Cooling Performance Analysis of The Primary Cooling System Reactor TRIGA-2000 Bandung

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Abstract. The conversion of reactor fuel type will affect the heat transfer process resulting from the reactor core to the cooling system. This conversion resulted in changes to the cooling system performance and parameters of operation and design of key components of the reactor coolant system, especially the primary cooling system. The calculation of the operating parameters of the primary cooling system of the reactor TRIGA 2000 Bandung is done using ChemCad Package 6.1.4. The calculation of the operating parameters of the cooling system is based on mass and energy balance in each coolant flow path and unit components. Output calculation is the temperature, pressure and flow rate of the coolant used in the cooling process. The results of a simulation of the performance of the primary cooling system indicate that if the primary cooling system operates with a single pump or coolant mass flow rate of 60 kg/s, it will obtain the reactor inlet and outlet temperature respectively 32.2 °C and 40.2 °C. But if it operates with two pumps with a capacity of 75% or coolant mass flow rate of 90 kg/s, the obtained reactor inlet, and outlet temperature respectively 32.9 °C and 38.2 °C. Both models are qualified as a primary coolant for the primary coolant temperature is still below the permitted limit is 49.0 °C.

Keywords: Cooling System, the primary pump, mass flow rate, temperature.

1. Introduction
The Bandung TRIGA Mark II reactor is one of the research reactors in Indonesia that is used for research activities related to nuclear technology as well as for the production of isotopes. As a research reactor, this reactor is used as a neutron source to irradiate material, while the heat energy from the reactor is discharged through the cooling system. This reactor is a swimming pool type reactor in which the reactor core is placed at the bottom of the pool with a natural convection cooling system. As a common TRIGA reactor, the reactor fuel type is rod type fuel. This reactor has been upgraded to be able to achieve the thermal power 2000 kW [1], then is called reactor TRIGA-2000 Bandung. To support this upgrade process, some studies to accomplish this upgrading have been done. The reactor coolant system including the modification of the heat exchanger, the core or the neutronic design [2] and the reactor core support structures need to be redesigned to be able to cool the reactor core which the thermal power is 2000 kW. The new design of support system also consists of new reactor core assembly i.e. top and bottom grid plates, which fit within the existing reflector assembly.
The next upgrading is to convert the reactor fuel type from the rod-type into the plate-type. Replacement the rod-type fuel assembly into the plate-type fuel assembly is an innovation to find the solutions for the stop production of the rod-type fuel assembly of TRIGA reactor in the world. The use of plate-type fuel assembly in the reactor TRIGA-2000 Bandung demanding changes the cooling system from natural circulation mode into forced circulation mode. Sudjatmi[3] reported that to operate the reactor TRIGA-2000 Bandung using plate-type fuel assembly with the thermal power more than 600 kW, the temperature at the fuel cladding temperature is 108.88 °C and at the reactor outlet coolant temperature is 82.39 °C. Therefore, to operate the reactor TRIGA-2000 Bandung using plate-type fuel assembly, the primary cooling system has to be set into forced circulation mode. To support this fuel type conversion, the entire support system design of the reactor is needed to be redesigned. The fixing bar at the top of the standing fuel assembly has to be constructed to avoid the impact cases to the fuel assembly such as an impact from a dropping fuel assembly[4].

In reactor TRIGA-2000 Bandung, the reactor coolant system consists of two loops of the cooling system, i.e. primary cooling system and secondary cooling system. According to the modification of the cooling system, the flexibility of cooling pipe has to be considered [5]. The primary cooling system serves to take heat from the reactor to be moved to the secondary coolant and then discharged into the environment. The main components of the primary cooling system which be forced circulation mode are a delay tank which is mounted directly on the outlet of the reactor, primary pump and a heat exchanger which connected the primary cooling system and the secondary cooling system[6,7]. The function of delay tank is to lower the content of N-16 in the cooling water by extending the cooling trajectory before going to the other components. This is important because the N-16 are radioactive. N16 is radioactive which be produced from the interaction of the fission neutron with the oxygen atom which presents in the water around the reactor core [8].

This work is conducted in the design of the primary cooling system in the reactor TRIGA-2000 Bandung that has been upgraded to the thermal power 2000 MW and has to convert the reactor fuel type from the rod-type into the plate-type. The modification to improving the core cooling system of reactor TRIGA-2000 Bandung has to be studied by numerical simulation. Analysis of the cooling performance of the primary cooling system reactor TRIGA-2000 Bandung has been done by using computer code ChemCad. The ChemCad software has been widely used in the modeling and simulation of the cooling system [9,10] and in energy conversion system simulation [11]. The purpose of this study was to determine the minimum mass flow rate of the primary cooling system that is able to cool the reactor core of reactor TRIGA-2000 Bandung which uses plate-type fuel.

2. Current Reactor Description
The reactor TRIGA-2000 Bandung has had a license from the regulatory body for steady state operation at the nominal power 2000 kW[12]. The main function of this reactor is for isotope production such as Mo-99, I-131, and P-32. This reactor is a swimming pool type surrounded by a concrete shield. The configuration of the reactor is a hexagonal grid plate surrounded by a graphite reflector. The vertical cross section of the reactor TRIGA-2000 Bandung is shown in Figure 1[13].

The reactor coolant system of reactor TRIGA-2000 Bandung consists of two coolant system loops, i.e. primary coolant system, and secondary coolant system. The primary coolant system was designed to take a bulk water out from the reactor tank, circulate it through a heat exchanger and return it to the reactor tank. The function of the heat exchanger is to transfer heat from the reactor tank to the secondary coolant system. The schematic diagram of the primary coolant system is shown in Figure 2 [14].

The maximum temperature allowed for the primary cooling fluid is 49 °C, this temperature is the maximum temperature limit for resins used in water purification systems unit. The temperature difference between the water outlet of reactor tank and the water inlet reactor tank at normal operation in the power 2000 kW is 10 °C. The outlet coolant water temperature from the heat exchanger is 32.2 °C, and the inlet coolant temperature to the heat exchanger is 42.2 °C [14].
3. Theory

3.1. Pressure drop calculation.

The pressure loss due to friction with wall and the turbulence in the channel of uniform cross section is normally calculated as follows [15]:

$$\Delta P = f \frac{L}{D} \left( \frac{\rho u_{\text{mean}}^2}{2} \right)$$  

(1)
where $\Delta P$ is the pressure drop (Pa) between two points in a pipe of diameter $D$ (m) that are separated by an axial distance $L$ (m). $u_{mean}$ stands for the mean flow speed (m/s), and $\rho$ is the fluid density (kg/m$^3$), and $f$ is the friction factor. The frictional pressure drop coefficient could be taken to be proportional to the length of the flow channel and inversely proportional to the channel diameter. So in practice, the pressure drop is [15]:

$$\Delta P = \sum_{i} f_i \frac{L_i}{D_e} \left( \frac{\rho u_{mean}^2}{2} \right)$$

(2)

where $f_i$ is dimensionless friction factor, $L_i$ is channel length, and $D_e$ is the equivalent diameter of the channel.

### 3.2. N-16 Production.

During reactor in operation, the exposure of neutron radiation and gamma ray radiation around the reactor are in the very high level. Gamma-ray radiation emanating from the N-16 gave a significant radiation exposure around the reactor. N-16 is radioactive derived from the interaction between oxygen in water with a neutron, according to the following reaction:

$$\frac{1}{2}H + \frac{16}{8}O \rightarrow \frac{1}{2}p + \frac{16}{7}N$$

(3)

$$\frac{16}{7}N \rightarrow \frac{16}{8}O + \frac{0}{-1}\beta + \gamma \quad (6.13 \text{ MeV})$$

(4)

$\frac{16}{7}N$ produce and radiate gamma rays (6.13 MeV) and $\beta$ particles during its decay chain. Nitrogen-16 ($\frac{16}{7}N$) is an isotope in the primary coolant system of TRIGA reactor which has a very short half-life time $(T_{1/2} = 7.2 \text{ s})$[8].

### 4. Methodology

The purpose of this study was to determine the minimum mass flow rate of the primary cooling system that is able to cool the reactor core of reactor TRIGA-2000 Bandung as a result of the modification of the type of fuel rod into a plate type and assesses the opportunities for modification. The redesign of the reactor coolant system of reactor TRIGA-2000 Bandung shall refer to the condition of the cooling system that is currently installed. The change of the convection mode in the cooling process such as natural convection mode into forced convection mode is necessary to add a component such as a delay tank.

The cooling performance analysis of the primary cooling system for reactor TRIGA-2000 Bandung is done by simulation calculations using the program package ChemCad 6.1.4. The step calculation can be shown below:

- First, prepare the model of the primary cooling system for reactor TRIGA-2000 Bandung.
- Then provide primary cooling system data input for reactor TRIGA-2000 Bandung model which includes the geometry of the primary cooling system.
- Then give the thermal-hydraulic input parameters to the primary cooling system including mass flow rate, temperature, and pressure.
- After all, inputs are completed, set the boundary conditions in the reactor cooling system reactor TRIGA-2000 Bandung such as ambient temperature.
- Once ready, program execution to calculate the thermal-hydraulic parameters of the primary cooling system.
- Finally, the analysis of the output calculations.

### 5. Results and Discussion

The cooling performance analysis of the primary cooling system is intended to measure the performance of the reactor coolant system for reactor TRIGA-2000 Bandung, especially the performance due to the fuel element conversion. There are some modifications or additions to the main component in the reactor coolant system of reactor TRIGA-2000 Bandung. One of the main
components of the primary cooling system in reactor TRIGA-2000 Bandung is a delay tank. As shown in Equation (3), in the primary coolant will be formed N-16 as a result of the reaction of oxygen with neutrons. N-16 is a radioactive compound that emits gamma rays. Delay tank is used to remove or lower the radiation exposure of radiation N-16 prior to entry into the primary pump. Working principle of the delay tank is to extend the travel time so that the activity of N-16 radioactive decays. In her research report, Wardani[16] managed to model a delay tank using a curved pipe with length 118.0760 m. The results showed that the optimum time required to decrease the activity of N-16 to 3% was 5 times the half-life of N-16 or 36.7047 seconds.

The thermal energy generated from the reactor core were taken through the primary cooling system and transferred through a heat exchanger to the secondary cooling system for further discharged into the environment. As a consequence of the conversion of fuel elements, the cooling system needs to be changed from natural convection mode into a forced convection mode. In addition, the performance of the cooling system must be improved. The cooling system performance can be improved, among others, modification of the heat exchanger as an intermediary heat transfer between the primary cooling system and a secondary cooling system [17, 18]. Nazar [19] reported the results of his research that the addition of the chimney and the plate in the heat exchanger capable of lowering the temperature of the reactor primary coolant reactor TRIGA-2000 Bandung. In addition to modifications with the addition of plate heat exchangers, the cooling performance of the primary cooling systems can also be improved by adjusting the mass flow rate of the primary coolant [17].

Analysis of the performance of the cooling system of reactor TRIGA-2000 Bandung is carried out by means of simulations using a computer code ChemCad. Two models of the primary cooling system are configured while considering the cooling system configuration conditions attached. The first model is the model of the primary cooling system with one main pump, while the spare pump is not operating as shown in Figure 3. In the second model, the two primary pumps are operated in parallel as shown in Figure 5. To measure the performance of the primary cooling system in the reactor TRIGA-2000 Bandung, thermal power of the reactor was set at 2000 kW. With the thermal power of the reactor constant, the primary coolant mass flow rate varied from 40 kg/s up to 100 kg/s. The capacity of the existing primary pump is 950 gpm[19].

**Figure 3.** The simulation model of the reactor cooling system of reactor TRIGA 2000 Bandung with one primary pump using ChemCad.

The simulation results for first primary cooling system model which using one primary pump with a capacity of 950 gpm or 59.9 kg/s as shown by the graph in Figure 4. The first model of the cooling system is the model as on the condition of the installed systems now is the one that operates the primary pump. Data input to the maximum pump capacity is 950 gpm or 59.9 kg/s, set at 10 MW power reactor and coolant mass flow rate varied from 40.0 kg/s up to 60.0 kg/s with a range of 5.0 kg/s.
Figure 4 shows the simulation results of the primary cooling system on the first model that shows the graph of inlet and outlet temperature of the reactor as a function of the mass flow rate of the primary coolant. In Figure 4 it appears that at maximum pump capacity with the primary coolant mass flow rate of 59.9 kg/s, an inlet and outlet temperature of the reactor was 32.2 °C and 40.2 °C. For comparison in a study reported by Daeseong Jo [20] on a Canadian McMaster Nuclear Reactor (MNR) reactor, at 2 MW of power with a cooling mass flow rate of 75 kg/s, the inlet, and reactor temperature are 30.0 °C and 36.4 °C. This temperature is lower than the maximum allowable temperature in the primary cooling system. In the safety analysis report of reactor TRIGA 2000 Bandung, the maximum allowable temperature in the primary cooling system is 49.0 °C. Determination of the maximum temperature is based on the maximum temperature limit for resins used in water purification systems unit. If the cooling fluid temperature is greater than 49.0 °C will result in the resin is not effective for use, meaning the reactor has to be stopped. With this result, conceptually it can be said that the primary cooling system with one primary pump installed is still possible to cool the TRIGA reactors with thermal power 2000 kW.

![Figure 4. Inlet and outlet temperature of the reactor as a function of the coolant mass flow rate](image)

Model of the second primary cooling system is a model with two primary pumps are installed in parallel and operated jointly. Thus the coolant mass flow rate of the primary coolant can reach 100 kg/s. For the purposes of the simulation, the model primary cooling system with two primary pumps mounted parallel is shown in Figure 5. Characteristics of all the major components on the second models are same as the characteristics of all the major components in the first model. In the second model, both the primary pump operates with the same capacity is 45 kg/s or 75% of the maximum capacity. Simulations are carried out by setting the reactor operates at a maximum power of 10 MW thermal. The primary coolant mass flow rate is varied from 40 kg/s up to 100 kg/s with a range of 5 kg/s. Keep in mind that to obtain the mass flow rate of the primary coolant of more than 60 kg/s, in the primary system has to be done by operating two primary pumps of 59.9 kg/s. From the simulation results as shown in Figure 6 the inlet and an outlet temperature of the reactor are respectively 32.9 °C and 38.2 °C.
Figure 5. The simulation model of the reactor cooling system of reactor TRIGA 2000 Bandung with two primary pumps using ChemCad.

On the condition of the system that is mounted as shown in Figure 4, with one pump and one spare pump operates, conceptually it is still possible to cool the TRIGA reactor with a thermal power of 2 MW. The maximum pumping capacity of the pump is 950 gpm or 59.9 kg/s of water. The simulation results, as shown in Figure 5 and Figure 6, the maximum pump capacity (59.9 kg/s) inlet and an outlet temperature of each reactor are 32.2 °C and 40.2 °C.

Figure 6. Inlet and outlet temperature of the reactor as a function of the coolant mass flow rate

From the simulation results obtained reactor inlet and outlet temperature respectively 32.9 °C and 38.2 °C. Keep in mind that to obtain a coolant mass flow rate of 90 kg/s it is necessary to pump replacement due to the capacity of existing pumps a maximum of 59.9 kg/s. As an alternative to simulation is done both by operating both pumps as shown in Figure 6. The simulation results obtained reactor inlet and outlet temperature respectively of 32.4 °C and 37.7 °C for a refrigerant mass flow rate of 90 kg/s.
6. Conclusions
The simulation of the primary cooling system of TRIGA 2000 reactor Bandung has been done. There are two primary pumps that exist in the primary cooling system TRIGA 2000 Bandung, each with a capacity of 60 kg/s. In case two primary pumps are operated simultaneously at 75% capacity or a mass flow rate of 90 kg/s, the inlet and outlet temperatures of 32.9 °C and 38.2 °C are obtained. Conversely, if it operates only one primary pump with the primary coolant mass flow rate of 60 kg/s, it obtains the inlet and outlet temperatures of 32.2 °C and 40.2 °C respectively. The reactor temperature which is still lower than the maximum permitted is 49.0 °C. Basically by operating one primary pump which the primary coolant mass flow rate of 60 kg/s is enough to cool the reactor TRIGA 2000 Bandung with 2000 kW thermal power.

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