s



a) Bulk Temperature of Water Pool

(b) Surface Temperature of Cooling Pipe

Figure 11. Temperature distribution of Heat=4.0 kW and Velocity=58 m/s

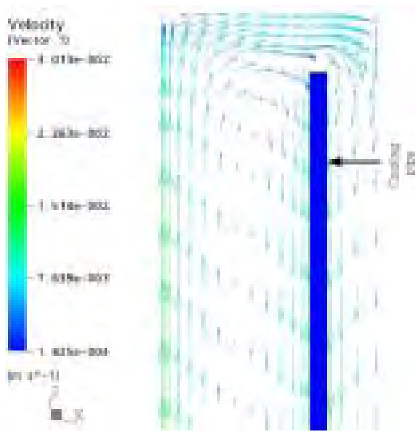


Figure 12. Velocity distribution in Water Pool

6. CONCLUSION

This study is focused on preliminary analysis by CFX code and RETRAN-3D/INT system code in the view of heat transfer phenomena on water pool type RCCS. The evaluation of CFX code and RETRAN-3D/INT was conducted for a quarter section of water pool to investigate the heat transfer phenomena such as natural circulation and convection. And the surface temperature of CFX code was input by the results of RETRAN-3D/INT, without considering the inside of cooling pipe.

The CFX5.7 calculation results were compared with those of RETRAN-3D/INT. Calculation of both CFX code and RETRAN-3D/INT for heat transfer phenomena of water pool results in good agreement. It was found that this facility for evaluation of water pool type RCCS had a sufficient cooling capacity and water pool temperature was maintained under boiling temperature. In the future, experimental analysis of test facility will be performed to validate the bulk temperature of water pool and heat transfer phenomena.

NOMENCLATURE

Q Heat [W]
D Diameter [m]
R Radius [m]

Subscript
in Inlet
out Outlet
cp Cooling pipe
v Volume

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