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Fuel rod design for a high burnup small modular nuclear reactor

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Abstract: PWR is a type of nuclear reactor that is widely used as a nuclear power plant. Even though PWR has been around for a long time, technology continues to develop. The direction of development of PWR technology is to create a more compact design with a modular system (SMR) and more efficient fuel. More efficient fuel can be obtained by increasing fuel burnup. By increasing burnup, the fuel usage period is longer, thereby increasing the economic value of the fuel and reducing the volume of radioactive waste produced from spent fuel. High burnup means the fuel will be exposed to radiation for longer. Therefore, it is necessary to calculate both thermal and mechanical aspects with the new fuel rod design, to see whether the fuel can be used until the end of the fuel cycle. Calculations were conducted using the Femaxi version 6 code. From the calculation results, it was obtained that the dimensions of the fuel rods were capable of reaching a burnup of 60 GWd/TU. The dimensions obtained include the diameter and length of the pellets of 7.4 mm and 10 mm, the diameter and depth of the disc of 4.7 mm and 0.51 mm, and the inner and outer diameters of the cladding of 7.8 mm and 9.3 mm. The calculation results show that the temperature distribution in the fuel rods during reactor operation is still within safe limits, and pellet cladding interaction (PCI) does not occur until the end of the fuel consumption cycle.

Keywords: SMR, fuel rod, FEMAXI, PCI.

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1. Introduction

Indonesia is committed to reducing greenhouse gas emissions by setting a net zero emission target no later than 2060 (NZE 2060) through the development of new renewable energy. One of the efforts is the construction of a nuclear power plant. Nowadays, around 10.9% of the world's electricity is supplied from nuclear power plants, and the number will continue to increase because there are at least 67 new reactors under construction (Tonks et al., 2017). In the National Research Priorities (PRN) 2020-2024, the development of nuclear power plants according to the 2020-2024 RPJMN is directed at the choice of low-power commercial nuclear power plants (small modular reactors, SMR) from generations III and III+ based on light water reactors.

The reactor type that is most widely used in the world is the pressurized water reactor (PWR). Even though PWR has been in operation for a long time, this technology continues to undergo developments to increase efficiency and safety. Since it was first developed, PWR has experienced various innovations and significant design improvements. One of the main directions in the development of PWR is to create a more compact reactor design. Apart from a more compact design, higher burnup is also the focus in developing PWR. By achieving a higher burnup, PWR can produce more energy from the same amount of fuel, thereby reducing the frequency of fuel changes and the amount of radioactive waste produced. This not only increases economic efficiency but also reduces the environmental impact of nuclear power plant operations.

In this research, a fuel design was conducted for the PWR-type small modular reactor (SMR), which can achieve high burnup. Similar research on fuel with high burnup has been conducted using the Femaxi version 6 code (Lüley et al., 2022). This research has gone through the experimental stage with the IFPE/IFA-519.9 program code, so indirectly, this Femaxi code has been validated. The modeling of thermohydraulic and thermomechanical aspects was carried out in detail to ensure that the resulting design was able to endure extreme operational conditions (Sanchez-Torrijos et al., 2023). The thermal aspect of hydraulics includes heat transfer from the fuel, cladding, and gaps, as well as convection on the outer surface of the fuel cladding (Ding et al., 2021). Mechanical aspects include stress and strain in the fuel rod material, especially in the fuel cladding, which must be able to withstand high pressure and radiation during the reactor operation. Through this comprehensive approach, it is hoped that the new PWR-type SMR fuel can achieve high burnup without compromising safety and reliability.

2. Methods

The analysis of the SMR fuel rod design includes thermal and mechanical aspects, which are calculated using the Femaxi 6 code. This code allows detailed modeling to predict the performance of the fuel pin in various operational conditions (Mutiara et al., 2019; Udagawa & Amaya, 2019). Femaxi 6 has been used since 2013, has been validated, and has become a reference for newer similar codes (Hernandez-Lopez, 2014; Kriventsev et al., 2015; Rice, 2015; Van Uffelen et al., 2019). Using Femaxi version 6 requires input parameters to be able to conduct calculations.

Fuel design

Fuel design includes pellet diameter, height, and pellet shape; cladding diameter and thickness; and the number of pellets in the cladding. The fuel design also includes the pellet density and enrichment of the uranium. The fuel design will be varied to obtain fuel that can be used with a 60 GWd/TU burnup safely and securely.

Reactor core environment

Environmental conditions in the reactor core include temperature, coolant flow rate, and coolant pressure. This research aims to obtain a fuel design so the parameters related to environmental conditions in the reactor core are not varied but refer to the system-integrated modular advanced reactor (SMART) (KAERI, 2006). Detailed environmental conditions are shown in Table 1.

Table 1. Reactor core environment

Power	330 MWt
Fuel assemblies (FA)	57
Fuel element in one FA	264
Coolant temperature	285 °C
Coolant flow rate	3 m/s
Pressure	15 MPa

The reactor operates at 330 MWt. The number of fuel assemblies (FA) is 57 units, with the number of fuel elements (FE) in each FA being 264 units. This condition will produce a linear heat rate in each fuel of around 110 W/cm. Under normal conditions, the linear heat rate will be input into the reactor operating history parameters.

Axial power distribution

Axial power distribution in this simulation uses power ramp test facility (PRTF) axial power distribution data at the G.A. Siwabessy multi-purpose reactor (RSG-GAS). RSG-GAS is an

Indonesian research reactor that is used for the research and development of nuclear fuel for research reactors and power reactors. The power ramp test facility is used specifically for power reactor fuel research (Sulistyono & Yulianto, 2013; Susilo et al., 2017). Details of the PRTF axial power distribution are shown in Figure 1 (Susilo & Kuntoro, 2016).

The axial power distribution of the PRTF may differ slightly from that of SMART. However, SMART is only designed to operate at normal power levels, unlike the PRTF, which is specifically designed for fuel testing. This is important because the fuel must be designed to meet safety limits and withstand abnormal conditions. Therefore, the axial power distribution used in the calculations is based on the axial power distribution of the PRTF at RSG-GAS

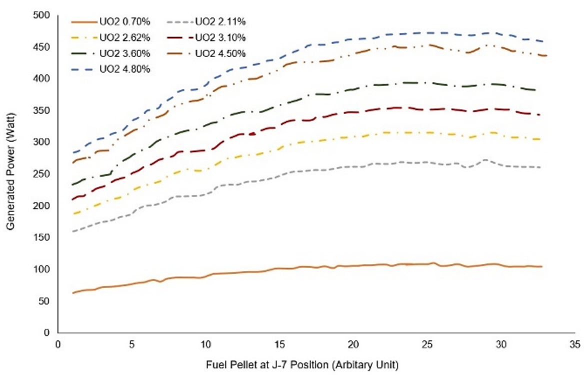

Figure 1. PRTF axial power distribution data.

Reactor operation history

The reactor's operating history includes operating data throughout the reactor's life cycle, including load variations, shutdown periods, and other operational fluctuations. This operating history is a very important parameter because it is closely related to safety. Therefore, this operational history not only includes parameters in accordance with reactor operations under normal conditions but also includes extreme conditions such as when the reactor is operated at a load that exceeds the permitted limits or when the power experiences fluctuations. A detailed reactor operating history is shown in Figure 2. It is assumed that the reactor will be refueled every time the burnup reaches 20 GWd/TU. This means that in a 60 GWd/TU burnup, there will be a three-time shutdown process for refueling.

During the startup process, the power will be increased slowly to 110 W/cm. This is a normal condition of reactor operation (Sulistyono & Wigayati, 2013). Then the power is increased slowly to 130 W/cm. Nearing the end of the cycle, the power will be increased 2-3 times from normal operating conditions to see the effects of the reactor operation under abnormal conditions. This is important for ensuring that the fuel has an adequate safety margin. This is also a requirement for advanced fuels, where the fuel must have good performance up to 430 W/cm (Beauvy et al., 2009).

The output from Femaxi includes thermohydraulic and thermomechanical aspects. These aspects include pellet and cladding temperatures, gap changes to see the interaction between pellets and cladding, as well as pressure generated due to changes in temperature and fission product gas.

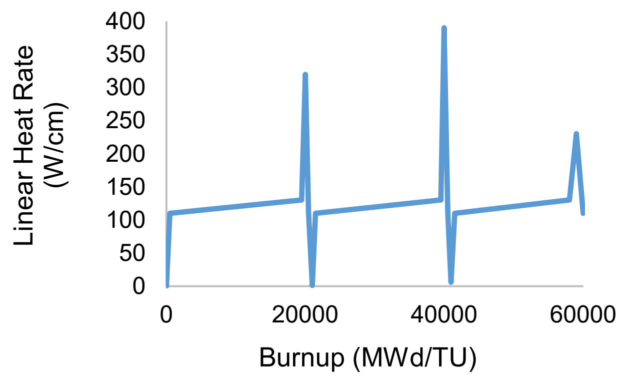

Figure 2. Reactor operation history.

3. Result and discussion

Femaxi code output has been obtained based on previously defined modeling parameters. To achieve a burnup of 60 GWd/TU, it takes 43,135 hours or 60 months of operation, with an operating history as shown in Figure 2. High-burnup fuel will save up to 66% in fuel consumption because, generally, the fuel usage period is 36 months of operations or 36 GWd/TU. The fuel design parameters to be simulated using the Femaxi code are shown in Table 2.

Several fuel design parameters have significant differences compared to existing PWR fuel designs. The first parameter is the smaller diameter of the pellet, namely 7.4 mm. The pellet diameter in PWR is generally around 9–10 mm, while the SMART reactor design has a pellet diameter of 8.19 mm. This reduction in diameter aims to reduce the significant temperature difference between the middle and the surface pellet. As shown in Figure 3, in extreme conditions where the linear heat rate (LHR) value is very high (>300 W/cm), the temperature difference between the middle pellet and the surface is more than

1000 °C. This is because pellets are a ceramic material, where ceramic has very low heat conductivity.

Table 2. Fuel design parameters.

Parameters	High burnup fuel design	SMART design
Pellet		
Diameter	7.40 mm	8.19 mm
Length	10.00 mm	7.58 mm
Diameter of disc	4.70 mm	-
Depth of disc	0.51 mm	-
Enrichment	5%	5%
Density	93% TD	95% TD
Cladding		
Inner diameter	7.80 mm	8.93 mm
Outer diameter	9.30 mm	9.50 mm
Other parameter		
Gas	He	He
Gas pressure	2.5 MPa	2.5 Mpa
Plenum volume	6 cm3	-

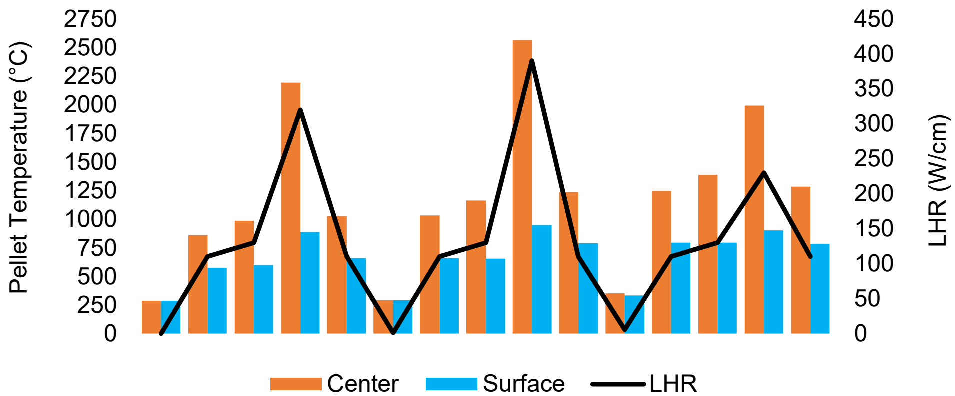

Figure 3. Distribution of pellet temperature on changes in LHR.

The next parameter that has a significant difference is the gap width. Generally, the gap width is 0.1 mm. In Table 2, the difference between the pellet diameter and the inner cladding diameter is 0.4 mm. This means that the gap width is 0.2 mm. Even though this gap is only an empty area between the pellet and the cladding, it has a very important function in temperature distribution. Figure 4 is a graph of the temperature distribution on the cladding. It can be seen that the temperature of the inner cladding when the reactor is operating is in the range of 340°C–460°C, while the surface temperature of the pellets is in the range of

570°C–950°C. The temperature difference is quite high. If there are no gaps, the inner cladding surface will have the same temperature as the pellet surface. This poses a serious risk to the safety of reactor operations.

The cladding is designed to have good thermal conductivity. This means that the temperature difference between the inside and outside of the cladding is not significant. If the cladding has the same temperature as the fuel, boiling will occur in the outer area of the cladding, thereby creating a layer of steam in the outer area of the cladding. This layer of steam will inhibit heat transfer from the cladding to the coolant, thereby potentially compromising the mechanical integrity of the cladding. For this reason, the gap between the pellets and the cladding plays a very vital role.

Another important thing that needs to be considered in fuel design is the interaction of the cladding with the fuel pellets (PCI). As previously explained, gaps have a vital role in reactor operation. Dimensional changes in pellets and cladding due to the temperature and pressure of fission gas products have the potential to change the gap width. Expansion of the pellet diameter that is too large will make the pellet contact with the cladding, causing PCI (Hong et al., 2020; Saad et al., 2021; Yang et al., 2008). Dimensional changes during irradiation are shown in Table 3.

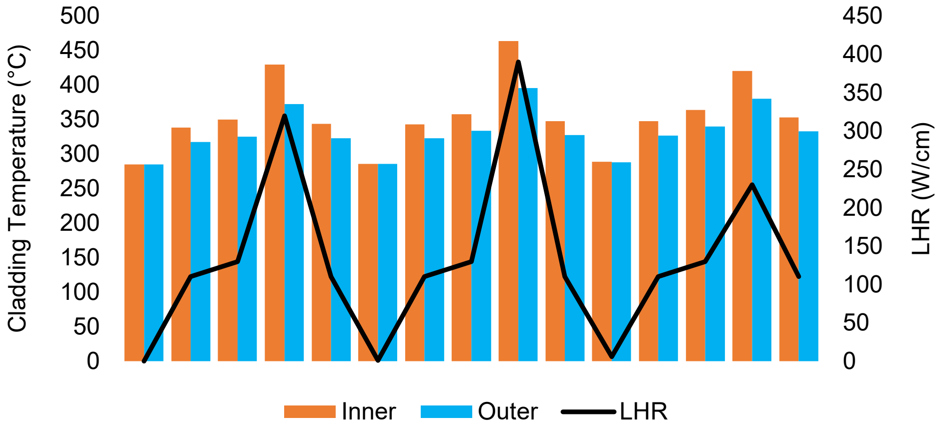

Figure 4. Distribution of cladding temperature on changes in LHR.

Table 3. Dimension change of pellet, gap, and fuel cladding.

Burnup (MWd/TU)	LHR (W/cm)	Pellet	Cladding	Gap	
		Rad. disp. (µm)	Rad. disp. (µm)	Rad. gap (µm)	Contact press. (MPa)
0	0,00	65,60	4,19	138,59	0,00
500	123,10	79,92	3,51	123,58	0,00
19500	145,50	80,83	-9,59	109,59	0,00
20000	358,10	132,73	-19,41	47,86	0,00
20500	123,10	85,70	-22,54	91,76	0,00
21000	1,10	67,13	-24,51	108,36	0,00
21500	123,10	85,71	-22,67	91,61	0,00
39500	145,50	104,28	-26,05	69,67	0,00
40000	436,40	170,78	-13,86	15,36	0,00
40500	123,10	108,91	-12,70	78,39	0,00
41000	6,70	82,69	-15,26	102,05	0,00
41500	123,10	109,46	-12,81	77,73	0,00
58000	145,50	128,86	-11,95	59,19	0,00
59000	257,40	159,07	-7,95	32,99	0,00
59990	123,10	126,89	-9,40	63,71	0,00

In general, dimensional changes in pellets are predominantly influenced by temperature. Although not linear, it is known that LHR influences temperature. The most significant change in pellet dimensions was 170.78 µm, which occurred at the highest LHR. Conversely, when the LHR value decreases, the dimensional changes also decrease.

The dimensional changes in this cladding are quite interesting, because almost all of them are negative. This means that there is a shrinkage in the diameter of the cladding. To prevent boiling of the coolant, PWR-type reactors work at very high pressure. This pressure not only presses the pressure vessel but also the cladding inside the reactor core. This is what causes the cladding shrinkage.

Dimensional changes in the pellets and cladding cause changes in the dimensions of the gap. In general, there is a thinning of the gap width during operation, which is predominantly influenced by changes in pellet dimensions. The minimum gap thickness, based on the simulations carried out, is 15.36 µm. This shows that during use in the reactor, the cladding and pellets never come into contact, so PCI does not occur. This is also confirmed by the absence of pressure caused by fuel on the cladding during operation. In the mechanical aspect, PCI is not a limit that must be met. However, the presence of PCI causes many significant changes in the calculation results from both thermal and mechanical aspects, so fuel performance becomes difficult to predict. Based on the simulation results, the fuel pin design with the specifications in Table 2 can be used up to a burnup of 60 GWd/TU.

4. Conclusions

Increasing fuel burnup will extend the fuel usage period to 60 months of operation. The burnup value can be increased without ignoring safety limits by reducing the diameter of the fuel pin and both the diameter of the pellet and the cladding. Reducing the diameter causes heat transfer to the coolant to be faster. It was found that the optimal diameter values for pellets, inner cladding, and outer cladding were 7.4 mm, 7.8 mm, and 9.3 mm. The results of calculations using Femaxi show that the temperature distribution on the fuel pin is still within safe limits, and during the operation period, there was no interaction between the cladding and the fuel pellets.

Conflict of interest

The authors have no conflict of interest to declare.

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