Heat transfer simulation in reactor cavity cooling system for experimental power reactor (RDE)

M Yunus*, R Kusumastuti, and M Subekti

Center for Nuclear Reactor Technology and Safety, BATAN
Puspiptek Complex, Building No.80, Serpong, Tangerang Selatan 15310, Indonesia.

*e-mail: muhammad-yunus@batan.go.id

Abstract. To enhance the safety of experimental power reactor (RDE), Reactor Cavity Cooling System (RCCS) is required to support primary helium coolant. RCCS can be utilized for both normal condition or under accident. During the reactor accident with no power supplies and cooling pump down, RCCS works in a natural-circulation by using air in cavity and water in the cooling pipe. In this study, the process of radiation heat transfer from Reactor Pressure Vessel (RPV) to Water Cooled Pipe (WCP) was simulated. The natural circulation of air cavity and around the WCP was studied in three dimensional numerical model. The analyses are performed with Fluent code, which is a computational fluid dynamic code. Three parameter conditions of simulation were studied to compare the difference of them, so in this primary study, it can be known the influence of each parameter to the obtained results and it can be considered for development of future safety simulation in RDE reactor. From the simulation result, the temperature at bottom air cavity is higher than the top of the cavity. The temperature profile of water in the pipe also changes because of influence the heat transfer from Reactor Pressure Vessel. Gravity and radiation are very important parameter inputs to simulations in order to approach the real conditions.

Keyword: Heat transfer, Reactor Cavity Cooling System, RDE reactor

1. Introduction

Recent years, BATAN’s project focusing on the developing the experimental power reactor (Reaktor Daya Eksperimental - RDE) that belong to High Temperature Gas-cooled Reactor (HTGR) with using pebble bed fuel and helium as coolant [1-3]. The structure of RDE refers to design and concept features of HTR-10 reactor that was built and operated in China. HTGR is considered for RDE design because it is one of the best candidates for the next generation of nuclear power plants that has inherent safety features, graphite-moderated, helium cooled thermal reactor, high core exit temperature, high efficiency system and economic competitiveness [4-6].

In generation IV reactor including RDE reactor, safety improvement is the main focus area to ensure the reactor working properly both normal condition or under accident. Because of the average outlet temperature of RDE reactor can exceed 700°C [7], it requires passive heat removal system to keep the temperature of a reactor in safe. To support the helium coolant as primary cooling system, passive heat removal system was developed in several nuclear reactor projects. Reactor Cavity Cooling System (RCCS) is the new safety system designed based on passive heat removal system that can operate
without requiring external power supplies. The design and characterization of the RCCS is an important feature to the realization of a new concept for an HTGR. RCCS is used to cool down the Reactor Pressure Vessel (RPV) and the reactor cavity area in operating condition and also remove the residual heat after the reactor shutdown [5,8,9].

RCCS is consist of water cooled panel, hot water mains, hot water pipes, expansion tanks, air coolers, cold water pipes, cold water mains, and air cooling towers [4]. The principle of RCCS based on natural-circulation driven cooling system using water in the Water Cooled Pipe (WCP) so it can remove heat on the cavity. In the event of accident condition, where power is lost and the cooling pump doesn’t work, the residual heat from core vessel will be transferred to RPV by convection and radiation. From the RPV, the heat is transferred to the WCP surrounding the RPV. The hot water naturally flows upward through vertical WCP and the residual heat is released in cooling towers and finally exhausts into the atmosphere [11, 12].

To ensure whether RCCS is capable to remove heat transfer from the pressure vessel, especially during an accident scenario, the temperature distribution in the reactor cavity is important to be known. Therefore, it is necessary to study the heat transfer process in reactor cavity including in numerical simulation approach. Several studies have investigated the temperature distribution in the air cavity either in a reactor or experimental facility with various designs of RCCS [5,6,9,13-15]. Frisini, et. al [13] studied the influence of different geometrical parameters on the balance of heat transfer across the RCCS cavity for Very High Temperature Gas-Cooled Reactors. Zhao et. al [6] developed a three-dimensional numerical model used to simulate the heat transfer process in the reactor cavity of HTR-10 and analyzed the local and global heat transfer processes. Although these research explained comprehensive results of temperature distribution in HTR-10, airflow vector was not included in the result whereas the air flow can explain the natural circulation flow in the air cavity.

This research focuses on developing the heat transfer simulation of RCCS in RDE reactor. Heat transfer of air cavity and water flow in WCP was analyzed in a three-dimensional model. In this preliminary study, three parameter conditions of simulation were studied to compare the difference between them, in order to know the influence of each parameter to the result. Finally, this result can be considered for developing the full-scale heat transfer simulation of RPV and the RCCS in the future research.

2. Computation Model of the RDE’s RCCS

2.1 Geometry Design

RCCS of RDE reactor is designed to remove the heat transfer from core reactor to reactor cavity. To keep temperature reactor vessel normal and prevent overheat, the RCCS is located inside the concrete wall of the cavity, surrounding the reactor vessel as shown in Figure 1. In this research, the heat transfer phenomena in reactor cavity, the area between reactor cooling system and RCCS, is investigated to know the temperature distribution in air cavity, airflow velocity, and temperatures of water in cooling pipe.

The configuration of reactor cavity and RCCS is shown below in Figure 2. From the Figure 2a, it shows parts used in computational model that consist of RPV wall, reactor cavity, pipe, and concrete. The structure inside the RPV is not included because this research only simulates heat transfer process in the reactor cavity. The detailed design of RPV wall can be neglected because sizes of some local structure are very small compared to the size of reactor cavity, so the scheme for the computational model is simplified in order to reduce computational cost. The configuration of reactor cavity and its component can be considered as axisymmetric because the shape of RPV, reactor cavity, and WCP arranged in a circle. Therefore, to simplify the scheme, it uses symmetry boundary condition with half diameter pipe sectorial model as shown in Figure 2b and 2c. Although the model is simplified, size of the configuration does not scale down, and water in the WCP is included. In Table 1 is given detail parameter of the geometry design of RPV and WCP.
The configuration of reactor cavity for the computational model is drawn by using Gambit 2.4.6 software. It is also used to make the mesh in the sectorial model with all of the meshes are tetrahedral volume mesh. It requires fine mesh enough in order to obtain accurate simulation results. The mesh of this configuration consists of 1975465 cells, composed of 75157 solid cells (pipe) and fluid cells consisting of 1847256 air cavity cells and 53052 water cells. The maximum value of the mesh quality about 0.835485, it means that the mesh quality is good enough because there is no greater than 0.97.

Figure 1. Geometry design of RCCS.

Figure 2. Simplified model and configuration of RPV and WCP.
Table 1. Detail parameter of RPV and WCP.

| Parameter                        | Value (cm) |
|----------------------------------|------------|
| Height of RPV                    | 1150       |
| Diameter of RPV                  | 480        |
| Distance of RPV - reactor cavity | 45         |
| Height of WCP                    | 930        |
| Distance of RPV – WCP            | 40         |
| Interval of WCP                  | 1.3        |
| Inner diameter of WCP            | 3.2        |
| Outer diameter of WCP            | 2.6        |

2.2 Mathematical Model and Boundary Condition
The analyses of heat transfer in air cavity for RDE reactor are performed with Fluent Code, which is a thermal hydraulic analysis code. The simulation accuracy of heat transfer in radial direction is the most important factor for simulation of the temperature of RPV and WCP. The residual heat from the RPV wall is transferred to reactor cooling system by radiation. P1 model of radiation heat transfer is adopted to compute the radiation in the reactor cavity. It is widely used for computations of various kind radiation heat transfer processes, because of The P-1 radiation model is the simplest case of the more general P-N model, which is based on the expansion of the radiation intensity I into an orthogonal series of spherical harmonics. This research is preliminary studies, so simple radiation transfer equation is good enough to use. The radiation transfer equation based on the P1 model is showed as [16]:

\[-\nabla \cdot q_r = aG - 4a\sigma T^4\]  \hspace{1cm} (1)

where \(q_r\) is the radiation flux, \(a\) is the absorption coefficient, \(G\) is the incident radiation, \(\sigma\) is the Stefan-Boltzmann constant, and \(T\) is the temperature.

Due to this research is designed as an early stage for understanding how to predict temperature distribution in air cavity by computational fluid dynamics, some parameter and boundary condition is assumed by considering data from some literature. The CFD analyses were carried out at accident scenario. The heat loss through the RPV of RDE Reactor during accident scenario is an approximation temperature based on the temperature profile of RPV in the analysis of the HTR–10 heat up accidents with the TAC–NC Code [17]. The temperature of RPV wall is defined as fixed temperature and divided into 12 sections. The maximum temperature is assumed about 375°C at the middle of RPV because the core reactor is located in the middle and the minimum temperature is assumed about 275°C. The temperature profile of RPV wall is shown in Figure 3 in which the simulation inside the RPV could done by RDE simulator [7].

Besides radiative heat transfer, heat transfer process that also occurs in reactor cavity is natural convection in air. From previous studies on RCCS simulation, the natural flow of air in reactor cavity can be modeled with using \(k-\varepsilon\) turbulence model [6,13-15]. The change of air density in reactor cavity can be represented as ideal gas model (incompressible ideal gas) approach.

The symmetry boundary condition on both lateral faces is used because RPV, cavity region, and WCP are in a cylindrical configuration. Therefore, the section considered takes into half of a WCP sectorial. The boundary condition of concrete or reactor cavity wall is defined as adiabatic wall. The mass flow inlet boundary condition of water in the pipe is assumed 0.03 kg/s with the temperature of water about 39°C and the outlet boundary condition is defined as outflow.
By using first order upwind and SIMPLE algorithm, the heat transfer in reactor cavity model is calculated with Fluent code. Three parameter conditions are selected for these simulations that are model with radiation and gravity (condition 1), the model without gravity (condition 2) and the model without radiation (condition 3). In addition to 3 models with 3 different parameters above, all boundary conditions are similar. The three difference parameter condition is used in order to know the influence of each parameter to the result. This result can be considered for developing the full scale heat transfer simulation of RPV and the RCCS in the future research.

3. Result and Discussion

The simulation result for the model with the parameters of radiation and gravity conditions are shown in Figure 4. From Figure 4, it obtained that the maximum temperature in the air cavity is about 222.8748 °C, while the minimum temperature is about 39.0003 °C. Through the Figure 4, it is clear that the temperature at the bottom of air cavity is much lower than at the top of the air cavity. This is in accordance with some previous research results about simulation of heat transfer and natural circulation in RCCS [6,13-15]. From the previous studies also showed that the temperature at the bottom of the water cavity is much lower. This is due to the natural circulation that occurs in the air, in accordance with the working principles of passive heat removal system of RCCS.

During the operation of RCCS, heat from RPV wall is transferred to the air cavity by radiation and convection. Afterward, it causes decreasing air density due to temperature difference from RPV where the middle of RPV is the highest. Because of this, a pressure difference occurs in the air cavity. Under the influence of the pressure difference, air heated along RPV wall flows upward in the air cavity. Therefore, the temperature in the upper water cavity will be higher than the bottom. The same principle also occurs for water in the pipe. Because of the influence of heat transfer from the air cavity, so that the water in the WCP will receive the heat and there will be a temperature and pressure difference. As a result, water in the pipe will flow upward. The temperature difference in the WCP about 4°C, which the inlet temperature is ~ 39 °C and the outlet about 43°C. In the full scale of RCCS design, eventually the heat from water outlet will be released into the air outside condenser. Afterward, in effect of gravity, the cooled water flows downward to the main pipe. This principle of natural circulation is used in the passive heat removal system. Beside the water circulation, natural air circulation also has an important role to maintain cavity temperature stability. This principle can be explained easily by the flow vector of air.
Figure 4. Total Temperature distribution on air cavity of condition 1.

Figure 5 shows clearly how the flow patterns of air and water in the RCCS system. From the figure, as the air density decreases due to heated RPV wall, the air flows upward along near RPV. In effect of the gravity and difference temperature at the cooled concrete wall, the air density will increase and the air flows downward along the concrete wall. This principle leads to natural air circulation used for passive heat removal system. At the top and bottom cavity, turbulent flow occurs. This is due to the dome-like shape of top and bottom of RPV so that the flow will be deflected and turbulent flow occurs. The turbulent flow can accelerate the mixing process of heated and cooled air and it useful for accelerating heat transfer process and heat removal.

From the Figure 5, it shows that in effect of gravity the downward flow velocity is faster than upward flow velocity. The air velocity near RPV wall is about 1.95-2.1 m/s and the velocity near the concrete wall is about 0.6-0.9 m/s. Meanwhile, the water velocity in the WCP is about 0.1-0.15 m/s.

Figure 5. Velocity vector on air cavity of condition 1.
The simulation of condition 2 (without gravity) and 3 (without radiation) is shown in Figure 6. As mentioned above, the condition 2 and 3 was simulated to know the influence of gravity and radiation parameter to the result of heat transfer in reactor cavity. As shown in Figure 6a, gravity has an important role in natural circulation. Without gravity, in the numerical simulation, the direction of radiation heat is normal to the heated wall surface of RPV. This is indicated by the absence of heat flow toward the top of the cavity as it occurs in the condition 1. Moreover, in the velocity vector analysis, there is no flow pattern that can be described as shown in Figure 6b.

Meanwhile, for the condition without radiation (Figure 6c and 6d), it also takes effect to heat transfer process. Although, the air is heated by RPV wall followed upward flow along RPV wall, but the heat transfer that occurs is only convection without radiation process.

![Figure 6](image)

**Figure 6.** a) Total Temperature distribution and b) velocity vector on air cavity of condition 2, c) Total Temperature distribution and d) velocity vector on air cavity of condition 3.

### 4. Conclusions

Heat transfer simulation in the reactor cavity cooling system for experimental power reactor (RDE reactor) was carried out in three dimensional numerical simulation. In the calculation of accident scenario, the temperature of the RPV wall is assumed with temperature about 300 – 375 °C. As a result of three conditions with different parameter, gravity and radiation were very influential to heat transfer process in the cavity. The model with gravity and radiation parameter (condition 1), natural air circulation occurred in reactor cavity area. It was evidenced by the air flow along the RPV wall that leads upwards and downward around the concrete wall. It is contrary to the condition 2 model (without gravity parameter) that no flow pattern was formed. Meanwhile, in condition 3 the heat transfer process that occurred was convection heat transfer.

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