Acta Polytechnica **62**(4):438–444, 2022
https://doi.org/10.14311/AP.2022.62.0438

CFD SIMULATION OF PARTIAL CHANNEL BLOCKAGE ON PLATE-TYPE FUEL OF TRIGA-2000 CONVERSION REACTOR CORE

Sukmanto Dibyo[a,*], Wahid Lufthi[a], Surian Pinem[a], Ign Djoko Irianto[a], Veronica Indriati Sriwardhani[b]

[a] *Center for Nuclear Reactor Technology and Safety – BATAN, Puspiptek, Building No. 80, Tangerang Selatan, Indonesia*

[b] *Center for Applied Nuclear Science and Technology – BATAN, Jln.Tamansari, Bandung, Indonesia*

[*] corresponding author: sukdibyo@batan.go.id

Abstract.
A nuclear reactor cooling system that has been operating for a long time can carry some debris into a fuel coolant channel, which can result in a blockage. An in-depth two-dimensional simulation of partial channel blockage can be carried out using FLUENT Code. In this study, a channel blockage simulation is employed to perform a safety analysis for the TRIGA-2000 reactor, which is converted using plate-type fuel. Heat generation on the fuel plate takes place along its axial axis. The modelling of the fuel-plate is in the form of a rectangular sub-channel with an inlet coolant temperature of 308 K with a low coolant velocity of 0.69 m/s. It is assumed that blockage is in a form of a thin plate, with the blockage area being assumed to be 60 %, 70 %, and 80 % at the sub-channel inlet flow. An unblocking condition is also compared with a steady-state calculation that has been done by COOLOD-N2 Code. The results show that a partial blockage has a significant impact on the coolant velocity. When the blockage of 80 % occurs, a maximum coolant temperature locally reaches 413 K. While the saturation temperature is 386 K. From the point of view of the safety aspect, the blockage simulation result for the TRIGA-2000 thermal-hydraulic core design using plate-type fuel shows that a nucleate boiling occurs, which from the safety aspect, could cause damage to the fuel plate.

Keywords: Blockage, FLUENT, plate-type fuel, TRIGA-2000, reactor safety, low coolant velocity.

1. Introduction

TRIGA-2000 is an Indonesian pool-type nuclear research reactor that has been operating for a long time. This reactor uses rod-type fuel produced by General Atomic USA and nowadays, this rod-type fuel is no longer being produced. To maintain the reactor operation, modification of the TRIGA-2000 reactor core using plate-type fuel will be carried out [1–3]. The U_3Si_2Al is used as a fuel material, which is produced domestically, except uranium. This fuel has also been used in the Indonesian RSG-GAS reactor. For this reason, it is presumed that there will not be many changes in core parameters as compared to rod-type fuel. Based on the neutronic calculation, the conversion from rod-type to plate-type shows good results from the safety aspect of a reactor operation. Furthermore, several calculations related to reactor core thermal-hydraulic design have been carried out previously [4–6]. Calculations related to reactor safety analysis, simulations of Loss of Flow Accident (LOFA) and Reactivity Insertion Accident (RIA) have also been carried out [7, 8].

The plate-type fuel element is an arrangement of several fuel plates, which then become a bundle of fuel elements. The fuel plates are arranged in such a way that the gap between each plate can be used as a coolant channel. This plate-type fuel has several advantages over the rod-type fuel, namely its compact structure and high power density [9]. However, the coolant channel between these plates may experience blockage (become clogged) because the coolant channel is quite narrow. Channel blockage causes the heat transfer process to be disrupted so that it has an impact on fuel integrity and reactor safety. Channel blockage conditions can occur due to bending or swelling of fuel plates, caused by other material falling into the reactor pool, or debris carried by the coolant flow [10, 11]. Thus, an analysis of flow channel blockage becomes important for the conversion from rod-type fuel elements to a plate-type fuel assembly. Although the assumed blockage scenario occurs seldomly during the reactor operation.

Simulated blockage scenarios on plate-type fuel by a previous work have been carried out with the IAEA generic 10 MW pool-type benchmark of Material Test Reactor (MTR) [12]. The IAEA Research Reactor is a pool-type MTR, 10 MW. The core is cooled by light water in a forced circulation mode with an average coolant inlet velocity of 3.55 m/s, the operating pressure of 1.7 bar, inlet coolant temperature of 311 K and the core coolant flow direction is downwards [13]. Simulated flow blockage observations using the reactor data have been carried out for one sub-channel with an 80 % blockage ratio and several blockage positions including the inlet, middle, and outlet, in which no boiling occurs in all blockage cases [9].

The main objective of the following study is to perform a safety analysis of a coolant channel partially blocked by debris under steady-state operation, which can cause local heat peaks and ultimately, a loss of fuel integrity. The channel blockage simulation is carried out using FLUENT Code. This analysis is necessary because the thermal-hydraulic design for a fuel-plate type of TRIGA-2000 reactor has a low coolant velocity of 0.69 m/s for cooling the reactor core. The simulation is carried out with the blockage area assumed to be 60 %, 70 %, and 80 % at the inlet of the coolant sub-channel.

The channel blockage analysis using Computational Fluid Dynamics (CFD) simulations has been widely used to investigate fluid dynamics and heat transfer [14, 15]. Meanwhile, one of the main issues in the context of safety assessment of a research reactor plate-type fuel is flow blockages. In a reactor cooling system analysis, the flow phenomena in coolant channels are mostly modelled in Two-Dimensional space (2D), including the possibility of local eddies, which are impossible to observe using one-dimensional simulations. So, CFD modelling is useful to predict the coolant flow temperature and velocity profiles inside a fuel assembly for a blockage state. It can be used to determine the steady-state behaviour on most critical coolant channels. Meanwhile, there are no published experimental data on coolant channel blockage accidents considering heat transfer from the fuel plate to coolant, which is the subject of this simulation.

2. Description of reactor core

TRIGA-2000 is a pool-type research reactor, with a conversion core design consisting of 16 standard fuel elements and 4 control fuel elements as shown in Figure 1.

The reactor core is cooled by light water, forced circulation mode, and downward flow. There are 21 fuel plates in each standard fuel assembly. Coolant sub-channel dimensions of a standard fuel assembly are 67.10 mm in length, 2.557 mm in width, and 625 mm in height. Other parameters related to the fuel elements are given in Table 1. Meanwhile, Table 2 summarizes basic thermal-hydraulic design information of the reactor, in which the reactor power is 1 MW thermal. The power distribution of fuel elements in axial direction was obtained from Batan-Fuel and Batan-3Diff Neutronic Codes that were previously published [3]. A visual representation of the fuel element and its fuel plates arrangements are depicted in Figure 2. Horizontal and cross-section views of the fuel elements are shown in Figure 3. In the fuel element, each plate contains U_3Si_2-Al with 19.7 % enriched uranium. Currently, these fuel elements are used in the RSG-GAS reactor at Serpong, Indonesia.

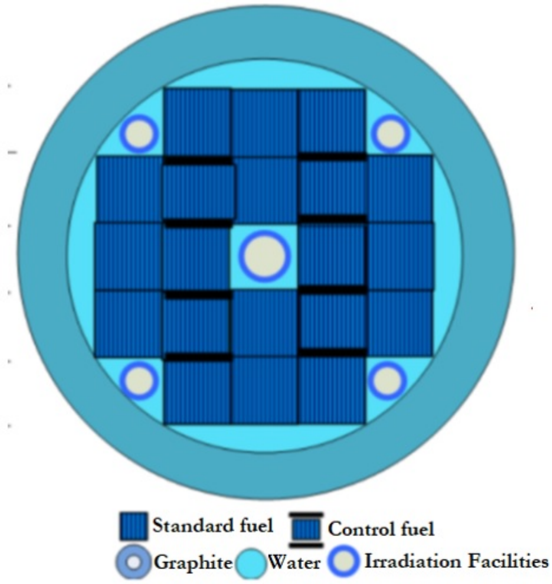

FIGURE 1. Core configuration [2].

Fuel element parameter	Design values
Number plate in standard fuel element	21
Fuel plate active length, mm	600
Type of fuel element	U_3Si_2-Al
Width of cooling channel, mm	67.10
Sub-channel gap, mm	2.557
Thickness of cladding, mm (average)	0.38
Cladding material design	$AlMg_2$
Plate thickness fuel, mm	1.30
Width of fuel plates, mm	70.75
Length of fuel plates, mm	625.00

TABLE 1. Fuel element specification.

Operating Parameters	Value
Fluid material	light water
Coolant mass flow rate to the core, kg/s	50.0
Mass flow rate/fuel element, kg/s	2.10
Average coolant velocity in core, m/s	0.69
Inlet coolant temperature to core, K	308.0
Inlet pressure to core, bar	1.583

TABLE 2. Input data of coolant operating parameters.

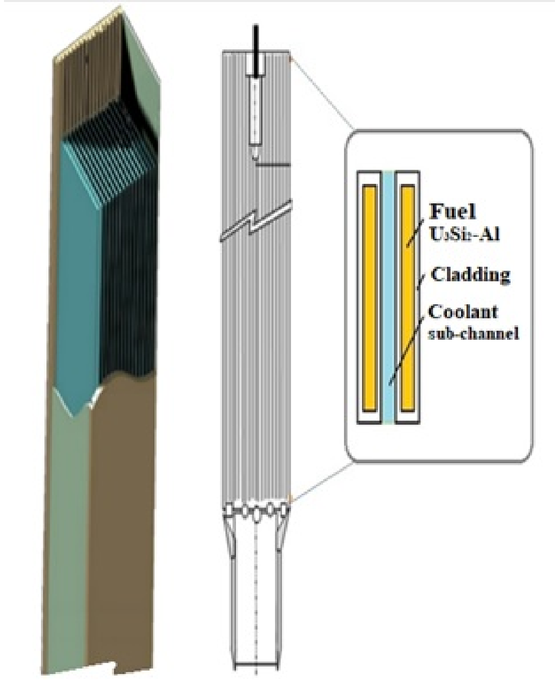

Figure 2. Visual representation of fuel element.

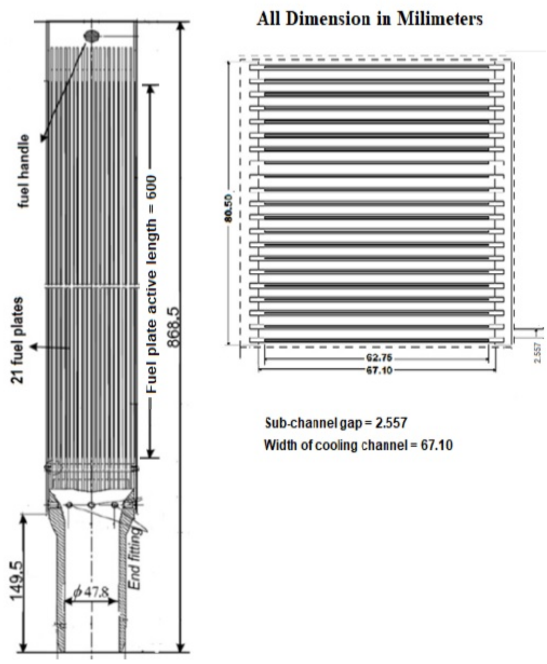

Figure 3. Vertical and horizontal cross-sections of the fuel assembly [16, 17].

3. Methodology

Simplification of the flow blockage case is done by assuming that the flow distribution can affect surrounding channels only by simulating a few sub-channels. This is because parameters from the blocked channel and the adjacent channel will interact and influence each other, especially because the geometry of each fuel plate and coolant channel is similar [9, 10].

Debris can take many forms, either due to material damage or other elements that can be carried away by the coolant flow. Using the CFD method of FLUENT code, any blockage shape can be modelled. In this study, there was no buckling on the fuel plate and the blockage was only caused by the debris. Another assumption is that the blockage only occurs at the inlet channel.

During the blockage scenario, heat generation on the fuel plate takes place along its axial axis with an effective length of 600 mm and a total channel length of 625 mm. The heat transfer received by coolant flow follows equation (1) below:

$$T_{cool}(n+1) = T_{cool}(n) + \frac{Q(n+1)}{m_{cool} \cdot Cp_{cool}} \qquad (1)$$

With $T_{cool}(n)$ being the coolant temperature on n^{th} segment, $Q(n+1)$ being the heat generated by fuel element on $n+1^{th}$ segment, m_{cool} and Cp_{cool} are coolant mass flow rate and specific heat, respectively.

In this simulation, the solution to turbulence flow problem are the assumptions and simplifications that the flow is steady-state, adiabatic, and turbulence *k-epsilon* (k-ε) standard model is set as a boundary condition.

4. Blockage scenarios

In this study, the modelling of the fuel-plate is in the form of a rectangular sub-channel. Due to the presence of blockage, the coolant flow in the blocked sub-channel will be decreased because of the obstruction.

Figure 4 shows a cross-section image of the simulated coolant sub-channel. It is assumed that one of the coolant sub-channels will be blocked by debris. The blockage was simulated as a very thin thickness plate instead of the actual debris. This blockage will cause a reduction in the cross-sectional area of the coolant flow at the inlet of the coolant sub-channel. The sub-channel no. 2 is a sub-channel that will be partially blocked at the top side or inlet stream. In this case, scenarios for the size of the blocked channel area of 60 %, 70 %, and 80 % are determined. These values are based on the study in which it has been investigated by Guo. et al., Salama et al. and Fan et al. [10, 11, 18].

The simulation was performed at a low coolant flow velocity of 0.69 m/s as shown in Table 2. The coolant velocity is an important variable that affects the fuel plate surface temperature. In addition, calculations for sub-channels in normal conditions or 0 % blocked channels were also carried out.

Figure 5 shows schematic steps of activities that include:

(a) data preparation: the design data of TRIGA-2000 conversion using plate-type fuel is used,

(b) steady state calculation without blockage: COOLOD-N2 code is used to validate the steady-state calculation,

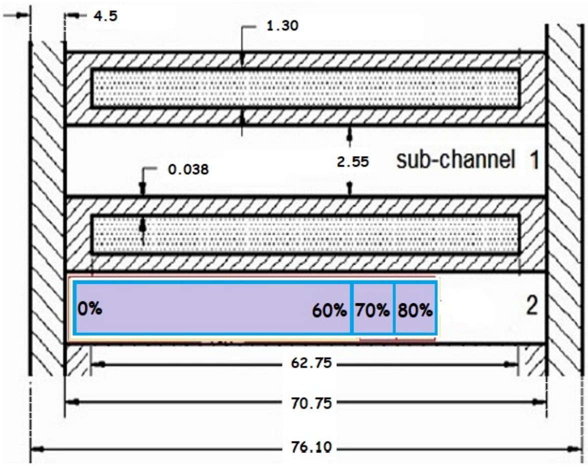

Figure 4. Cross-section view of sub-channel blockage simulation.

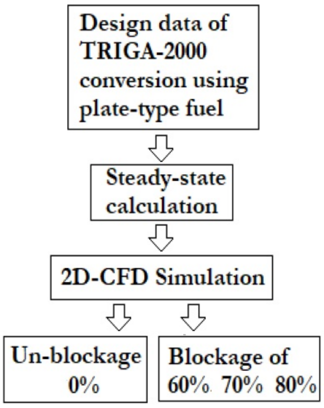

Figure 5. Schematic diagram of simulation.

(c) the partial blockage simulation: 60 %, 70 %, and 80 % flow area.

In this analysis, a CFD method is used, this program helps to solve mathematical equations that formulate the process of fluid dynamics in describing the phenomenon of fluid flow that occurs by making a modelling geometry that matches the actual state of both the shape and dimensions for the simulation. The results obtained in this simulation are in the form of data, images, and curves that show predictions of the system reliability.

5. Results and discussions

Gambit program is used to create geometry, grid, and mesh based on the modelled parts, namely inlet, outlet, and wall as part of the fuel plate. Figure 6 shows a visualization of the mesh from Gambit that will be executed with FLUENT code. One fuel plate with 2 sub-channels is divided into 21 faces in the axial direction, which is the hot surface with axial heat generation flux distribution available from the previous study.

There are no experimental data for the TRIGA conversion core with a plate-type fuel that could be used

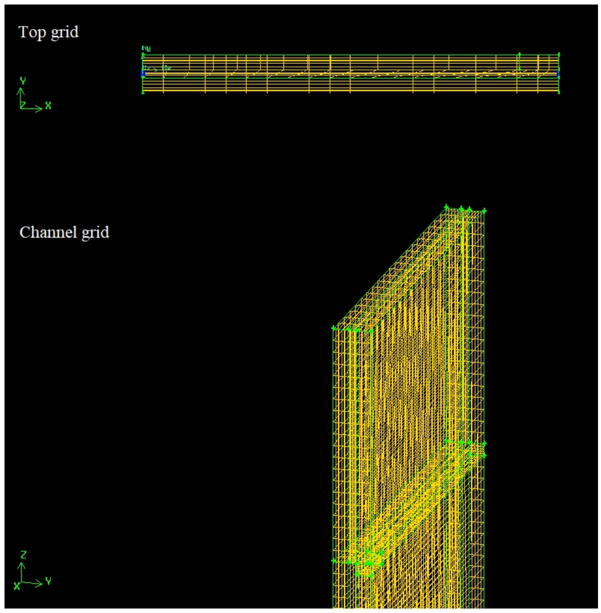

Figure 6. Meshing of channel blockage model.

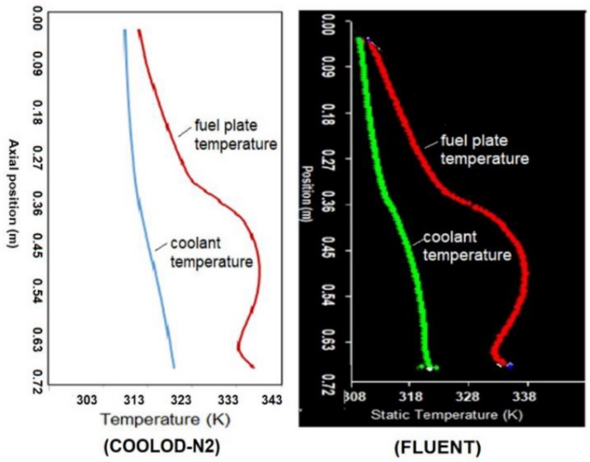

Figure 7. One Dimension fuel plate temperature and coolant temperature for steady state without blockage.

to validate the results of the steady-state calculation. Therefore, one dimension of the COOLOD-N2 code is used to calculate the steady-state at unblocked conditions. The COOLOD-N2 is a computer code for the analyses of steady-state thermal-hydraulics of both the rod-type and plate-type fuels [19, 20]. In this study, it is assumed that the blocked sub-channel was the hottest channel in the core. As part of a conservative approach, if the hottest channel remains safe, then other channels will also likely be safe.

Figure 7 shows the calculated result of the fuel plate surface temperature and coolant temperature by COOLOD-N2 and FLUENT code under normal conditions before the blockage occurs, and there are no significant differences, which gives confidence in the CFD simulation. In this steady-state calculation, a cosine-shape power distribution is utilized in an axial direction. The fuel maximum temperature is around 337 K for these two codes. Meanwhile, the maximum coolant temperature at the outlet channel is around 320 K. The maximum bulk temperature (T_{cool}) occurs at the outlet channel as written in equation (1). Furthermore, the FLUENT model used above can be used for the blocked case to find the temperature profile.

Figure 8 shows calculated results for the profile of the coolant velocity in the blockage area of 0 %, and 60 %. As shown in Figure 8(a), in the case of no blocked channel area, a coolant velocity is 0.69 m/s and the mass flow rate is 0.118 kg/s, which is the uniform velocity distribution at normal conditions. Then, Figure 8(b) shows the profile of flow velocity in the case of blockage of 60 %. When the blockage occurs, a partial blockage in this channel has a significant impact on the flow velocity. Because the inlet are of the coolant sub-channel is reduced to 40 %, the coolant velocity in this inlet sub-channel increases. It can be seen that there is a jet flow with a velocity of up to 1.60 m/s and a mass flow rate of 0.109 kg/s. It has an impact on the coolant velocity along the vertical direction (axial), and there is a localized eddy beneath the blockage plate. Furthermore, the coolant flows vertically, downstream to the outlet channel.

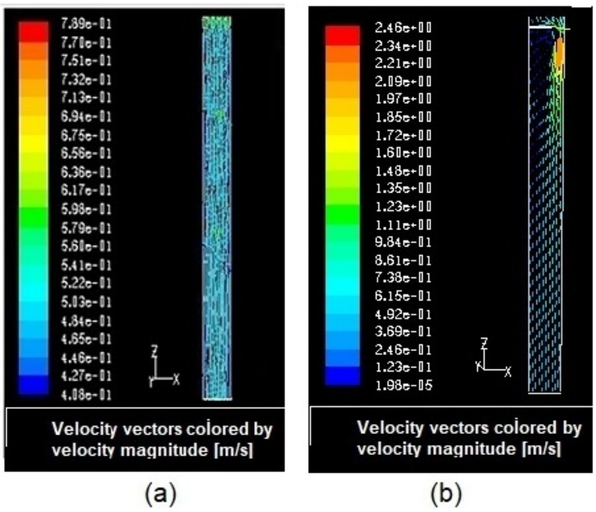

Figure 8. Profile of flow velocity for blockage areas within the range of 0 % and 60 %.

Figure 9(a) and Figure 9(b) show the simulation results for the coolant velocity profile for the blockage areas of 70 % and 80 %. As shown in Figure 8(b), the coolant velocity profile in the coolant channel follows a similar trend. However, the average flow velocity through the narrow channel for 70 %, and 80 % cases is 1.92 m/s and 2.34 m/s, respectively. This flow velocity gradually decreases along the channel's edge. Furthermore, the flow in the middle region appears to be non-homogeneous, and the flow velocity profile is quite complex. The coolant velocity on a fuel plate surface is higher than the velocity on the surface in front of it. The coolant velocity is a variable that significantly influences the fuel plate surface temperature.

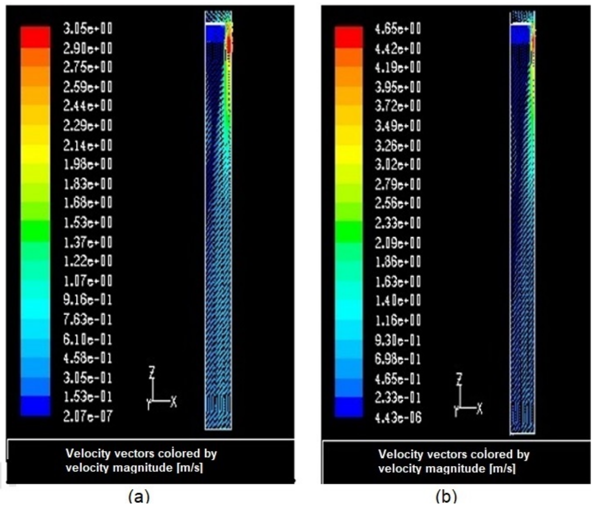

Figure 9. Profile of flow velocity for blockage areas within the range of 70 % and 80 %.

Figure 10(a) and Figure 10(b) depict the static coolant temperature profile of the un-blocked area (0 %) and the blockage of 60 %. A blockage here means a reduction in flow area in the obstructed channel, which could result in a reduction of flow rate. A non-homogeneous flow causes the heat transfer process to not occur properly. The coolant temperature becomes higher than in an unblocked channel. This hot spot temperature also affects the temperature on the opposite plate surface. This effect occurs by the conduction of heat through the thin plate. As depicted in Figure 10(b), it shows that when a channel is obstructed, the coolant temperature profile changes significantly. This simulation indicates that the maximum coolant temperature for the 60 % blockage is 377 K. This temperature is located at 0.52 m from the inlet flow direction. However, it is still below the limit of the coolant saturation temperature, 386 K.

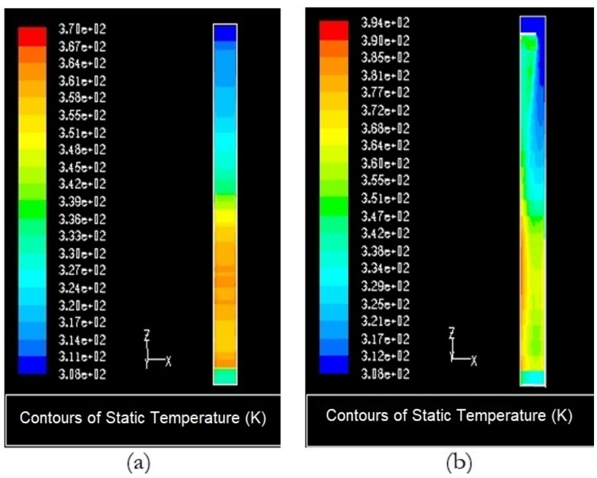

Figure 10. Profile of static temperature for blockage areas within the range of 0 % and 60 %.

Figure 11(a) and Figure 11(b) show that the coolant temperature profile for the 70 % blockage case was similar to the 80 % case. The maximum temperature for the 70 % blockage reached 380 K, which is slightly lower than the saturation temperature of 386 K. While in the case of 80 % blockage, as shown in Figure 11(b), the maximum temperature locally achieves 413 K. It means a nucleate boiling within a liquid may occur in a sub-channel coolant while the bulk fluid flow is sub-cooled, this could cause damage to the fuel plates. Furthermore, the damage to the plate ($AlMg_2$ cladding material) causes a release of fission products from the fuel element into the coolant through the damaged cladding.

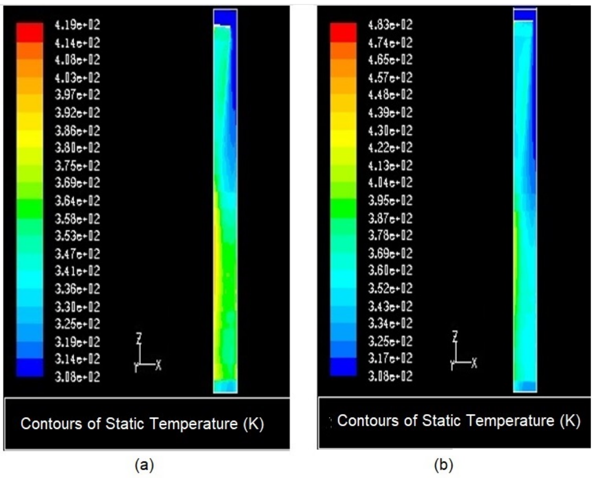

FIGURE 11. Profile of static temperature for blockage areas within the range of 70 % and 80 %

To ensure reactor safety, nucleate boiling should be avoided in the core, and the coolant should always remain in the super-cooled state, otherwise, it can cause damage to the fuel plate. From the point of view of the safety aspect, the blockage simulation result for TRIGA-2000 thermal-hydraulic core design using plate-type fuel shows a nucleate boiling occurring. It is different with the channel blockage for the reactor of IAEA generic MTR-10MW, in which the IAEA generic reactor has a high coolant flow velocity. There is no boiling occurrence for all blockage cases as can be found in an article published by Q. Lu et al. [12] S. Xia et al. [9].

6. Conclusions

A channel blockage simulation has been carried out using the thermal-hydraulic design for a fuel-plate type of TRIGA-2000 reactor with a low coolant velocity. Under the condition of a 70 % channel blockage, the cooling temperature is still below the nucleate boiling temperature. In the case of the 80 % blockage, a nucleate boiling may occur due to the maximum local temperature reaching 413 K with the saturation temperature being 386 K. This is insufficient for a safety margin and could cause damage to the fuel plate.

Acknowledgements

We would like to acknowledge the INSINAS program of Research and Technology - BRIN 2021 for funding this research, member of "TRIGA plate type fuel design team" and also to all staff of Center for Applied Nuclear Science and Technology – BATAN for supporting the activities.

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