Steady-state Thermal-hydraulic Analysis of the TRIGA 2000 Reactor Core when Using Configuration of 105 Fuels

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Abstract. The continuity of the TRIGA 2000 reactor operation is determined by the fuel temperature and the primary cooling water temperature. Currently operating the TRIGA 2000 reactor using 105 fuel configurations it is difficult to reach 1000 kW of power, because the fuel temperature and primary coolant temperature in the core are high. It causes boiling and bubble formation in the reactor core, thus reducing neutron moderation in the core. The results of neutronic calculations on the configuration of 105 fuels in the core at this time, it is known that heat generation is focused into the center of the core, and some fuels have large power fluxes, so that some of these fuels produce high cladding surface temperatures as well and cause boiling. In this research, thermal hydraulic analysis has been carried out using the CFD program package for the configuration of 105 fuels in the core. Based on the results of research on the reactor operated at 500 kW power, the hottest channel is at B5 fuel with the power it generates of 9.43 kW, the maximum surface temperature of the fuel cladding is 126.41 °C, and the temperature of coolant wets 119.92 °C. This temperature has exceeded the saturation temperature of the reactor cooling water 112.4 °C, so that sub-cooled boiling is possible. This situation is in accordance with the conditions that occur in the operation of the TRIGA 2000 reactor, where at 500 kW power has begun to observe bubbles coming out of the reactor core. One effort that can be done to reduce the temperature of the TRIGA 2000 reactor core is to do reshuffling and increase the amount of fuel used.

1. Introduction
The continuity of operation of a nuclear reactor is determined by the temperature of the fuel and primary cooling water. If the temperature of the fuel and primary coolant in the core are high, boiling and steam bubbles will occur, thereby reducing neutron moderation in the core, and the reactor is unable to reach a certain power.

The temperature of the fuel on the reactor core is high, partly because of the use of limited amount of fuel, the burn-up of the fuel is high (close to 50%), and the fuel configuration is not optimum. The fuel configuration in the core is determined by the amount of fuel used, burn-up of the fuel, and the age of the fuel. For example, when the TRIGA 2000 reactor is operated up to 2000 kW, it is known that the temperature at the fuel center is 568 °C and the primary coolant temperature coming out of the tank is 36 °C, bubbles have formed as a sign of boiling inside the reactor core. This
is consistent with the analysis of General Atomic (GA) and the results of other studies have predicted a boil (subcooled boiling) when the TRIGA 2000 reactor is operated at 2000 kW power [1-9].

When operating the TRIGA 2000 reactor at 500 kW, bubbles have begun to form as a sign of boiling inside the core. Therefore it is necessary to evaluate the amount of fuel used, fuel burn-up and fuel configuration in the core to determine the cause of the boiling.

The purpose of this study is to conduct a thermal hydraulic analysis using a CFD computer program on the TRIGA 2000 reactor which operates at 500 kW with 105 fuel configurations in the core to determine the core temperature that causes boiling.

2. Theory

2.1. Heat transfer in the TRIGA 2000 reactor core

Fuel configuration in the core depends on the amount of fuel used, fuel life, fuel burn-up. The TRIGA 2000 reactor core has 121 grids to arrange fuel inside the core. At present the TRIGA 2000 reactor core uses a configuration with 105 power plants, consisting of 97 fuels, 3 fuel follower control rods-FFCR, 5 instrumented fuel elements-IFE. In addition there is 1 neutron source-NS, 2 control rods without fuel-CRWF, 4 irradiation facilities-IF, 4 graphite bars, and 5 holes emptied, as shown in Figure 1.

The relationship between the power generated at each fuel to the fuel surface temperature, the temperature of the cooling water in the fuel gap, and the temperature of the cooling water that soaks the fuel surface is expressed in the form of a mathematical equation (1-4) [10].

The heat unit volume \(q^{ui}\) generated by the TRIGA 2000 reactor fuel is expressed in the following equation 1.

\[
q^{ui} = GN\sigma_f \Phi \quad \text{watt/cm}^3
\]  

(1)

Where \(G\) is the energy of each fission reaction (190 MeV = 3.04 x 10^{-11} joule), \(N\) is fuel atom density (atom/cm\(^3\)), \(\sigma_f\) is microscopic cross section of the fuel (cm\(^2\) ), and \(\phi\) is neutron flux (neutron/cm\(^2\) dtk).
The heat that comes out through the surface of the fuel rod \( (q_s) \) with the length of the fuel \( (L) \) and the radius of the fuel \( (R) \) is:

\[
q_s = \left( \pi R^2 L \right) q \quad \ldots \ldots (2)
\]

Fuel surface temperature \( (T_s) \) is

\[
T_s = T_w - \frac{q_s}{4\pi k_f L} \quad \ldots (3)
\]

where, \( k_f \) = heat conductivity of uranium, and \( T_m \) = temperature at the center of the fuel.

The temperature of the cooling water \( (T_f) \) that soaks the surface of the fuel cladding is expressed by the following equation

\[
T_f = T_m - \left( \frac{q_s R^2}{4 k_f} + \left( \frac{q_s R^2}{2} \right) \left[ \frac{1}{k_c} \ln \left( \frac{R + c}{R} \right) + \left( \frac{1}{h(R + c)} \right) \right] \right) \quad \ldots \ldots (4)
\]

where, \( h \) = coefficient of convection heat transfer, \( k_c \) = heat cladding conductivity, and \( c \) = cladding thickness. By using equations (1-4) can be calculated fuel surface temperature, the temperature of the cooling water that soaks the surface of the fuel cladding, and the temperature of cooling water in the fuel gap.

2.2. Description of CFD

This study uses a computational of fluid dynamic (CFD) computer program package [11-12] by making a 3-dimensional model of the TRIGA 2000 reactor reviewed. The type of CFD computer program package used in this study is FLUENT software, where the FLUENT program works through solving flow distribution equations, turbulent equations, and energy equations. Turbulent equations use equation of the k-epsilon viscosity, the k-omega viscosity, Reynolds Stress, or Large Eddy Simulation (LES). The FLUENT program solves flow distribution equations, turbulent equations, and energy equations using the finite volume method, where the model under consideration is divided into many discrete volumes. Differential equations are integrated into these discrete volumes into general equations of mass conservation, momentum equations, and energy equations. The conservation equation depends on fluid density, coolant flow area, stress tensor, and volume. The mass conservation equation is solved using a continuity equation and a momentum equation that refers to the Navier-Stokes equation. The analytical solution of the Navier-Stokes equation only applies to simple flows, such as flow conditions in sub-channels are ideal conditions. The energy conservation equation calculates energy based on the laws of thermodynamics.

Because the FLUENT program does the calculation by referring to the equation of continuity, momentum, and energy balance in a discrete volume that follows the fuel geometry, then the size and amount of the control volume will determine the accuracy of the calculation results. Calculation of energy and flow balance is done numerically based on predetermined boundary conditions.

The results of calculations performed by the FLUENT program, including the distribution of the fuel surface temperature, the temperature of the cooling water will be obtained in detail, so the accuracy of the calculation is largely determined by the modelling process.

3. Procedures

1. Modeling the TRIGA 2000 reactor system with the configuration of 105 fuels in the core as shown in Figure 1 using the Gambit computer program
2. Recalculate the power of each fuel for the 500 kW total power of the 2000 TRIGA reactor
3. Using the Fluent program to enter input data on the TRIGA 2000 reactor model as a result of the Gambit program, in the form of the power of each fuel, the temperature of the primary coolant water entering the core 30°C, the flow rate of the primary coolant water entering the core 775 GPM, the pressure on the primary pipe entering the reactor tank, and the physical properties of primary cooling water.
4. Perform the calculation execution process on the Fluent program
5. Analyzing output data from the calculation of the Fluent program
4. Results and Discussion

Figure 2 shows the current the TRIGA 2000 reactor system, the grid of reactor geometry, and grid of reactor core cross section formed by Gambit computer program.

![Figure 2](attachment:image.png)

**Figure 2.** (a) The current TRIGA 2000 reactor system, (b) grid of reactor geometri, and (c) grid of reactor core cross section of Gambit computer program

Table 1 is the result of data recalculating the power of each fuel for the 500 kW total power of the TRIGA 2000 reactor. Using the data in Table 1 were be calculated fuel surface temperature, the temperature of the cooling water that soaks the surface of the fuel cladding, and the temperature of cooling water in the fuel gap using Fluent computer program.

The surface temperature of the fuel cladding, the temperature of the cooling water that soaks the fuel surface, and the bulk temperature of the cooling water at each fuel gap are calculated using the FLUENT computer program. The input data used is the power of each fuel that has been previously calculated and shown in Table 1, the primary cooling water flow rate is 775 GPM, and the temperature of the primary coolant water entering the core is 30 °C.
Table 1. Power of each fuel at the reactor power of 500 kW

| Grid | Power (kW) | Grid | Power (kW) | Grid | Power (kW) | Grid | Power (kW) | Grid | Power (kW) | Grid | Power (kW) | Grid | Power (kW) | Grid | Power (kW) |
|------|------------|------|------------|------|------------|------|------------|------|------------|------|------------|------|------------|------|------------|
| A    |            | B    |            | C    |            | D    |            | E    |            | F    |            | G    |            |
| 0    | B1         | 7.90 | C1         | 6.64 | D1         | IFE  | 7.17       | E1   | 5.18       | F1   | 3.16       | G1   |            |
| B2   | 7.69       | C2   | 7.22       |      |            | D2   |            | E2   | 5.72       | F2   | 3.86       | G2   | 0          |
| B3   | 9.34       | C3   | 6.58       |      |            | D3   | 5.89       | E3   | 6.07       | F3   | 4.07       | G3   | 2.75       |
| B4   | 9.31       | C4   | 6.63       |      |            | D4   | 8.52       | E4   | 5.53       | F4   | 3.12       | G4   | 2.46       |
| B5   | 9.43       | C5   | 5.84       |      |            | D5   |            | E5   | 4.92       | F5   | 3.04       | G5   | 2.76       |
| B6   | 9.30       | C6   | 6.48       |      |            | D6   | IFE        | E6   | 4.96       | F6   | 2.81       | G6   | 0          |
| C7   | 6.41       | D7   | 7.71       |      |            | E7   | 4.36       | F7   | 2.82       | G7   |            |
| C8   | 6.63       | D8   | 8.88       |      |            | E8   |            | F8   | 2.92       | G8   |            |
| C9   | 6.56       | D9   |            |      |            | E9   | 4.72       | F9   | 6.13       | G9   | 2.80       |
| C10  | 6.92       | D10  | 8.35       |      |            | E10  | 4.12       | F10  | 3.34       | G10  | IF         | 0    |            |
| C11  | 6.80       | D11  | 6.76       |      |            | E11  | 4.45       | F11  | 2.96       | G11  | 2.47       |
| C12  | 6.92       | D12  | 9.38       |      |            | E12  | 4.22       | F12  | 3.50       | G12  | 2.34       |
| D13  | FFCR       |      |            |      |            | E13  | 3.57       | F13  | 2.99       | G13  |            |
| D14  | 7.44       | E14  | IFE        |      |            | E15  |            | F14  | 3.51       | G14  | 2.50       |
| D15  | 7.47       | GRPH |            |      |            | E15  |            | F15  | 3.42       | G15  | 0          |
| D16  | 4.16       | E16  | 4.33       |      |            | F16  |            | F16  | 2.95       | G16  | 2.67       |
| D17  | FFCR       |      |            |      |            | E17  | 4.03       | F17  | 3.13       | G17  | IF         | 0    |            |
| D18  | 7.54       | E18  |            |      |            | E18  | 5.40       | F18  | 3.58       | G18  | 0          |
| E19  | 4.51       | F19  |            |      |            | E19  | 3.65       | F19  |            | G19  |            |
| E20  | 4.34       | F20  | 3.43       |      |            | E20  | 3.43       | F20  | 2.06       | G20  |            |
| E21  | 3.76       | F21  | 2.42       |      |            | E21  | 2.42       | F21  | 2.25       | G21  | 2.25       |
| E22  | 4.31       | F22  | 3.43       |      |            | E22  | 3.43       | F22  | 2.38       | G22  | 2.38       |
| E23  | 0          | F23  | 3.60       |      |            | E23  | 3.60       | F23  | 2.30       | G23  | 2.30       |
| E24  | 4.30       | F24  | 2.61       |      |            | E24  | 2.61       | F24  | 2.28       | G24  | 2.28       |
| E25  | 3.41       | F25  | 2.41       |      |            | E25  | 2.41       | F25  |            | G25  |            |
| E26  | 3.07       | F26  |            |      |            | E26  | 3.07       | F26  | 2.36       | G26  | 2.36       |
| E27  | 3.13       | F27  |            |      |            | E27  | 3.13       | F27  | 2.53       | G27  | 2.53       |
| E28  | 3.53       | F28  |            |      |            | E28  | 3.53       | F28  | 2.53       | G28  | 2.53       |
| E29  | 3.47       | F29  |            |      |            | E29  | 3.47       | F29  | 2.54       | G29  | 2.54       |
| E30  | 3.31       | F30  |            |      |            | E30  | 3.31       | F30  | 2.54       | G30  | 2.54       |
| G31  |            |      |            |      |            | G31  |            |      |            |      |            |
| G32  | IF         | 0    |            |      |            | G32  | IF         | 0    |            |      |            |
| G33  | 2.29       |      |            |      |            | G33  | 2.29       |      |            |      |            |
| G34  | 2.18       |      |            |      |            | G34  | 2.18       |      |            |      |            |
| G35  | 4.24       |      |            |      |            | G35  | 4.24       |      |            |      |            |
| G36  | 0          |      |            |      |            | G36  | 0          |      |            |      |            |

Figure 3. The maximum temperature of each ring arrangement of the fuel in the reactor core
Figure 3 displays the maximum temperature of the fuel surface (cladding), the temperature of the cooling water that soaks the fuel surface, the bulk temperature of the cooling water in the fuel gap for each ring of fuel arrangement in the core.

The fuel surface temperature in ring B (grid B5) is 126.41 °C, and ring D (grid D12) is 125.87 °C. The temperature of the cooling water that soaks the surface of the fuel on the B5 grid is 119.92 °C and the D12 grid is 118.95 °C. This temperature value is above the saturation temperature of the cooling water in the core 112.04 °C, so that this fuel can be said to have occurred boiling, at least sub-cooled boiling (sub-cooled boiling) is possible.

Figure 4 displays the maximum fuel surface temperature, the temperature of the cooling water that soaks the fuel surface, the bulk temperature of the cooling water in the fuel gap for the inner ring of the fuel arrangement inside the core.

In ring B (grid B3, grid B4, grid B5, and grid B6) and ring D (grid D8 and grid D12), it is known that the fuel surface temperature and the temperature of the cooling water that wet the fuel surface is above the temperature saturation of cooling water in the core 112.04 °C, so that the grid can be said to have occurred boiling, at least sub-cooled boiling (sub-cooled boiling) is possible.

In ring D (grid D4, grid D6 and grid D10), it is also known that the fuel surface temperature is above the saturation temperature of the cooling water in the core 112.04 °C, so that the grid can also be said to have boiled, at least boiling sub-cooled (sub-cooled boiling) is possible, although the temperature of the cooling water that soaks the surface of the fuel is still below the saturation temperature of the cooling water in the core 112.04 °C.

This situation is in accordance with the conditions that occur when the TRIGA 2000 reactor is operated at 500 kW power has begun to observe bubbles coming out of the reactor core.

5. Conclusion

The results showed that operating the TRIGA 2000 reactor at 500 kW using a configuration with 105 power plants, consisting of 97 fuels, 3 fuel follower control rods-FFCR, 5 instrumented fuel elements-IFE. In addition there is 1 source neutron-NS, 2 control rods without fuel-CRWF, 4 irradiation facilities-IF, 4 graphite bars, and 5 holes emptied, bubbles have begun to form as a sign of boiling. Among the fuel grid B5 (the hottest grid) with a power of 9.43 kW known value of the surface temperature of the fuel is 126.41 °C, and the temperature of the cooling water that soaks the surface of the fuel is 119.92 °C. This temperature value is above the saturation temperature of the cooling water in the core 112.04 °C, so that in this grid it can be said that boiling has occurred, at least sub-cooled boiling (sub-cooled boiling) is possible.
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