Investigation of RDE thermal parameters during DLOFC in the absence of water inside the Reactor Cavity Cooling System

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Abstract. Reaktor Daya Eksperimental (RDE) is a 10MWt small modular of High Temperature Gas-cooled Reactor (HTGR) with passive safety features. This reactor has a Reactor Cavity Cooling System (RCCS) to evacuate heat loss through reactor vessel in operation condition and also the decay heat in the case of accident condition. One of the most important accidents to be considered is the Depresurized Loss Of Forced Cooling (DLOFC) for a long time period. During this accident, the reactor decay heat is evacuated to the cavity cooling system which is supposed in condition of totally loss its cooling water. The analysis simulation was performed by solving numerically the two-dimensional equation of heat conduction. The implicit approach was used in the discretization of the equation, Matlab application program was used to execute the simulation program. The simulation was performed in two periods such as 1500 hours calculation to reach the steady state condition in normal operation and 500 hours of DLOFC period. Three conditions to be compared in this analysis: condition with water panel, condition without water panel, and condition without water panel but with high conductivity of concrete. The results show the increasing temperature of core after reactor shut-down until attain the maximum temperature divers from 1048°C to 1080°C. According to reactor building, the peak temperature of internal concrete wall is 96°C in condition with water panel and rises to 141.6°C in condition without water panel. The temperature can be decreased to 94.3°C in increasing three times the concrete conductivity. In all conditions the reactor core remains safe because the peak temperature is still under the limit of 1600°C. Increasing the concrete conductivity is an alternative means to keep the concrete temperature under the limit of 100°C in accident condition.

Keywords: HTGR, DLOFC, RCCS without water panel, concrete conductivity, Matlab.

1. Introduction

This paper discuss about the alternative design for the reactor cavity cooling system (RCCS) in a small high temperature reactor with the thermal power of 10 MW. The kind of reactor is being design by BATAN to raise national capacity in design, manufacturing and construction to promote nuclear industry in Indonesia[1]. The name of the reactor is RDE, an abbreviation in Indonesian language of “Reaktor Daya Eksperimental” or experimental power reactor. This RDE reactor has a mean to evacuate heat loss through reactor vessel in operation condition and also the decay heat in the case of accident condition. The mean that is called Reactor Cavity Cooling System (RCCS) is located at the outside of the reactor pressure vessel. The heat loss during normal operation or the decay heat during accident condition is transferred to this mean through conduction inside the reactor and through...
radiation in the cavity to a cooling water panel and transferred through natural convection mechanism to an air cooler. One of the most important accidents to be considered is the Depressurized Loss Of Forced Cooling (DLOFC) for a long time period[2–5]. During this accident, the reactor decay heat is evacuated to the RCCS which is supposed in condition of totally loss its cooling water. The water panels role in limiting temperatures of concretes are shown by several research [6–8].

The research purpose is to evaluate the RDE thermal parameter response during long-term DLOFC accidents in condition of totally loss its cooling water. In the present work, sensitivity analyses on peak temperatures of both the core and reactor building (RB) after reactor shutdown was conducted. The use of concrete with high conductivity will be investigated in this research.

2. Methodology

The analysis has been done by developing an analysis program using Matlab[5,9]. The program solved numerically the equation of conduction in two dimensions, radial and vertical, and in a function of time as shown in Equation (1)[10].

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{\partial T}{\partial z} \right) + \frac{q}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad \text{.................................(1)}
\]

with the radius of \( r \) (m), the height of \( z \) (m), the generated power density of \( q \) (W/m\(^3\)), the heat conductivity of \( k \) (W/m°C), the thermal diffusivity of \( \alpha \)(m\(^2\)/sec), the temperature of \( T \)(°C) and the time variable of t(seconds).

The numerical method used is finite difference in the implicit schema. The heat transfer mechanism in the reactor is actually performed by combination of convection, radiation and conduction. In this analysis, all convection and radiation mechanisms are converted to the conduction with certain equivalent value of thermal conductivity. The investigation is limited to the thermal aspect only, that is to know whether the reactor core and concrete temperatures are still within the permitted limits[4,11,12].

The analysis area is bounded by the outer surface of side concrete, the outer surfaces of lower and upper concrete. By considering the analysis area as homogeneous region so the Equation (1) is applicable for all reactor parts such as the core, the reflector, the pressure vessel, the cavity and the concrete wall with the own physical properties different one part to another. For the conjunction surface between two parts such as Part 1 and Part 2 the continuity of heat flux is applied as boundary condition, ie for the \( r \) direction,

\[
k_1 \left( \frac{\partial T}{\partial r} \right)_1 = k_2 \left( \frac{\partial T}{\partial r} \right)_2 \quad \text{.................................(2)}
\]

and for the \( z \) direction

\[
k_1 \left( \frac{\partial T}{\partial z} \right)_1 = k_2 \left( \frac{\partial T}{\partial z} \right)_2 \quad \text{.................................(3)}
\]

The Neumann boundary conditions is applied on the outer concrete wall surface, ie for the direction \( r \)

\[
k_1 \left( \frac{\partial T}{\partial r} \right)_1 = h_0(T_1 - T_{ud})_2 \quad \text{.................................(4)}
\]

or for the \( z \) direction

\[
k_1 \left( \frac{\partial T}{\partial z} \right)_1 = h_0(T_1 - T_{ud})_2 \quad \text{.................................(5)}
\]

The heat transfer mechanisms in the cavity are mainly radiation combining with natural convection. For radiation, with surface emissivity coefficient of \( \varepsilon \) and Stefan Boltzmann’s constant of \( \sigma \), the radiation heat transfer coefficient equivalent from surface 1 to surface 2 is

\[
h_R = \varepsilon \sigma (T_1^3 + T_1^2T_2 + T_1T_2^2 + T_2^3) \quad \text{.................................(6)}
\]

By adding the natural convection heat transfer coefficient \( h_c \) in the cavity, the heat transfer coefficient equivalent in the cavity is equal to

\[
h_{RC} = h_R + h_c \quad \text{.................................(7)}
\]
Regarding the conduction equation applied for all analysis regions including the cavity, it is needed to define an equivalent thermal conductivity of the region even though actual heat transfer mechanism are radiation and natural convection. The equivalent thermal conductivity is defined based on the identical temperature value to the actual conditions, an approximation value is shown by Equation (8).

$$k_e = h_{RC} \times L$$  

with L is the width of cavity.

The equivalent physical properties as a function of temperature for all reactor parts is taken from the literature by approximate to the physical properties of the HTR-10 reactor parts. The numerical method used is finite difference in the implicit schema. Using this method, the area of analysis is discretized to elements and nodes that the local temperature is defined in each node.

The analysis area covering from the core to the outer concrete wall, either the radial direction or the vertical direction. Inside the area of analysis, it can be calculated the temperature distribution for three different analysis conditions, such as: actual concrete conductivity with fully water panel, actual concrete conductivity without water panel, and high concrete conductivity without water panel. Configuration of the analysis area is shown in Figure 1.

![Figure 1. Configuration of the analysis area](image)

Prior to get the steady state condition before starting the accident condition, a 1500 hours analysis is sufficient to get a steady state condition. Furthermore, the DLOFC accident analysis in the long term is for 500 hours. It is also expected to know the influence of concrete conductivity in reducing its maximum temperature during the long DLOFC.

3. Results and Discussion

There are 3 conditions of analysis to be compared in this research, such as:

a. Condition with existence of water panel with sufficient water inside.

b. Condition without water panel with actual value of concrete conductivity.

c. Condition without water panel with high value of concrete conductivity.

The parameters to be compared are principally the maximum temperature of the reactor core and the concrete wall. Table 1 shows a comparison between the three analysis conditions for each parameter compared.
Tabel 1. Comparison of the three conditions parameters

| Parameters          | With water panel (k=1.28 W/mK) | Without water panel (k=1.28 W/mK) | Without water panel (k=3.84 W/mK) |
|---------------------|---------------------------------|-----------------------------------|-----------------------------------|
| T-max of Core       | 1080°C                          | 1048°C                            | 1052°C                            |
| T-max Int-concrete  | 96°C                            | 141.6°C                           | 94.3°C                            |
| T-max Ext-concrete  | 36°C                            | 44.1°C                            | 49.2°C                            |

It is shown that for the core maximum temperature, the difference between the three analysis conditions is relatively small, which is less than 3%. In addition, for the three conditions, the maximum core temperature achieved is still within the allowable limit, which is below 1600°C. The maximum temperature from the reactor core is determined by the amount of heat that is evacuated by the RCCS. With the lower surface temperature of the concrete in the condition of the water panel existence, the equivalent conductivity in the cavity is also lower so that the heat evacuated from the core is also lower than the condition without the water panel. This is what causes the maximum reactor core temperature in the condition of the water panel is slightly higher than the condition without water panel, which is around 32°C or only less than 3%. In conditions without a water panel, if the concrete conductivity used is the same as the condition with the water panel, the inner temperature of the concrete will rise beyond the allowable limit of 100°C under accident conditions. By using high concrete conductivity, which is three times the original conductivity, the maximum temperature of the concrete can be reduced to 94.3 °C which means it is still within the permitted limit.

Figure 2 shows the comparison of concrete temperature with different conductivity as a function of time. From these results, it can be seen that with higher conductivity, the concrete temperature can be lowered, from 141.6 °C to 94.3°C.

![Figure 2](image_url)

**Figure 2.** The influence of concrete conductivity

4. Conclusion

By this analysis, it can be conclude that for all simulation model of RCCS with water panel or not, the increasing temperature of core is still under the limit of 1600°C, so the reactor core remains safe. In absence of panel water, using the concrete with typical conductivity, the concrete temperature is over the limit in accident condition of 100°C. By increasing the concrete conductivity of 3 times, the maximum concrete temperature decrease to 94.3°C. So, increasing the concrete conductivity is an alternative mean to decrease the concrete temperature.
Aknowledgent

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