Power Distribution Optimization of TRISO-Fueled and Salt-Cooled Reactor

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1. Introduction

The TRISO-Fueled Salt-Cooled Reactor (TFSCR) is an advanced reactor concept proposed by Pusan National University [1]. This design utilizes TRISO particles as nuclear fuel, molten salt as the coolant, and graphite as the moderator. The reactor core is equipped with circulating pipes through which the molten salt carries TRISO particles. This design enables continuous fuel replacement operations. The molten salt flows slowly through the pipes, expelling the burnt TRISO fuel through an outlet, while fresh fuel enters from an inlet to replace the spent fuel. Figure 1 illustrates the core structure of the TFSCR [1].

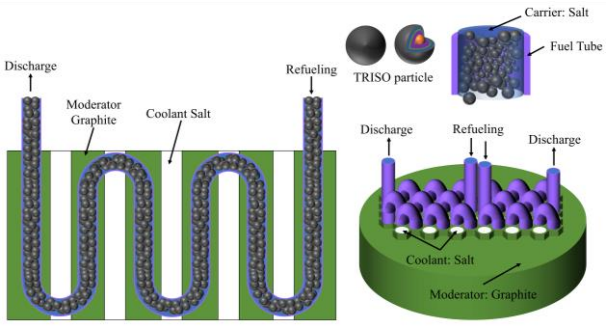

Fig.1. The reactor model diagram of TFSCR.

This design offers significant advantages in terms of safety, economy, and non-proliferation. Compared to traditional fuels, TRISO particles demonstrate greater resistance to neutron radiation, corrosion, oxidation, and high temperatures. This enables the reactor to operate at elevated temperatures, thereby enhancing power generation efficiency. The use of molten salt as a coolant eliminates the necessity for high-pressure operation and water cooling, reducing the likelihood of large-scale leaks and coolant loss accidents, thus improving safety. Furthermore, the absence of water cooling makes this reactor particularly suitable for construction in underground or arid regions.

This paper first introduces the unit-cell model selected based on thermal analysis and lists the basic parameters needed to calculate burnup and power distribution. Additionally, the fuel movement method is explained in detail, and different core inlet position cases are provided. The optimal inlet position is determined based on the power distribution. Finally, the temperature coefficient and void coefficient of the core are calculated to verify the reliability of the design.

The design calculations for TFSCR were performed using the MCS code, a 3D continuous energy Monte Carlo code developed by the Ulsan National Institute of Science and Technology (UNIST) [2]. The ENDF/B-VIII.0 library was utilized during the calculations. In the simulation process, the standard deviation of the k_{eff} value varied between 1.8 and 3.2 pcm. Additionally, the standard deviation of the power values ranged from 1.2% to 4.6%.

2. Calculation Data and Methods

2.1. Core Key Parameters

Figure 2 shows the reactor unit-cell model modified through thermal analysis. The ratio of the number of nuclear fuel channels to coolant channels was changed from the original 2:1 [1] to the new case of 1:2. In the figure, the green parts represent the moderator, made of graphite; the black particles are TRISO fuel with a packing fraction of 50% ; the purple parts are fuel pipes, made of zirconium alloy (Zry-4); the blue parts are the molten salt carrier for the TRISO particles; and the white parts are the core coolant. Both the carrier salt and the coolant salt are the same LiF-BeF_2 mixture. In this calculation, the purity of ^{7}Li is assumed to be 99.995%. The detailed calculation process for each key parameter is elaborated upon in the initial design [1].

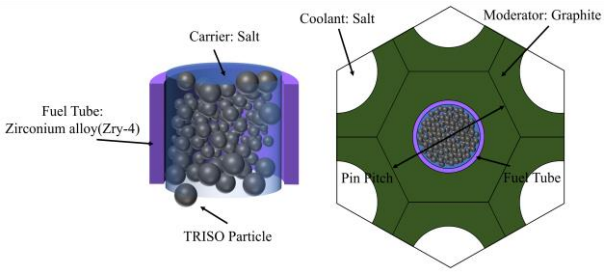

Fig.2. Modified unit-cell model.

Table 1 lists the reactor parameters used for the calculations. Since the main focus of this paper is the calculation of the fuel inlet position within the core, parameters such as the effective radius of the core, average power density, fuel movement speed, and discharge burnup are not considered as primary analysis data.

Table I: Core Design Parameters

Core parameters	Value	unit
Thermal power	100	MWth
Active core height	300	cm
^{235}U enrichment	10	Wt%
Fuel tube inner radius	1.2	cm
Fuel tube thickness	0.05715	cm
TRISO packing fraction	50	%
Coolant hole radius	1.5	cm
Pin pitch	4.5	cm
Total number of fuel channels	558	
Total number of coolant channels	1231	
Total number of control rods	12	
Reflector thickness (Graphite)	85	cm

2.2. Fuel Movement Method

Figure 3 illustrates the movement of fuel within the first two channels between two fuel loading steps. In odd-numbered fuel pipes, the fuel moves downward, while in even-numbered fuel pipes, the fuel moves upward. In actual operation, TRISO fuel particles are transported through the pipes by the carrier molten salt, both moving at the same speed. To simulate this fuel movement process, the fuel is evenly divided into 10 units along the z-axis. During actual operation, new fuel is continuously and gradually introduced into the pipes. In the simulation process, 5 units of new fuel are added to the core at each burnup stage. This fuel movement design helps to avoid errors caused by repeated burning of fuel at the same axial position in each fuel loading step.

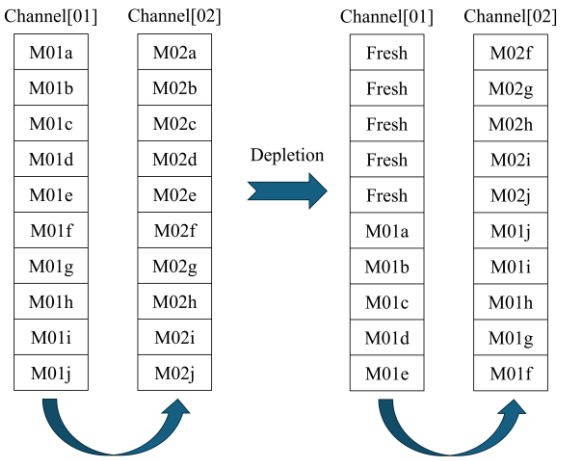

Fig.3. Fuel movement simulation.

2.3. Fuel Inlet Position Cases

Figure 4 shows the 1/6 distribution of the core, illustrating six different fuel inlet position cases. In the figure, position 1 indicates the fuel inlet position, and position 93 indicates the fuel exit position. The green parts represent the moderator, and the white parts represent the coolant. Other colors denote nuclear fuel, with different colors used to distinguish the fuel in different ring positions. The core model has been changed from the initial axial symmetry model [1] to the new rotational symmetry model.

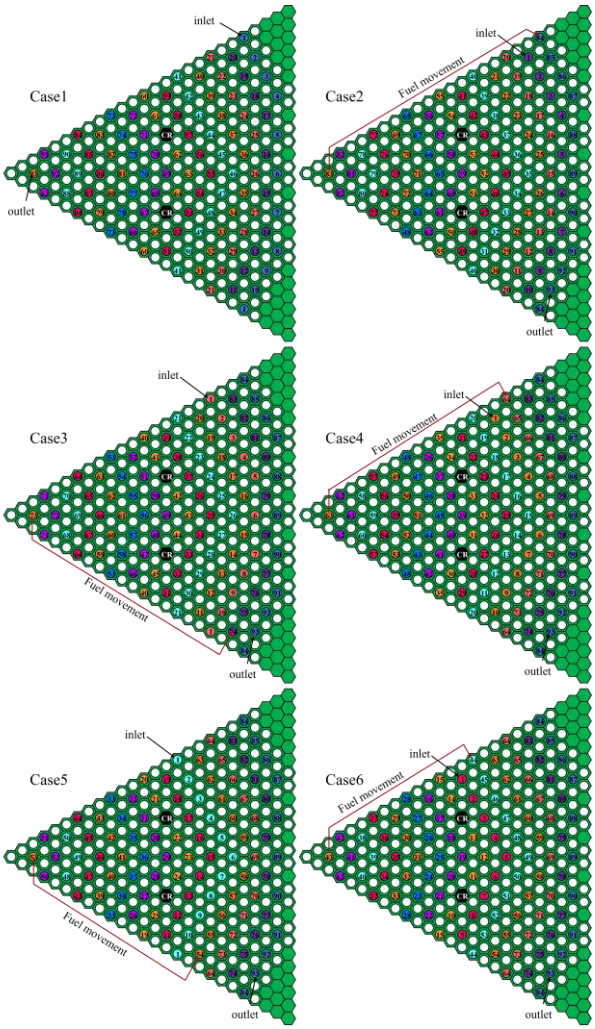

Fig.4. 6 fuel inlet cases.

3. Calculation results

3.1. *Burnup Calculation Results*

The burnup of the core was calculated based on the six different cases shown in Figure 4. The burnup results for different inlet positions were compared, with the enrichment of the initial fuel and the newly added fuel both being 10%. Figure 5 presents the burnup calculation results for different cases. It is evident from the results that as the fuel inlet position gets closer to the core center, the k_{eff} value at equilibrium gradually increases. Except for Case 1, where the k_{eff} value is less

than 1.05 after reaching equilibrium, the k_{eff} values for the other cases range from 1.05 to 1.10. This range is maintained to provide a margin for subsequent core analysis. Therefore, except for Case 1, the results of the other cases meet the expected outcomes.

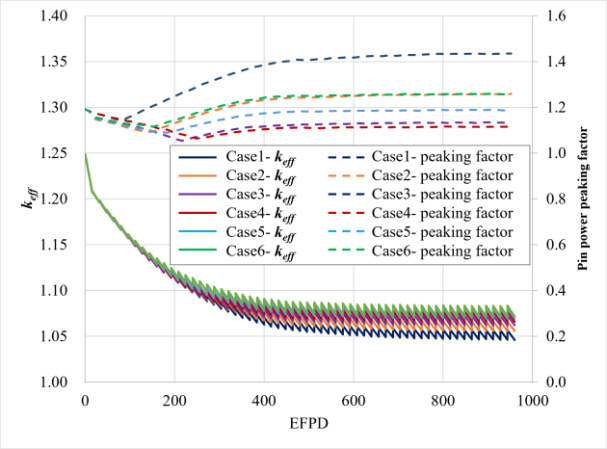

Fig.5. Core burnup calculation.

3.2. Core Power Distribution Results

Figure 6 presents the power distribution calculation results for the six different cases when the k_{eff} value reaches equilibrium. The results include the normalized maximum and minimum power values for different cases. It can be seen from the results that as the fuel inlet position gradually approaches the core center, the maximum power value continuously decreases. In Case 4, the maximum power value reaches its minimum, but as the fuel inlet position moves even closer to the core center, the maximum power value gradually increases again. The power results directly affect the temperature variation, with higher power peaks indicating higher maximum core temperatures, which is undesirable. Therefore, it is necessary to find the situation with the lowest power peak. Evidently, Case 4 better meets the expected outcomes.

3.3. Temperature and void coefficient

Table II shows the core temperature coefficient and void coefficient, which have been calculated in accordance with Case 4, while also considering the volumetric expansion of molten salt as a function of temperature variations. The rate of volume expansion for LiF-BeF_2 with respect to temperature is approximately 2.52×10^{-4} (1/ºC) [3]. Table II demonstrates that the void coefficient is positive in the case of carrier salt alone. However, it should be noted that this condition is not limited to carrier salts or cooling salts, but rather applies to all molten salts. When evaluating the void coefficient of the entire system, an overall negative feedback effect will be observed. Furthermore, these initial calculations will necessitate final adjustments to the design data in order to achieve near-zero or negative void coefficients for carrier salts.

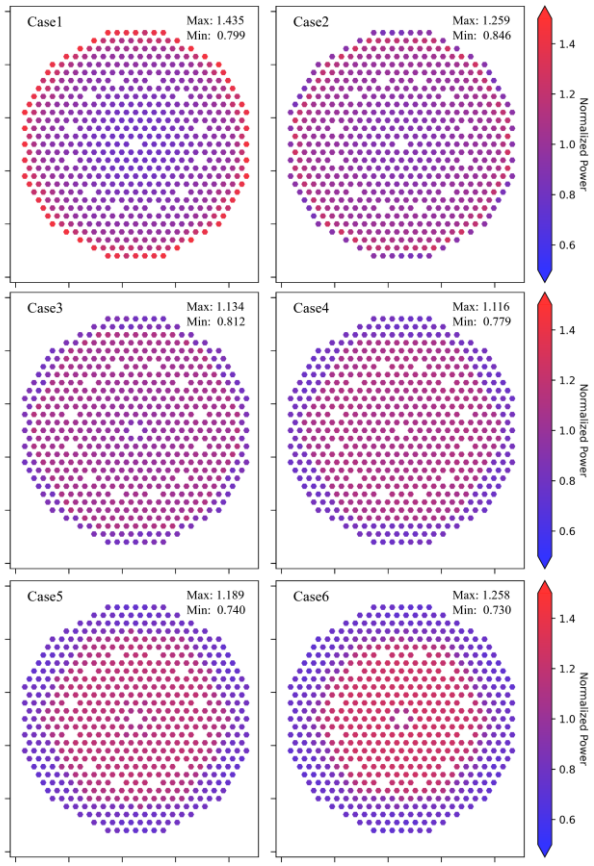

Fig.6. Normalized power distribution at equilibrium state.

Table II: Temperature and void coefficient of the core

Parameters at equilibrium state	value	Unit
Coolant temperature coefficient	-0.03	pcm/K
Fuel temperature coefficient	-3.03	pcm/K
Isothermal temperature coefficient	-5.04	pcm/K
Moderator temperature coefficient	-1.96	pcm/K
Void coefficient of coolant salt	-45.75	pcm/%void
Void coefficient of carrier salt	9.97	pcm/%void
Void coefficient of salt (coolant and carrier)	-41.97	pcm/%void

4. Conclusions

First, based on the initial design case, the ratio of the number of fuel channels to coolant channels in the core was changed after thermal analysis, resulting in a new core model. The new core model was then calculated to determine the fuel inlet position as well as the

temperature coefficient and void coefficient of the core. According to the calculations, Case 4 is the relatively optimal position for fuel inlet, with the smallest power peak ensuring the temperature reliability of the core. The temperature coefficient and void coefficient were also calculated, taking into account the volume expansion of molten salt with temperature changes. Although the molten salt does not evaporate or boil within the operating temperature range, voids gradually appear as the temperature rises. The calculation results indicate that, except for the carrier salt, which has a positive void coefficient, the void coefficients are negative when considering the occurrence of voids in both the coolant molten salt and the carrier molten salt, consistent with the negative feedback mechanism.

Additionally, it is necessary to calculate the initial fuel loading case for the core to ensure that the burnup k_{eff} value quickly reaches equilibrium. Furthermore, a thermal analysis needs to be redone, and core data should be optimized in combination with nuclear performance.

REFERENCES

[1] Xiaoyong Feng, Hyun Chul Lee, A Concept of on-line refueling TRISO-Fueled and Salt-Cooled Reactor, International Journal of Energy Research, Article ID 2548688, Volume 2024.
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