Two Dimensional Performance Analysis of Small HTR Residual Heat Removal System in DLOFC Condition

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Abstract. This research is aimed to investigate a 10 MWth HTR thermal parameter response to long-term Depressurized Loss Of Force Cooling (DLOFC) accidents. By using two dimensions analysis in radial and vertical direction, comparing to one dimension in radial, the results are expected to be closer to real conditions. The method used is firstly develop a Matlab-based temperature distribution analysis program that solves the two-dimensional conduction equation in cylindrical coordinates and also in a function of time. Using the program, DLOFC simulations were conducted over a period of 588 hours after 200 hours of time needed to reach steady state close to normal operating conditions. It can be evaluated how far the temperature of all reactor components starting from the core to the concrete wall will rise and whether they are within their safety limits. The results show that during DLOFC, temperature of all reactor components increase toward the maximum value before decreasing again. The maximum temperature of the reactor core, reactor vessel and concrete wall are respectively 1080°C, 231°C, and 96.1 °C. The maximum value of the core temperature is reach at 11.1 hours after accident. The water temperature in the cooling panel, for 50 m³ of water volume, has reached its boiling point of 100°C at around 100 hours after DLOFC and decreasing again at the time of 360 hours. Evacuation of the residual heat is not only through the cooling water panel, but also through the three directions of concrete wall, ie top surface, peripheral surface and bottom surface. During DLOFC, the maximum heat power evacuated through top, bottom and peripheral surface are respectively 4.57 kW, 4.84 kW and 29.04 kW. The maximum heat power evacuated by water panel is 52.7 kW. It can be concluded that the reactor remains safe in very long time of DLOFC.

Keywords: small HTR, two-dimensional model, Matlab, DLOFC.

1. Introduction
This study is an outgrowth of a previous study that also aims to determine the response of a Small High Temperature Reactor (HTR) called RDE thermal parameters to long-term Depressurized Loss Of Force Cooling (DLOFC) accidents [1]. The RDE is an small pebble beds HTR that the research activities are on-going progress in Indonesia [2]. The difference from the previous study is in the dimensions of analysis, ie previously only one dimension of radial, now in two dimensions of the radial and vertical direction so the results expected is to be more representative. In addition to the number of dimensions, the reactor geometry analyzed also differs mainly with the lower concrete thickness, ie only 1 m as compared to the previous one dimensional model which is up to 3 m. The
The purpose of this research is to investigate a 10 MWth HTR thermal parameter response during long-term DLOFC accidents. The investigation is limited to the thermal aspect only, ie whether the reactor core and reactor components temperature are within the permitted limits [3,4]. The method used is firstly develop a Matlab-based temperature distribution analysis program that solves the conduction equation in two-dimensional cylindrical coordinates and also the time function [5,6]. Using the analysis program, DLOFC simulations were conducted over a long period and evaluated the extent to which all parts of the reactor from the terrace to the concrete wall will rise and whether they are within the prescribed safety limits or not [7].

Several results of research on the ability of Residual Heat Removal System (RHRS) of reactor which in HTR is performed by Reactor Cavity Cooling System (RCCS) indicate the role of water panels in limiting concrete temperatures [8–10]. The heat is then transported to a water reservoir tank with an active cooler inside. So the RCCS is a close loop natural circulation or “thermo syphon” with the cavity takes a role as hot source and the reservoir tank as cold source. The performance of the kind of loop is studied experimentally in an experimental model called PASSIVE-01 that a predictive study is also performed analytically by Tjahjono[11]. As long as the cooling water inside the panel is still present, the concrete temperature is guaranteed not to exceed the boiling temperature of 100°C. If this water is empty, the maximum temperature of the concrete depends on the ability of the concrete to evacuate the heat to the ambiance. For concrete that is not too thick, evacuation of heat to the outside air becomes easier so that the temperature of concrete can be reduced. If the temperature in the water panels can be maintained below 100 °C by evacuating the heat through the concrete wall, there will be no boiling of water in the panel so that the amount of water in the water tank can be maintained constant. In this study, the analysis begins with an analysis to get the steady conditions that is near the normal operating conditions of the reactor before the accident. This preliminary analysis was conducted in 200 hours that a steady condition is approximately achieved. Furthermore, the analysis on the condition of DLOFC accident in the long term is for 588 hours. With this analysis it is expected to predict how much heat is discharged through RCCS and on all sides of the reactor under normal operating conditions as well as in DLOFC conditions. It is also expected to know the extent to which the temperature of the reactor and other reactor parts increases when there is a loss of active heat-removal capability.

2. Theory
This study used two dimensions of radius r and height z. The boundaries of the analysis area are the outer periphery of the side concrete, as well as the lower and upper concrete outer surfaces. Although heat transfer mechanisms throughout the analysis area are conduction, convection and radiation, but in this analysis the whole mechanism is represented by a single conduction mechanism. So for convection and radiation mechanisms, all heat transfer values are replaced with the value of the conductive equivalent parameters. Thus, in all parts of the reactor, starting from the core to the outer surface of the concrete wall, the heat conduction equation is applied in the two dimensional cylindrical coordinates under transient conditions in the form of differential equations with three variables, namely the spatial (r) and (z) and time variables (t) as follows:

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

with r is the radius variable (m), z is height variable (m), q is the generation power density (W/m³) and k is the heat conductivity (W/m°C), α is the thermal diffusivity (m²/sec), T is the temperature parameter (°C) and t is the time variable (seconds). The equation is then discretized using the finite difference method using implicit scheme with the space segments \(\Delta r\) and \(\Delta z\) as well as the time step \(\Delta t\). With the use of implicit scheme, the stability criterion of calculation as in the explicit scheme is no longer needed. However, caution in choosing \(\Delta r\), \(\Delta z\) and \(\Delta t\) values is still required for increasing the accuracy of the calculations. If an explicit scheme is used, the selection of \(\Delta r\), \(\Delta z\) and \(\Delta t\) must be such that it satisfies the stability criteria of the calculation as follows:
\[ \frac{\Delta r^2}{\alpha \Delta t} > 4 \] (2)

as well

\[ \frac{\Delta z^2}{\alpha \Delta t} > 4 \] (3)

with \( \alpha \) is the thermal diffusivity \((m^2/s)\). If \( i \) is the \( z \) direction number, \( j \) is the direction number \( r \) and \( k \) is the time series number then using the implicit scheme, the relation between the temperature at time \( t_k \) and the temperature at the previous time \( t_{k-1} \) is formulated in the equation as follows:

\[
T_{i,j,k-1} + \frac{\alpha q \Delta t}{k} = \left(1 + \frac{\alpha \Delta t}{2r_i \Delta r^2} (2r_j + r_{j+1} + r_{j-1}) + \frac{2 \alpha \Delta t}{\Delta z^2} \right) T_{i,j,k} + \frac{\alpha \Delta t}{2r_i \Delta r^2} (r_j + r_{j+1}) T_{i,j+1,k} - \frac{\alpha \Delta t}{2r_i \Delta r^2} (r_{j-1}) T_{i,j-1,k} - \frac{\alpha \Delta t}{\Delta z^2} T_{i+1,j,k} - \frac{\alpha \Delta t}{\Delta z^2} T_{i-1,j,k} \] (4)

The schematic relationship between nodes in the analysis area is given in Figure 1.

![Figure 1. Schematic relationship between nodes](image)

Since the conduction equation applies for a homogeneous region so the Equation 4 is applied for each reactor section separately such as the core, reflector, pressure vessel, cavity and concrete as the physical properties are different one part to another. For the border area between region 1 and 2 the boundary condition of heat flux continuity is applied, ie for the direction \( r \)

\[ k_1 \left( \frac{\partial T}{\partial r} \right)_1 = k_2 \left( \frac{\partial T}{\partial r} \right)_2 \] (5)

or for the \( z \) direction

\[ k_1 \left( \frac{\partial T}{\partial z} \right)_1 = k_2 \left( \frac{\partial T}{\partial z} \right)_2 \] (6)

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

\[ k_1 \left( \frac{\partial T}{\partial r} \right)_1 = h(T_s - T_{ud})_2 \] (7)

or for the \( z \) direction

\[ k_1 \left( \frac{\partial T}{\partial z} \right)_1 = h(T_s - T_{ud})_2 \] (8)

As long as the cooling water in the RCCS is still present, the temperature in the cavity cooling wall is calculated separately and its value is entered into the conduction calculation.

In the cavity, the actual heat transfer takes place in radiation that combines with natural convection within the cavity. For radiation, with surface emissivity coefficient \( \epsilon \) and Stefan Boltzmann’s constant \( \sigma \), we can formulate the coefficient of convective equivalent heat transfer from surface 1 to surface 2 by

\[ h_R = \frac{\epsilon \sigma(T_1^3 + T_1^2 T_2 + T_1 T_2^2 + T_2^3)}{1} \] (9)
So if added to the natural convection heat transfer coefficient $h_C$ in the cavity will be obtained the equivalent heat transfer coefficient in the cavity is equal to

$$h_{RC} = h_R + h_C$$

(10)

Considering the equation used in this analysis is the conduction equation, then for cavity, it is given a special treatment that is equivalent to a conduction region even though it actually takes place by convection and radiation. In order to produce a temperature value that is identical to the actual conditions, an approximation of the value of the equivalent thermal conductivity to the corresponding is required, ie

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

(11)

with $L$ is the width of cavity.

The equivalent physical properties of the reactor parts, ie the core, reflectors, vessels, cavity, are arranged in a separate subprogram to be used by the main program. The formulation of equivalent physical properties as a function of temperature for all parts of the reactor is taken from the literature with approaches to the physical properties of the HTR-10 reactor portions.

3. Methodology

RDE geometry is approximated by the geometry model shown in Fig. 2 with the dimensions of each reactor component is given in Fig. 3. The geometry used in this analysis is an approximative geometry based on assumptions only because it is still to be formulated by the design team. The area of analysis includes areas covering from the porous core to the outer surface of the concrete wall, either the side (radial direction) or the top and bottom (vertical direction). With the area of analysis, it can be calculated the distribution of heat to each of these surfaces as well as the temperature at each of the boundary’s surface. Figure 3 shows the dimensions of the analysis area. The area of analysis begins with the overall segmentation of the analysis area. In this segmentation is avoided the existence of segments that include two parts or more with different physical properties. Thus in one segment only applied the physical properties of the part only. Especially for the two segments encountered at the border between sections, the boundary conditions of heat flux continuity are applied as described in Equations (5) and (6). After the segmentation, the number of node in vertical and radial direction are given. Numbering is done sequentially from the core center to the outer boundary of the radial direction, and starting from the lower surface boundary to the upper surface boundary for the vertical direction. Table 2 gives segmentation data and numerical node numbering with 36 nodes, and in Table 3 is given for vertical direction with the number of node is 72. Node 36 in the radial direction is the outer surface of the concrete wall, whereas node no. 72 in the vertical direction is the floor surface in the space above the reactor.

The equivalent physical properties of the reactor parts, ie the core, reflectors, vessels, cavities, are arranged in a separate subprogram to be used by the main program. The formulation of equivalent physical properties as a function of temperature for all parts of the reactor is taken from the literature with an approach to the physical properties of the HTR-10 reactor.
In this study, the analysis begins with an analysis to get to steady conditions near the normal operating conditions of the reactor before the accident. This preliminary analysis was conducted over 200 hours with an estimated steady state condition to be achieved. Furthermore, the analysis on the condition of DLOFC accident in the long term is for 588 hours. With this analysis it is predicted how much heat is removed through RCCS and on all sides of the reactor under normal operating conditions as well as in DLOFC conditions. It is also expected to know how far the temperature of the reactor and other reactor parts increases when there is a loss of active heat removal ability.

4. Results and Discussion
An important result for the development of safety analysis of high temperature reactors is the acquisition of a Matlab-based analysis program that can be used for accident analysis of Depressurized Loss Of Forced Cooling (DLOFC) [12,13] of a high temperature reactor through configuration adjustments and physical properties data. With the reactor model given, Figure 4 shows the maximum temperature transient (on the reactor core) starting from the initial condition of the overall temperature.
equal to the outside air temperature of 30 °C. Steady conditions were achieved within 200 hours and then continued with the DLOFC condition for 588 hours.

**Figure 3.** Transient of maximum core temperature

**Figure 4.** Change of vessel and concrete wall temperature

From Figure 3 it is shown that the steady condition of the core temperature is in accordance with the normal operating temperature conditions. The condition is achieved by providing 25 kW of reactor power which means the estimation of power that is lost radially when the reactor is in nominal operation is 25 kW. After an DLOFC followed by shutting down the helium circulator, the reactor will remove the residual heat which can no longer be carried by the helium flow to the secondary side. The temperature of the core rises rapidly, and along with the radial heat removal through the Reactor Cavity Cooling System (RCCS) [5] also takes place, the heat resource is a decay heat that is getting smaller in value. As a result the rate of temperature rise also decreases, the temperature will reach a certain peak value before then drops slowly along with the decline of decay heat. In this analysis the peak temperature values were obtained at 1080°C within 11.1 hours after the reactor shutting down or after the DLOFC occurred. This temperature value is still below the safety limit of 1600°C in the design [14]. The inherent safety behavior is also present in this reactor, ie, by increasing significantly the equivalent thermal conductivity of the core with rising temperature. The higher the core temperature, the higher the thermal conductivity, the easier it is to remove the heat out. This property primarily prevents the continued rise in temperature of the core in addition to the declining factor of decay heat. In addition to the maximum core temperature, safety criteria also require that temperature rises in other components of the reactor should also be maintained not to exceed its specified safety limits. The temperature change of reactor vessel, internal concrete wall, and external concrete wall are shown in Figure 4.

From Figure 4 it can be seen that the maximum temperature reached by the vessel is only 233 °C, the maximum temperature of internal concrete wall is only 97 °C, while the external concrete wall is only 35 °C. The maximum temperature of this cavity cooler is still below the boiling temperature of 100°C water which means no boiling occurs which causes a decrease in the amount of cooling water. If the reference to the HTR-PM temperature limit[12], for the vessel is limited to 400°C, the concrete is limited to 100°C, then the result of the analysis is still far below the limit so the reactor can be said to be safe. Temperatures in the external concrete wall are also still safe because it only reaches 35°C. This low temperature value is supported by the use of two-dimensional analysis method which takes into account heat dissipation through the upper and lower concrete walls beside the concrete wall in the side direction. In addition, the thickness of the wall that is not too thick (only 1 m) also helps the heat dissipation.
Figure 5 shows the radial temperature profile at some elevation positions at the peak temperature condition (at t=11 hours of DLOFC), in addition to the center of the core also shown the radial profile at the end of the simulation, ie at 588 hours of DLOFC.

From the profile it is seen that the temperature gradient on the core is very dominant compared to other reactor parts. This is because the equivalent thermal conductivity of the reactor core is very low compared to the reflector or other reactor components. At the time of peak core temperature (ie 11.1 hours after the reactor shutting down), the concrete temperature is still low. In contrast to 588 hours, the temperature of the concrete has increased, inversely the core temperature has decreased. Figure 6 shows the vertical profile of temperatures in three radial positions, ie at the center line of the core, at r = 0.5 m and on the edge of the reactor core at peak temperature. The results show that at the top of the core, the temperature is relatively low, while at the bottom is still quite high. This is due to the existence of used fuel with a high enough decay heat at the bottom of the core.

Figure 7. Transient distribution of decay power to the entire boundary surface of the analysis area and to the cooling water panel

Figure 8. Contour temperature at the time of maximum core temperature conditions
Figure 7 shows the change of heat evacuation distribution through the three boundary surfaces and through the cooling water panel. It appears that the largest portion of the decay is evacuated through the surface of the side concrete, followed by evacuated bottom and upper concrete surfaces, while those absorbed by the cooling water panel are relatively high in the beginning of the accident and decreasing until zero at the time when the evacuation of the decay heat through the three boundary surfaces is sufficient.

Figure 8 illustrates the temperature contours when the core temperature is maximum, ie, 11.1 hours after the shutdown of reactor. From the description it is seen that the less tight isothermal lines, the smaller the heat evacuation. This is evident in the upper regions of the core because the heat evacuation through the upper direction heat is relatively small.

5. Conclusion
From this research it has been obtained a transient program of two-dimensional safety analysis using Matlab07 in DLOFC condition. The results of the program implementation for transient analysis both to steady-state for 200 hours or after DLOFC has been done up to 588 hours DLOFC time. The results show that the reactor temperature rises from its normal condition of 800°C to reach a maximum of 1080°C at 11.1 hours after the reactor trip which means still far below the safety limit of 1600°C. The maximum temperature of the reactor vessel and the concrete wall during the DLOFC is still below the safety limit of 500°C and 100°C respectively.

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