Core Thermal-Hydraulic Design of a Sodium Cooled Fast Reactor for the U/TRU Fuel Modification

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1. Introduction

The Korea Atomic energy Research Institute (KAERI) has been developing an advanced SFR design technology with the final goal of constructing a demonstration plant by 2028. The main objective of the SFR demonstration plant is to verify TRU metal fuel performance, large-scale reactor operation, and transmutation ability of high-level wastes. However, in the early stage, the SFR will run on low enriched uranium fuel due to a lack of TRU fuel qualification. After sequential evaluations of the fuel performance, the fissile fuel material will transform from uranium to LTRU (LWR-TRU), and then finally to MTRU (Mixed TRU of LTRU and recycled TRU) [1]. At the same time, the core configurations will be modified to meet the nuclear design requirements. Therefore, there is also a strong need to ensure a proper cooling capability during modifications of the entire core.

In this work, the core thermal-hydraulic design for U/TRU fuel modification is performed using the SLTHEN (Steady-State LMR Thermal-Hydraulic Analysis Code Based on ENERGY Model) code [2]. As the power distribution in a reactor core is not uniform, it requires a suitable flow allocation to each assembly. There are two ways of allocating the flow rates depending on the orifice positions. The inner orificing scheme locates orifice plates in the lower part of the fuel assembly. Therefore, it is possible that the flow distribution is redesigned according to the core configurations. On the other hand, the outer orificing scheme fixes orifice plates within the receptacle body throughout the entire plant lifetime. This has the advantage lower of fabrication costs and operating errors but included insufficient design flexibility. This paper provides comparative studies of orifice position for the core thermal-hydraulic design.

2. Core Configurations

Figure 1 shows the operating strategy of the SFR demonstration plant. As the reactor undergoes fuel type changes, core layouts are also required to be modified to ensure several design criteria. However, it is difficult to deal with changes in hardware specifications and BOP (balance-of-plant) conditions during its operation. Therefore, the core layout modifications such as geometric dimension need to be minimized in order to satisfy the nuclear design guidelines.

The representative core layouts are displayed in Fig. 2. It completely eliminates the blanket assemblies to enhance the proliferation resistance. The fuel region reveals identical structure specifications, but consists of two different enrichment zones to create a more flatted power distribution over the core. The MTRU core contains reflector assemblies in the central part to decrease the sodium void reactivity.

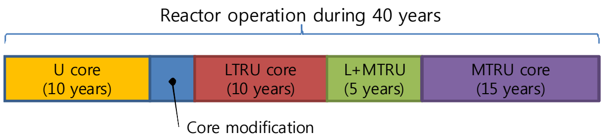
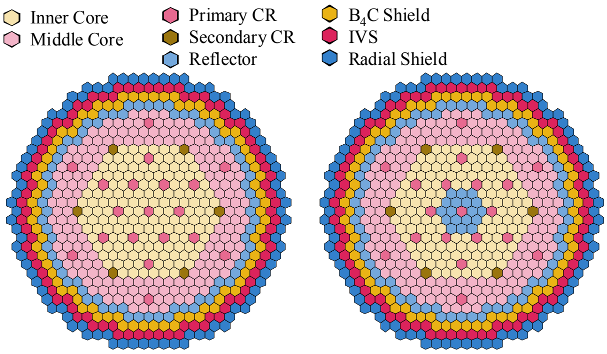


Fig. 1. Operating strategy for the SFR demonstration plant



(a) U/LTRU core configuration (b) MTRU core configuration

Fig. 2. SFR demonstration plant core layouts

3. Thermal-Hydraulic Design

In carrying out the core thermal-hydraulic design, several design criteria need to to be met to assure proper performance and safety for the core and upper structure where design limits are highly related to temperature distribution in fuel, cladding, and sodium under various operating conditions. The present analysis is conducted based on the following design criteria [3].

1. The maximum power during the equilibrium cycle must be utilized to calculate the temperature distribution of each assembly.
2. For the uranium fuel type, the maximum cladding mid-wall temperature must be lower than the creep limit temperature (620 ^{o}C) including uncertainties.
3. For the TRU fuel type, the maximum inner wall temperature must be lower than the eutectic limit temperature (650 ^{o}C) including uncertainties.

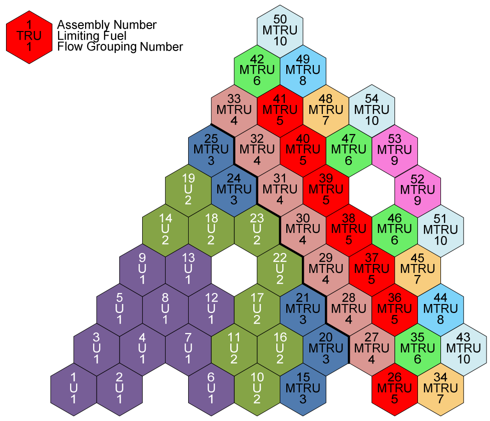


Fig. 3. Core configuration of flow allocation and limiting factor for the outer orificing scheme

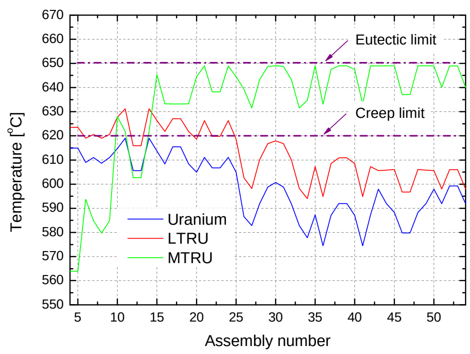


Fig. 4. Maximum temperature variation with 2σ uncertainty as a function of each assembly number

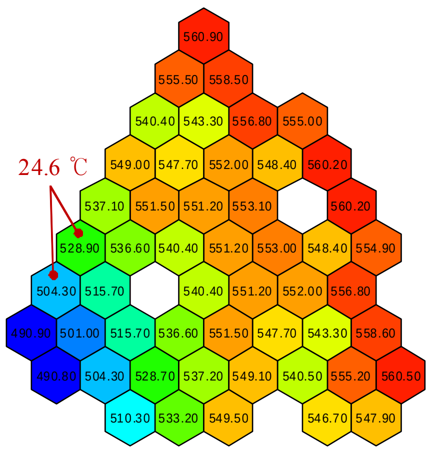


Fig. 5. Outlet temperature distribution for the MTRU core

4. The maximum difference of outlet temperatures between neighboring assemblies within the same flow group must be minimized (generally 7-8%).

5. The number of flow zones must be minimized for practical reasons.

Based on the above design criteria, the coolant flow allocation to the assemblies and temperature distributions were calculated using the orificing and heat transfer codes, respectively. In particular, as the outer orificing scheme should operate with both uranium and TRU fuel, the detailed flow grouping is required to endure simultaneously the creep failure and eutectic melting. Considering the two thermal criteria, the resulting flow allocation using the outer orificing scheme was conducted as shown in Fig. 3. For the core interior, since the U core revealed more thermal power, the limiting design factor was the cladding mid-wall creep. In the outer region, the eutectic melting in the cladding inner wall was the dominant failure criteria.

The remaining flow rates for the non-fuel assemblies were about 11.06-16.29 % and 5.6 % for the inner and outer orificing schemes, respectively. This means that the inner orifice offers a greater thermal margin compared to the outer scheme. The maximum temperature variation within each assembly considering 2σ uncertainty was estimated as shown in Fig. 4. The entire core region was kept below the limiting temperatures. The maximum temperature differences exiting in adjacent assemblies for the inner and outer schemes were 17.1 °C and 24.6 °C, respectively, which demonstrate the superior structural integrity of the inner orificing scheme. This is highly related to the thermal striping failure of the upper internal structure. The outlet temperature distribution of the MTRU core is displayed in Fig. 5, and indicates the neighboring assemblies having the most temperature difference.

It is obvious that the inner orificing scheme is superior in performance efficiency and safety margin compared to the outer orificing scheme. However, the inner orifice should be fabricated for every assembly during the entire plant operation. Moreover, a single mismatch of fuel assemblies on the inlet plenum may lead to severe accidents over the entire core.

4. Conclusions

This paper focuses on an SFR core thermal-hydraulic design for U/TRU fuel modification by comparing the inner and outer orificing schemes. The results demonstrate that the inner orifice provides superior performance over the outer orifice. However, considering the orifice fabrication cost for each assembly and the operating errors arisen for the refueling process, a profound investigation should be preceded before determining the orifice scheme.

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