Optimization of TRISO-Fueled and Salt-Cooled Reactor according to maximum temperature

Xiaoyong Feng[a], Hyun Chul Lee[a*]
[a]*School of Mechanical Engineering, Pusan National University, 2, Busandaehak-ro 63beon-gil, Geumjeong-gu. Busan, 46241, Korea*
[*]*Corresponding author: hyunchul.lee@pusan.ac.kr*

1. Introduction

The TRISO-Fueled Salt-Cooled Reactor (TFSCR) is a novel reactor design concept [1]. Its uniqueness lies in the use of molten salt as a coolant while utilizing TRISO particles as the nuclear fuel. This design differentiates itself from traditional solid-fuel cores that use graphite as a medium by innovatively employing molten salt as the medium, facilitating the flow of TRISO particles through the piping. By allowing the fuel to flow slowly through the piping, the reactor enables online refueling. Both the coolant and fuel medium used in this reactor are LiF-BeF_2, and the core uses graphite as a moderator.

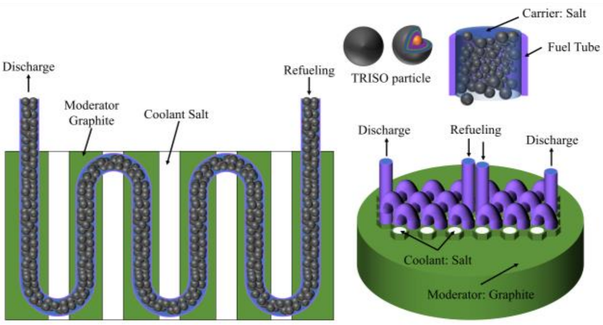


Fig.1. The reactor model diagram of TFSCR.

This design offers significant advantages in terms of safety, economy, and non-proliferation. Compared to traditional fuels, TRISO particles exhibit superior resistance to neutron radiation, corrosion, oxidation, and high temperatures. The use of molten salt as a coolant allows the reactor to operate near atmospheric pressure, with operating temperatures reaching 700-750°C. This not only enhances power generation efficiency but also effectively reduces the risk of large-scale leaks and coolant loss in the event of an accident, further improving safety. Moreover, due to its independence from water cooling, this reactor is highly suitable for construction in underground or arid regions.

This study utilizes the Gamma+ 2.1 code for simulation calculations. The maximum temperature of TRISO particles within the reactor core is calculated when the core reaches a stable state and reactivity balance. By adjusting the three controllable variables: fuel radius, coolant mass flow rate, and average fuel power density; the final core parameters are determined. Due to the time-consuming nature of full-core calculations, a simplified model is initially used to identify a suitable core configuration. Subsequently, based on the parameters of the selected model, the maximum particle temperature across the full core is calculated, leading to the determination of the new core parameters.

2. Calculation conditions

2.1. Temperature and power conditions

First, based on the physical properties of LiF-BeF_2 (66-34), its melting point at standard atmospheric pressure is 460°C, and its boiling point is 1400°C. The thermal conductivity of molten salt increases from 1.28 to 1.32 W/m·k in the temperature range of 800 k < T < 1200 k [2]. Referring to other core designs that use molten salt as a coolant, the outlet temperature of the TFSCR core is tentatively set at 750°C. Since the molten salt-cooled core does not require high-pressure operating conditions, the outlet pressures of the coolant are set to 0.1 MPa.

In the calculations, it is assumed that the thermal power of the core is 100 MWth. A burnup calculation was performed for the entire core, and since the core has an online refueling capability, it will eventually reach an equilibrium state. In this state, the power distribution of the core was obtained and used in the temperature calculations. Figure 2 shows the distribution of the power factor in the axial and radial directions. In the full-core calculation, both radial and axial power distributions are considered. However, in the simplified core calculation, due to the small amount of fuel in the core, only the axial power distribution is considered.

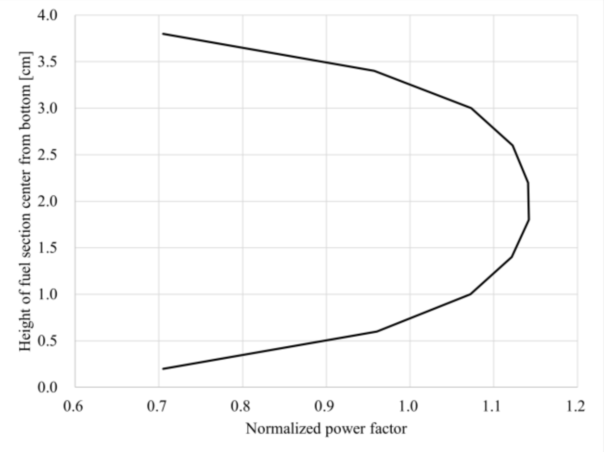


Fig. 2. (a) Axial power distribution

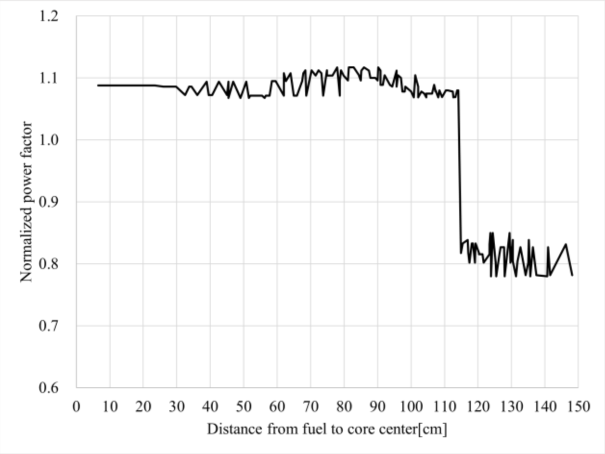


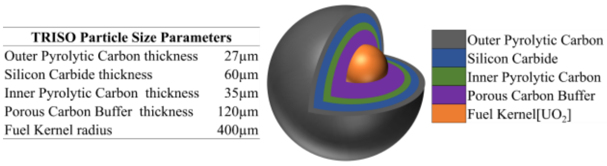
Fig. 2. (b) Radial power distribution
Fig. 2. TFTR reactor model figure.

2.2. Core size parameters

Special attention should be given to ensuring the consistency of nuclear properties in temperature calculations. Therefore, adjustments to fuel dimensions must be accompanied by corresponding changes in coolant size and core dimensions. Table I provides essential data for the core and the range of variations necessary for calculation. By maintaining constant area ratios of the various materials within the core when modifying fuel dimensions, the consistency of nuclear properties can be upheld. And there is no heat exchange between the core and the external environment during the calculation process.

Table I: Core calculation parameters

Core parameters	Value	unit
Active core height	400	cm
TRISO packing fraction	50	%
Fuel tube inner radius	0.7-1.3	cm
Average fuel power density	30-70	W/gU
Coolant mass flow rate	50-400	kg/s
Fuel zone area: coolant zone area	0.32	-
Fuel zone area: unit-cell zone area	0.086	-



TRISO Particle Size Parameters	
Outer Pyrolytic Carbon thickness	27μm
Silicon Carbide thickness	60μm
Inner Pyrolytic Carbon thickness	35μm
Porous Carbon Buffer thickness	120μm
Fuel Kernel radius	400μm

Figure 3. Schematic diagram of the TRISO particle structure.

Figure 3 illustrates the basic dimensional parameters of the TRISO particles and their cladding materials [1]. Assuming that the TRISO particles are affected by the SiC layer, there is a maximum thermal conductivity of 18.5 W/m·k [3]. This design can maintain the integrity of nuclear fuel at temperatures up to 1600°C, avoiding nuclear leakage accidents. However, when the temperature exceeds 1250°C for an extended period, the SiC cladding material may become thinner due to the effects of nuclear radiation [4]. Therefore, to ensure the safe operation of the core, the maximum operating temperature must be kept below 1250°C.

2.3. Computational Model

Figure 4 presents three core design options. The entire calculation process was conducted using the Gamma+ code simulation program. Since the unit cells cannot be directly modeled and calculating the entire core would consume a significant amount of computation time, the calculations were first performed on a simplified model to quickly identify the target values. In the simulations using the simplified model, the required power values and mass flow rates are calculated based on the average power density, number of fuel elements, and size data, ensuring consistency in the calculation conditions.

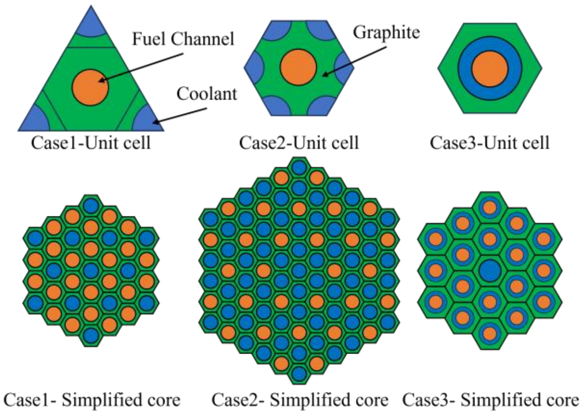


Fig. 4. Three simplified core models.

3. Calculation results

3.1. Simplified core model

Figure 5 shows the temperature variation when the fuel radius, average fuel power density, and coolant mass flow rate are considered as single variables.

First, Figure 5(a) illustrates the analysis of the analysis of the changes in fuel radius, under the conditions of constant average fuel power density and mass flow rate, the maximum temperature of the particles in the reactor core gradually increases with the increase in fuel radius. Particularly in Case 1, even with a fuel radius of only 0.7 cm, the maximum temperature of the particles exceeds 1250°C, which clearly does not meet safety standards. In contrast, the temperature trends in Case 2 and Case 3 are relatively consistent as the radius changes, but temperature differences begin to emerge as the fuel radius further increases. This phenomenon can be attributed to the increase in graphite volume due to the increase in fuel radius under the condition of the same material ratio, which, coupled with differences in the models, results in variations in the maximum temperature. Considering that the maximum temperature must be controlled below 1250°C, with some margin left for further analysis, the fuel radius is tentatively set at 0.8 cm.

Next, Figure 5(b) illustrates the impact of varying average fuel power density on the maximum particle temperature in the reactor core, under the conditions of a fuel radius of 0.8 cm and a mass flow rate of 300 kg/s. Additionally, a new curve has been introduced to depict the changes in the effective core radius as a function of the average fuel power density. The changes in effective core radius for Case 2 and Case 3 are generally consistent. According to the initial design requirements, the effective core radius needs to be controlled at approximately 1.5 meters to ensure the reactor core can operate under a wider range of conditions. The results indicate that when the power density approaches 45 W/gU, the effective core radius is close to 1.5 meters, and the maximum particle temperature remains below 1250°C. Therefore, the average fuel power density is set at 45 W/gU.

Finally, based on the determined fuel radius of 0.8 cm and an average fuel power density of 45 W/gU, the coolant flow rate was established. The results shown in Figure 5(c) indicate that the maximum core particle temperature is inversely proportional to the coolant mass flow rate. When the flow rate exceeds 300 kg/s, the temperature change becomes less pronounced. Consequently, the final parameters were set to a fuel radius of 0.8 cm, an average fuel power density of 45 W/gU, and a mass flow rate of 300 kg/s. Overall, the maximum particle temperature curves for Case 2 and Case 3 are similar; however, due to the greater complexity in assembly and process requirements in Case 3, Case 2 was selected.

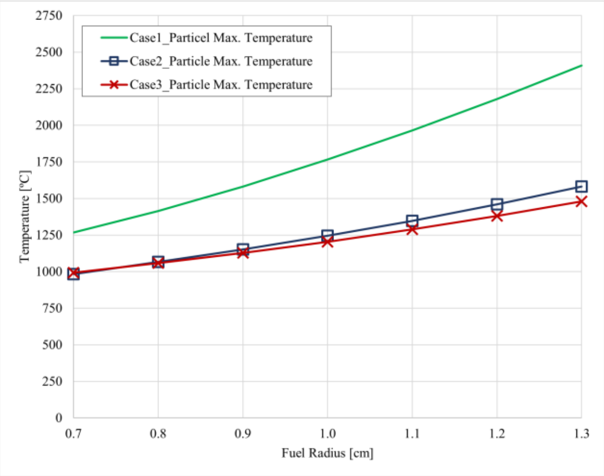


Fig.5. (a) Variable: fuel radius

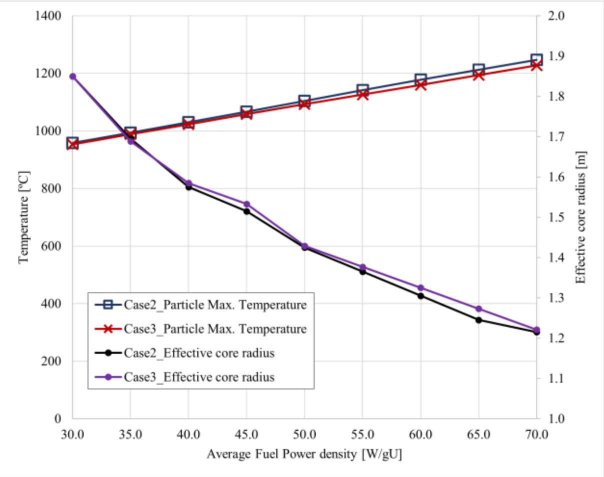


Fig.5. (b) Variable: average fuel power density

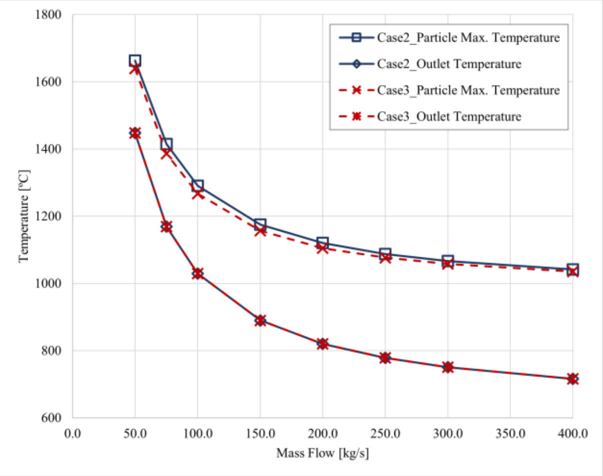


Fig.5. (c) Variable: Mass Flow

Fig. 5. Simplified model calculation results.

3.2. Full core model

According to the data calculated using the simplified model, which includes a fuel height of 4 meters, a fuel radius of 0.8 cm, and an average fuel power density of 45 W/gU, the total amount of fuel required to establish the new core size can be determined, given the core's thermal power is set at 100 MWth. Based on these updated values, the optimized core parameters and corresponding temperature results are listed in Table II. In the new core configuration, the average fuel power density reaches 45.38 W/gU while maintaining an effective core radius of 1.49 meters. The maximum particle temperature in the core is 1114°C, which is below the operating limit of 1250°C. Additionally, an inlet temperature of 611°C is set to achieve an outlet temperature of 750°C. The calculation results indicate that both the temperature and size requirements meet the basic design specifications, with an allowance for further analysis in subsequent calculations.

Table II: Core Design Parameters

Core parameters	Value	unit
Thermal power	100	MWth
Average power density	45.38	W/gU
Active core height	400	cm
Fuel tube inner radius	0.8	cm
TRISO packing fraction	50	%
Coolant hole radius	1.0	cm
Coolant mass flow rate	300	kg/s
Pin pitch	3.0	cm
Core effective radius	1.49	m
Total number of fuel channels	2448	#
Total number of coolant channels	5101	#
Particle max. temp. in the core	1114	℃
Particle avg. temp. in the core	924	℃
Inlet temperature	611	℃
Outlet temperature	750	℃

4. Conclusion

This paper primarily uses power distribution information to adjust four parameters: fuel radius, height, average power density, and mass flow. By combining these with temperature and dimensional boundary conditions, the core data close to the target values were identified using a simplified core model. Finally, through full-core calculations, the final parameters and temperatures were determined. The final confirmed parameters are a fuel radius of 0.8 cm, a fuel height of 4 m, an average fuel power density of 45.39 W/gU, and a mass flow rate of 300 kg/s. The calculated maximum temperature of the particles in the core is 1114 ℃, which meets the limit operating temperature requirements. The effective radius of the core is controlled at 1.49m, which also meets the design requirements.

Subsequently, the calculation of pipe radius and its impact on solid-liquid flow must be conducted to assess the suitability of a 0.8 cm radius for meeting flow requirements. Following this, adjustments to core fuel distribution and recalculation of core temperature distribution are necessary. Finally, an evaluation of temperature variations within the core from initial operation to steady-state operation is essential, in order to determine whether the core design meets safety temperature standards in case of an accident.

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