THERMAL-HYDRAULICS PARAMETER ANALYSIS OF THE BANDUNG TRIGA 2000 REACTOR BASED ON CFD AND RELAP5/MOD3.2

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ABSTRACT

THERMAL-HYDRAULICS PARAMETER ANALYSIS OF THE BANDUNG TRIGA 2000 REACTOR BASED ON CFD AND RELAP5/MOD3.2. Reactor TRIGA 2000 Bandung is result of upgrading TRIGA Mark II reactor from nominal power of 1 MW becomes 2 MW and has been opened its the operation in the year 2000. In this period change of operation parameters had been occurred, especially the parameter related to thermo-hydraulic aspect, like the height of reactor core temperature and the formation of vapor bubble in the core, which is on the contrary with the safety aspect. Safety is the priority in the reactor operation, hence reactor core temperature and vapor bubble in core need to be reduced. One of methods to reduce the core temperature and vapor bubble formation is the operation at limited power of 1000 kW. To examine the safety margin of Bandung TRIGA 2000 reactor operation at 1000 kW power, the analysis of thermo-hydraulic characteristic have been carried out by theoretical study using computer code of CFD (Computational of Fluid Dynamics) and RELAP5/Mod3.2 (Reactor Excursion and Leak Analysis Program). The result of the study indicates that reactor reaches steady state condition at 1000 kW power in 1500 seconds after critical condition, and maximum temperature of reactor core is in C4 position, whereas the maximum temperature of fuel center, cladding, and cooling water at related fuel are 529.35 °C, 103.12 °C, and 90.67 °C, respectively. Maximum temperature of cladding and primary cooling water at related fuel are below saturation temperature (112.4 °C), so the sub-cooled boiling or bubbling of saturation and vapor bubble formation can be predicted not to be happened. Besides when the reactor was operated at 1200 kW and 1250 kW power was obtained the maximum temperature of fuel cladding are 111.04 °C and 115.53 °C, respectively. This thing informs that, when the reactor was operated up to 1200 kW power sub-cooled boiling has not happened, but when the reactor was operated at 1250 kW power has started the happening of the sub-cooled boiling and the formation of vapour bubble. The result of this study can be used as a valuable information in operating Bandung TRIGA 2000 reactor at the limited power of 1000 kW and revising safety analysis report (SAR) of Bandung TRIGA 2000 reactor.

Key words: Bandung TRIGA 2000 reactor, 1000 kW limited power, thermal-hydraulic aspect, computer code of CFD, computer code of RELAP5/Mod3.2.

ABSTRAK

ANALISIS PARAMETER TERMOHIDROLIK REAKTOR TRIGA 2000 BANDUNG BERBASIS CFD DAN RELAP5/MOD3.2. *Reaktor TRIGA 2000 Bandung merupakan hasil upgrading dari reaktor TRIGA Mark II berdaya nominal 1 MW menjadi 2 MW dan telah diresmikan pengoperasiannya pada tahun 2000. Dalam periode tersebut telah terjadi perubahan parameter operasi, terutama parameter yang berkaitan dengan aspek termohidrolik, seperti suhu teras reaktor yang tinggi dan menyebabkan terjadi pembentukan gelembung uap di dalam teras. Hal ini bertentangan dengan aspek keselamatan. Mengingat masalah keselamatan merupakan hal yang utama, maka perlu dilakukan penurunan suhu teras reaktor dan pengurangan pembentukkan* *gelembung uap di dalam teras, diantaranya dengan mengoperasikan reaktor TRIGA 2000 Bandung pada daya terbatas 1000 kW. Untuk mengetahui tingkat keselamatan pengoperasian reaktor TRIGA 2000 Bandung pada daya 1000 kW, dilakukan analisis karakteristik termohidrolik melalui kajian teoritik menggunakan program computer Computational Fluid Dynamics (CFD) dan RELAP5/Mod3.2 (Reactor Excursion and Leak Analysis Program). Hasil kajian menunjukkan bahwa reaktor mencapai kondisi tunak pada daya 1000 kW setelah 1500 detik reaktor kritis, suhu maksimum bahan bakar di dalam teras reaktor berada di posisi C4 dimana suhu maksimum pusat bahan bakar 529,35 °C, suhu maksimum kelongsong bahan bakar 103,12 °C, dan suhu maksimum pendingin pada posisi bahan bakar terkait 90,67 °C. Suhu maksimum kelongsong bahan bakar dan suhu maksimum pendingin yang diperoleh berharga jauh di bawah suhu saturasi 112,4 °C, sehingga pendidihan prajenuh (sub-cooled boiling) atau pendidihan saturasi dan pembentukan gelembung uap di dalam teras diprediksi tidak terjadi. Selain itu ketika reaktor dioperasikan pada daya 1200 kW dan 1250 kW diperoleh suhu maksimum kelongsong bahan bakar berturut-turut 111,04 °C and 115,53 °C. Hal ini menginformasikan bahwa ketika reaktor dioperasikan hingga daya 1200 kW belum terjadi pendidihan prajenuh (sub-cooled boiling) atau pendidihan saturasi, tetapi ketika reaktor dioperasikan pada daya 1250 kW telah mulai terjadi pendidihan prajenuh (sub-cooled boiling) atau pendidihan saturasi dan pembentukan gelembung uap. Hasil kajian ini dapat menjadi informasi dalam mengoperasikan reaktor TRIGA 2000 pada daya terbatas 1000 kW dan merevisi Laporan Analisis Keselamatan (LAK) reaktor TRIGA 2000 Bandung.*

Kata kunci: reaktor TRIGA 2000 Bandung, daya 1000 kW, aspek termohidrolik, program komputer CFD, program computer RELAP5/Mod3.2.

INTRODUCTION

At present, the operation of Bandung TRIGA 2000 reactor at 2000 kW power wit the temperature of primary cooling water into tank of 32.2 °C and the flow rate of 3.29 m/s will lead to the maximum temperature of primary cooling water exit from around C3 fuel reach 116.02 °C and the maximum temperature of C3 fuel cladding reach 160 °C [1]. These temperatures have exceeded the saturation temperature of primary cooling water (112.4 °C), so sub-cooled boiling or saturation has been occurred in Bandung TRIGA 2000 reactor core, indicated with the vapor bubbles exit from the reactor core. Such phenomenon is reasonably happened since the Bandung TRIGA 2000 reactor has been operated for about 10 years, where during this period several operation parameters have changed, especially the parameter related to the thermal-hydraulics aspect, such as the temperature and flow rate of primary cooling water into tank, the flow rate of secondary cooling water and the characteristic of heat exchanger system.

The operation of the reactor in such condition lead to the vapor bubble formation that increase the intensity of gamma radiation from N-16 on the surface of reactor tank water. In the other hand if sub-cooled boiling or saturation boiling in reactor core develops into film boiling, the damage or leakage will be resulted at fuel cladding and the radioactive materials accumulated in the fuel will escape.

Safety is the primary factor in nuclear reactor operation, hence the safe and useable method in operating Bandung TRIGA 2000 reactor is needed. A method of operating the Bandung TRIGA 2000 reactor in limited power of 1000 kW was considered to be applied, however the experimental and theoretical study related to thermal-hydraulics aspect are needed to identify the operation paramaters of Bandung TRIGA 2000 reactor at 1000 kW power. In this research theoretical study on thermal-hydraulics aspect of Bandung TRIGA

2000 reactor have been conducted using computer code of CFD (Computational of Fluid Dynamics)[2] and RELAP5/Mod3.2[3,4] for completing the unavailable information of the CFD.

The main purpose of this research is to obtain the limit of safety parameter to be applied in operating Bandung TRIGA 2000 reactor at limited power of 1000 kW.

METHOD

Description of CFD and RELAP5/MOD3.2

Thermal-hydraulics characteristic of Bandung TRIGA 2000 reactor was analyzed using computer code of CFD (Computational of Fluid Dynamic) and RELAP5/Mod3.2. The CFD is a computing program for simulation of fluid flow dynamics, heat transfer and other phenomenon by numerical solution of the finite volume method to three basic equations of Navier-Stokes, those are continuity, momentum and finite energy equation.

Computer code of CFD is equipped with preprocessor and main module. The function of the preprocessor is to create geometry of the model evaluated, beside it also functions as grid maker of the geometry created. The grids divide the geometry into many cells of volume units as domain for the calculation using finite volume method, so all positions at the created geometry can be analyzed. The main module is used to execute the calculation of all volume unit cells after applying the boundary condition values of involving parameters.

The RELAP5/Mod3.2 best estimate system transient code is a modification of RELAP5/Mod3 developed by the Idaho National Laboratory for the thermal-hydraulics transient analysis of the Pressurized Water Reactors (PWR)[3,4]. The RELAP5/Mod3.2 thermal-hydraulics model solves 8 field equations for 8 primary dependent variables, i.e. pressure, vapor and liquid specific internal energies, void fraction, vapor and liquid velocities, non-condensable quality, and boron density; however the boron density is not applicable in this analysis. The secondary dependent variables used in the equations are vapor and liquid densities, vapor and liquids temperatures, saturation temperature, and non-condensable mass fraction in gas phase. The independent variables are time and distance. The constitutive relations and correlations to close field equations are interphase friction, and wall heat transfer. The field equations are two phases mass, two phases momentum and two phases energy equations, respectively.

Hydrodynamic system evaluated with RELAP5/Mod3.2 is modeled by components which is a simulation of system as a whole. The models include volume, pump, valve, pipe, heat release structure, absorption structure of heat, reactor kinetics, electric heater, jet pump, turbine, separator, accumulator and control systems component. The realistic input model is needed in the application of RELAP5/Mod3.2 to carry out best-estimation in thermal-hydraulic analysis of Bandung TRIGA 2000 reactor. The input model should not only take into account the correct geometry, but also include the necessary control model, heat structures, appropriate boundary condition and system heat loss.

Assumption and Boundary Condition

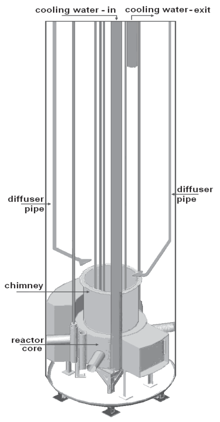

Figure 1. Bandung TRIGA 2000 reactor and the components

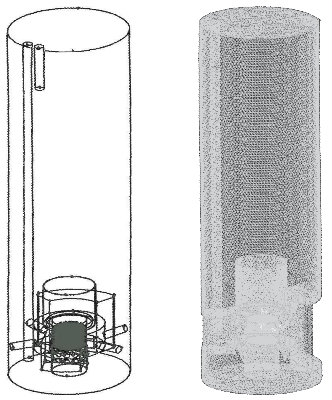

Figure 2. CFD geometry and grids for Bandung TRIGA 2000 reactor

The model of Bandung TRIGA 2000 reactor created with computer program of CFD is showed in Figure 1 and Figure 2. Heat flux is assumed to be homogenously distributed along the active fuel.

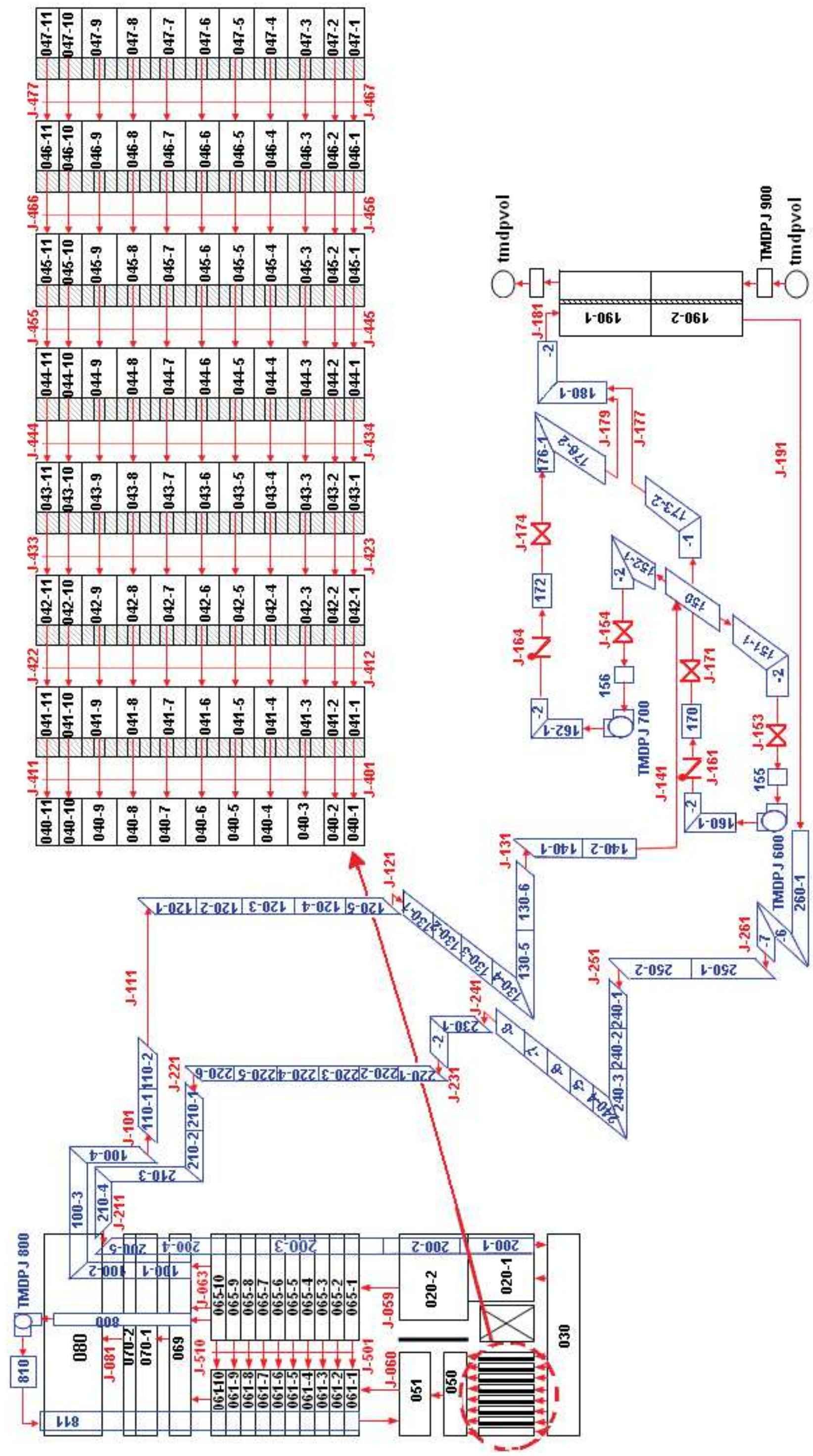

Figure 3. RELAP5/Mod3.2 nodalization for Bandung TRIGA 2000

Using the computer code of RELAP5/Mod3.2, Bandung TRIGA 2000 reactor is also modeled in the form of nasalization as shown in Figure 3. The reactor core with 107 fuels modeled as 8 channels representing the 8 different areas in the reactor core. Channel 1 represents the core area that is not occupied by fuels. The channel 2 until 7 represent the hottest channel consecutively in B, C, D, E, F, G ring area, whereas channel 8 represent the channel with average heat flux. The reactor model accommodates the underside core geometry influencing the direction and flow rate of primary cooling water into core, the position of primary pipe tip in core below, and the diffuser pipe to turn some of cooling current directions from reactor core.

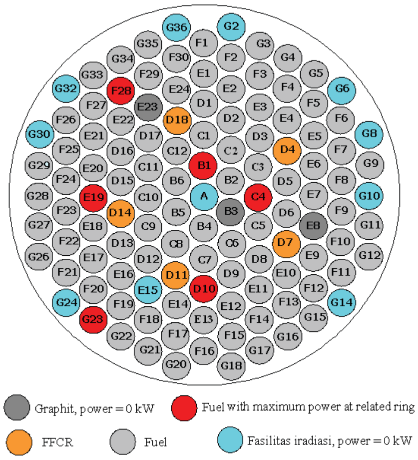

Figure 4. Fuel configuration in core with 107 fuels

The boundary conditions were applied for reactor power of 1000 kW, saturation temperature at reactor core of 112.4 °C [5], and the power in each fuel as listed at Table 1[6]. The other conditions are as follow: fuel configuration in core is as expressed in Figure 4, primary cooling water temperature into reactor tank is 32 °C, flow rate of primary cooling water into reactor tank is 50.21 kg/s[7], temperature of cooling water into secondary side is 29 °C, flow rate of secondary cooling water is 75.30 kg/s[7], and the flow rate of diffuser is 3.73 kg/s[7].

Table 1. The distribution of power resulted from neutronic calculation with total power of 1000 kW

Fuel	Power (kW)	Fuel	Power (kW)	Fuel	Power (kW)	Fuel	Power (kW)	Fuel	Power (kW)
A	0	B1	16.77	B2	15.85	B3	0	B4	16.45
B5	16.60	B6	16.50	C1	15.23	C2	15.83	C3	15.16
C4	16.87	C5	15.96	C6	16.27	C7	15.07	C8	15.72
C9	15.72	C10	15.76	C11	15.47	C12	15.64	D1	16.31
D2	9.85	D3	14.36	D4	16.73	D5	7.79	D6	14.25
D7	16.65	D8	13.70	D9	7.61	D10	16.82	D11	14.27
D12	14.79	D13	11.84	D14	13.73	D15	13.88	D16	8.10
D17	14.14	D18	13.65	E1	7.31	E2	9.65	E3	10.19
E4	9.31	E5	7.40	E6	9.39	E7	10.31	E8	0
E9	8.66	E10	9.35	E11	10.23	E12	9.79	E13	7.54

E14	9.83	E15	0	E16	12.79	E17	7.47	E18	9.51
E19	14.76	E20	9.31	E21	7.74	E22	8.56	E23	0
E24	9.38	F1	6.30	F2	7.18	F3	7.13	F4	7.03
F5	6.57	F6	6.17	F7	6.48	F8	6.85	F9	7.14
F10	6.59	F11	6.24	F12	7.11	F13	7.22	F14	5.80
F15	5.36	F16	5.65	F17	5.67	F18	7.37	F19	7.17
F20	5.95	F21	5.51	F22	5.51	F23	6.48	F24	5.45
F25	5.82	F26	5.23	F27	5.63	F28	7.38	F29	6.53
F30	5.66	G2	0	G3	5.31	G4	5.14	G5	5.20
G6	0	G8	0	G9	5.52	G10	0	G11	5.23
G12	5.00	G14	0	G15	5.42	G16	5.05	G17	5.28
G18	4.84	G20	4.27	G21	4.69	G22	4.91	G23	5.70
G24	0	G26	4.58	G27	5.08	G28	4.85	G29	5.21
G30	0	G32	0	G33	4.44	G34	4.42	G35	4.87
G36	0	-	-	-	-	-	-	-	-

RESULTS AND DISCUSSION

By using computer code of CFD, it is obtained the radial distribution of maximum temperature of fuel cladding in core and the cooling water at related ring, when reactor operated at 1000 kW power, such as shown in Figure 5 and Table 2. The maximum temperature of cladding in the core was 103.12 °C in C4 position, and the maximum temperature of cooling water at related fuel was 90.67 °C. This condition is attributed to the highest power of fuel is in the C4 position. The maximum temperature obtained is still below the saturation temperature of reactor primary cooling water, that is 112.4 °C, so the predicted sub-cooled boiling (bubbling of saturation) has not happened.

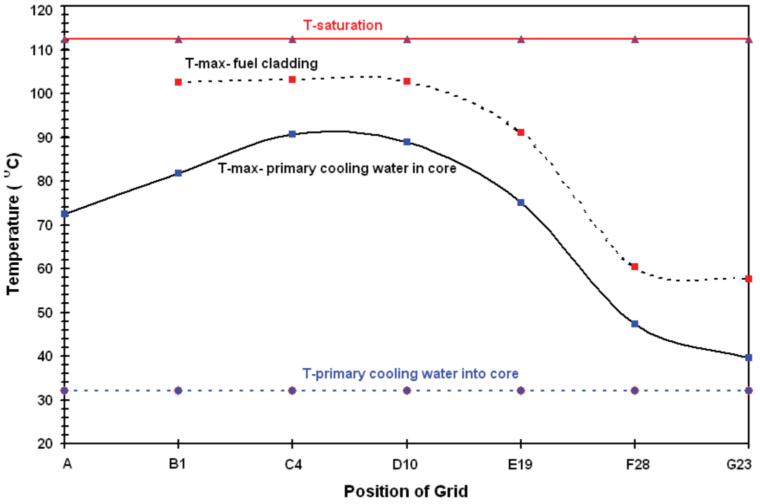

Figure 5. Radial distribution of the maximum temperature of fuel cladding and cooling water at related ring

Table 2. Maximum temperature of fuel cladding and primary cooling water at related ring

Position of fuel	Power (kW)	The maximum temperature (°C)	
		Fuel cladding	Cooling water
A		-	72.56
B1	16.77	102.53	81.74
C4	16.87	103.12	90.67
D10	16.82	102.83	89.0
E19	14.76	91.07	75.0
F28	7.38	60.38	47.34
G23	5.7	57.55	39.55

The application of CFD computer code resulted axial distribution of temperature. Figure 6 shows that maximum temperature of cooling water in the core is between position of C4 and C5, that was 90.67 °C. The maximum temperature of cooling water is far below the saturation temperature, so if the reactor was operated at 1000 kW power, the sub-cooled boiling in the reactor core is not happened yet.

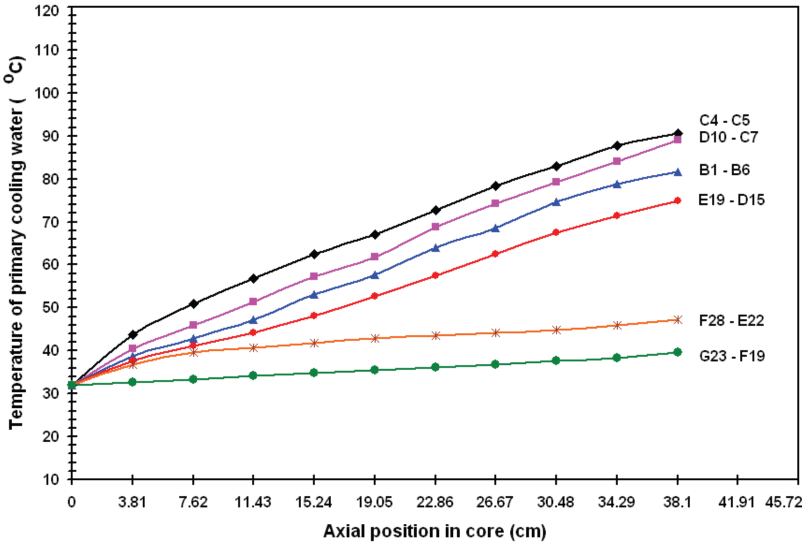

Figure 6. Axial distribution of cooling water maximum temperature in the position of fuel with maximum cladding temperature

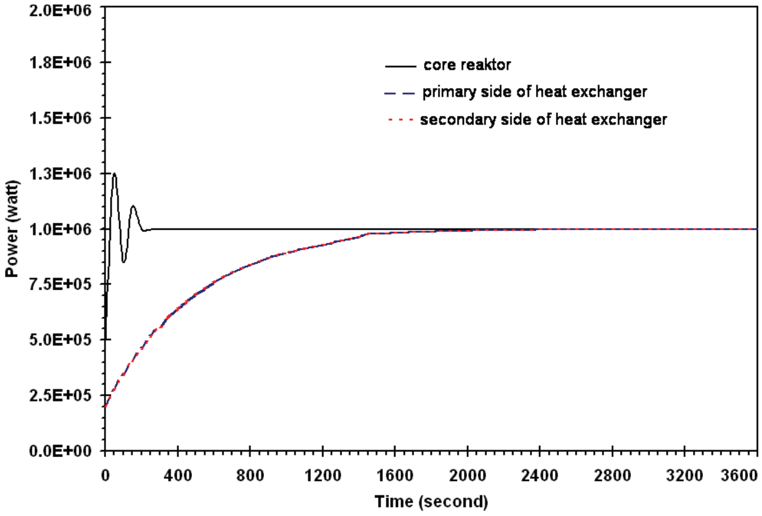

Figure 7. Reactor power moving to primary and secondary side of heat exchanger at steady state and transient condition

The time required to reach steady state condition is obtained by applying RELAP5 Mod3.2 computer code. Based on the study conducted in Bandung TRIGA 2000 reactor, it is known that the area farthest from core would reach steady state condition lately, the area is between the primary and secondary side. The power moving from reactor core and primary cooling water to the secondary cooling water reach the steady state condition after 1500 seconds since the reactor starts to operate at 1000 kW power, as shown in Figure 7.

The temperature of fuel center is obtained by applying RELAP5/Mod3.2 computer code. Figure 8 and Table 3 show radial distribution of fuel center maximum temperature in core and maximum temperature of primary cooling water exit from core, when reactor operated at 1000 kW power, the fuel center maximum temperature in reactor core was 529.35 °C in C4 position, and the maximum temperature of cooling water exit from core at related ring was 74.43 °C. The maximum temperature of cooling water is far below the saturation temperature, so the sub-cooled boiling in the reactor core is not happened yet.

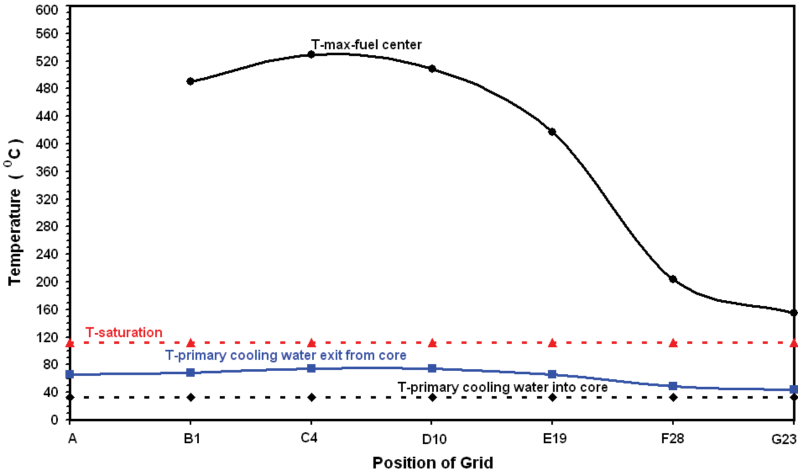

Figure 8. Radial distribution of fuel center and maximum temperature of cooling water into core and exit from core at related ring

Table 3. Maximum temperature of fuel center and primary cooling water exit from core at related ring

Position of Fuel	Power (kW)	Maximum temperature of fuel center (°C)	Maximum temperature of primary cooling water exit from core (°C)
A	-	-	65.48
B1	16.77	489.72	68.12
C4	16.87	529.35	74.43
D10	16.82	508.99	73.87
E19	14.76	416.89	65.71
F28	7.38	203.06	48.93
G23	5.70	154.37	43.92

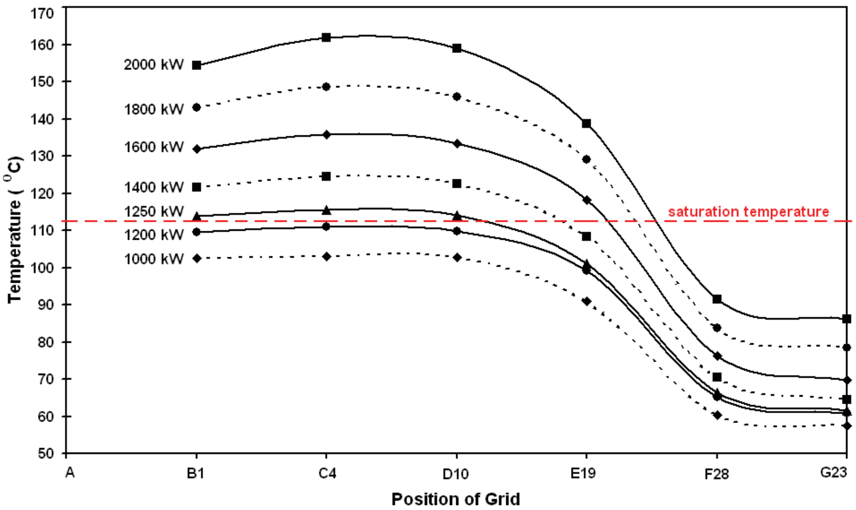

Figure 9. Radial distribution of the maximum temperature of fuel cladding for various of power by using CFD

Table 4. The maximum temperature of fuel cladding (°C) for various of power

Position of Fuel	The maximum temperature of fuel cladding (°C)						
	1000 kW	1200 kW	1250 kW	1400 kW	1600 kW	1800 kW	2000 kW
A	-	-	-	-	-	-	-
B1	102.53	109.57	113.83	121.63	132.03	143.03	154.33
C4	103.12	111.04	115.53	124.53	135.73	148.45	161.73
D10	102.83	109.86	114.12	122.52	133.32	146.00	159.03
E19	91.15	99.07	101.11	108.28	118.27	129.07	138.56
F28	60.38	65.18	66.38	70.58	76.18	83.78	91.38
G23	57.55	60.75	61.55	64.55	69.75	78.55	86.05

By using computer code of CFD, it is obtained the radial distribution of maximum temperature of fuel cladding in core for various of power, such as shown in Figure 9 and Table 4. The maximum temperature of fuel cladding for various of power core was in C4 position. The maximum temperature of fuel cladding for 1000 kW and 1200 kW power was 103.12 °C and 111.04 °C. This temperature is still below the saturation temperature of reactor primary cooling water, that is 112.4 °C, so the predicted sub-cooled boiling (bubbling of saturation) has not happened. But if the reactor was operated at 1250 kW power, the maximum temperature of fuel cladding was 115.53 °C, and this temperature is above the saturation temperature of reactor primary cooling water. So the sub-cooled boiling or bubbling of saturation and the formation of vapour bubble have been happened if Bandung TRIGA 2000 reactor is operated at 1250 kW power.

CONCLUSION

Thermal-hydraulics analysis of Bandung TRIGA 2000 reactor at 1000 kW power has been carried out using computer code of CFD and RELAP5/Mod3.2, and it can be concluded as follow :

1. The operation of Bandung TRIGA 2000 reactor at various of power resulted the maximum temperature of reactor core resides in C4 position. The maximum temperature of fuel cladding for 1000 kW, 1200 kW and 1250 kW power are 103.12 °C, 111.04 °C and 115.53 °C, respectively. When the reactor was operated up to 1200 kW power, sub-cooled boiling (bubbling of saturation) has not happened, because the maximum temperature of core happened still below the saturation temperature of reactor primary cooling water, that is 112.4 °C, but when the reactor was operated at 1250 kW power has started the happening of the sub-cooled boiling or bubbling of saturation and the formation of vapour bubble.
2. When the reactor was operated at 1000 kW power were resulted the maximum temperatures are 529.35 °C, 103.12 °C, and 90.67 °C for fuel center, fuel cladding, and the cooling water at related fuel, respectively.
3. The reactor reach steady state condition at 1000 kW power in 1500 seconds after critical condition.

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