Neutronic Analysis on Conceptual Design of Dual-Fluid Fusion-Fission Hybrid System for Waste Transmutation

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1. Introduction

Fusion–Fission Hybrid System (FFHS) is one of the promising options for waste transmutation (WT) of spent nuclear fuel (SNF). Various studies for FFHS has been conducted by many organizations including Kyung Hee University (KHU) design team [1-6]. Recently, molten-salt reactor (MSR) type-FFHS using liquid fuel has attracted attention as a new concept [7-9]. The use of liquid molten-salt (MS) plays dual role as fuel and coolant providing significant benefit; high compatibility with complex blanket geometry. There is no need to consider integrity of the fuel structure such as cladding in high temperature and high neutron irradiation environment by using liquid fuel. Additionally, the most demanding benefit is the capability of online-refueling. Fission products (FP) are continuously removed through online-refueling during operation period, as a result required fusion power is reduced in a FFHS due to reduction of reactivity swing. However, using the MS is not suitable for transmutation of TRU nuclides due to side effect of neutron spectrum softening [5].

Therefore, in this paper, FFHS with dual fluid (DF) concept is proposed. DF concept is combining MSR with fast reactor. The MS as a fuel flows in the pipe and PbBi or Na coolant which can maintain fast spectrum flows out of the pipe [10-11]. In other words, advantages of MSR as already mentioned are maintained, the FFHS becomes more suitable for WT by using DF concept. In addition, because fuel and coolant are separated, high power density is acceptable compared to conventional MSR.

In this paper, preliminary nuclear design of FFHS with dual fluid concept for WT was conducted. Transmutation performance was evaluated to the various design options; strategy of online-refueling, refueling cycle time and blanket geometry.

2. Calculation Model

The concept of the FFHS with DF was designed based on Hyb-WT (reference model of the previous study). Configuration and design parameters are represented in Fig. 1 and Table I. The MS fuel was replaced from Pu (in NaCl + $PuCl_3$) to transuranic (TRU). The TRU in the MS have the same compositions as that reprocessed from a 3,000 MW_{th} pressurized light water reactor with depleted burnup rate of 55,000 MWD/ton after 10 years of cooling. The MS flow into the numerous pipes and PbBi coolant cooling outside of the pipes as shown in molten-salt fuel zone of Fig. 1. It is possible that long cycle operation through online-refueling. However, amount of the produced tritium also increased to cover the long cycle operation. Therefore, ^{6}Li was enriched to 90 w/o and pebbles of Be were added in the tritium breeding zone. There are many design options for the tritium breeding zone, however this paper only focused on the DF concept as preliminary nuclear design.

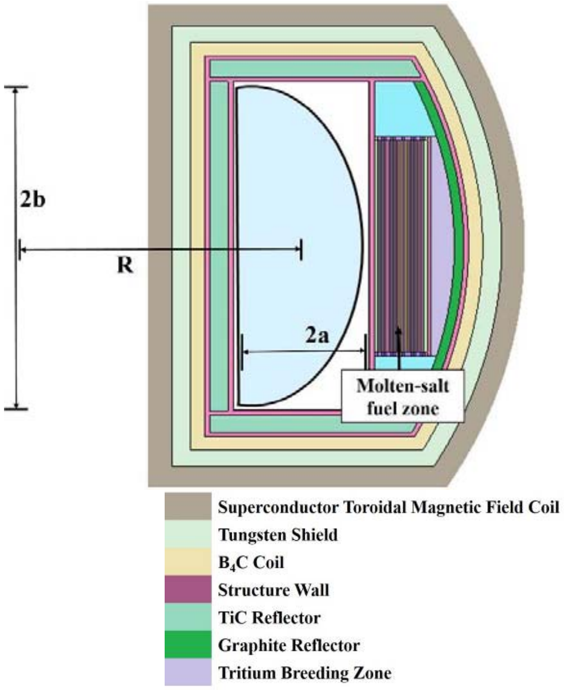

Fig. 1. Configuration of fusion-fission hybrid system with dual fluid concept for waste transmutation.

Table I: Design Parameters of fusion-fission hybrid system with dual fluid concept for waste transmutation.

Major Radius (R)	3 m
Minor Radius (a)	0.7 m
b	1.26 m
Total Operation Period	2400 day
Max. Fusion Power	300 MW
Thermal Fission Power	3000 MW
Molten-Salt Fuel	NaCl + $TRUCl_3$ (66/34 mole %)
Fuel Tube Inner Radius	0.725 cm
Fuel Tube Outer Radius	0.825 cm
SiC Coating Thickness	0.1 cm
Fuel Pin Pitch	1.961 cm

Coolant	PbBi (44.5/ 55.5 w/o)
Tritium Breeder	Li_4SiO_4 + Be (60/20 %, pebble) ^{6}Li is enriched to 90 w/o

3. Calculation Results

All neutronic calculations were performed by SERPENT2.1.29 with ENDF/b-VII.0 neutron cross section library instead of MCNP codes. It is possible in SERPENT to simulate online-refueling using mass flow option [12].

3.1 Check of online-refueling strategies

In this section, effect of online-refueling strategy was checked in order to maximize the benefit of the DF concept. Comparison models are three. The first one is the option of once-through cycle without refueling until 2,400 days. It is named as w/o refueling. The second is the refueling option with 1,200 day cycle. In this option, 2/3 of the MS within the fuel zone was removed and then the fresh MS was filled up to initial mass of the MS. The third one is the continuous refueling option with the rate of 35 L/day [13]. In this option, the amount of soluble FP was replaced the fresh MS under the continuous removal of MS at 35 L/day. In addition, in this option, the MS within the fuel zone was refueled at 1,200 day like the second option.

There are no differences on flux in the MS fuel zone at the beginning of the cycle (BOC) as shown in Fig 2. However, flux with cycle refueling is high by refueling, flux with 35 L/day refueling is hardening by continuous removing of the FP compared to w/o refueling model at 1200 day. There is no big difference on flux between w/o refueling and with cycle refueling, while flux with 35 L/day refueling is high in the tritium breeding zone due to high flux in the MS fuel zone. The k_{eff} level with cycle refueling is changed after refueling time at 1,200 day compared to w/o refueling as shown in Fig 3. However, the k_{eff} level with 35 L/day refueling are significantly reduced after the BOC compared to w/o refueling, it is beneficial to FFHS. Tritium Breeding Ratio (TBR) is also increased by reduction of reactivity swing. Transmutation performances of SL TRU and minor actinides (MA) in the w/o refueling are degraded compared to with refueling models as listed Table in Ⅱ. This is because capture reaction of TRU nuclides are increased due to FP within the MS fuel zone. Transmutation of LL TRU with 35 L/day refueling model, especially MA is reduced compared to with cycle refueling model. Because plutonium nuclides that have high neutron cross section are continuously refilled, reaction rates with MA that has low neutron cross section are relatively reduced. In addition, MA are produced from plutonium. However, low reactivity swing with 35 L/day refueling model is significantly beneficial to the system, although transmutation performance with MA are degraded.

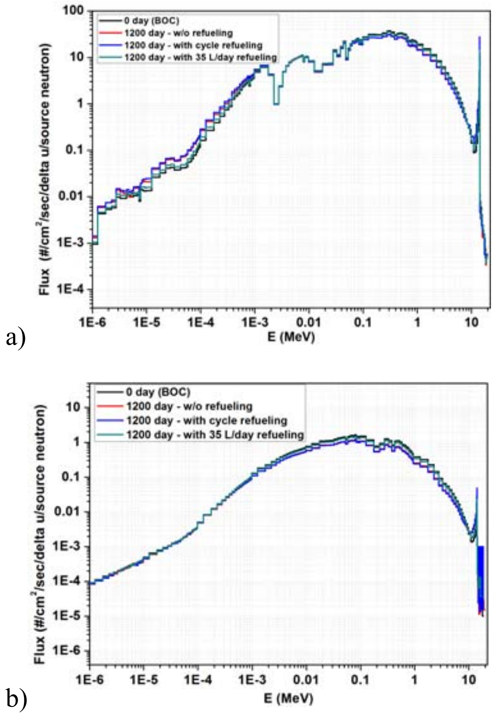

Fig. 2. Neutron flux over total volume for online-refueling strategies : a) in the molten-salt fuel zone, b) in the tritium breeding zone.

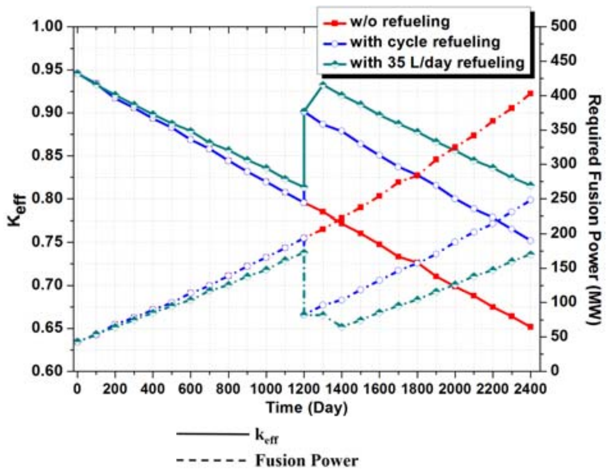

Fig. 3. k_{eff} and required fusion with time function for online-refueling strategies.

Table II: Tritium breeding ratio (TBR) and mass variation of TRU nuclides for online-refueling strategies.

Options	w/o refueling	cycle refueling	35 L/day refueling
TBR	0.879	1.24	1.58
TRU (kg / fpy)	-1040.94	-1056.38	-1002.99
LL TRU (kg / fpy)	-1000.83	-1003.06	-952.19
SL TRU (kg / fpy)	-48.63	-66.42	-63.90
Pu (kg / fpy)	-902.04	-929.88	-923.06
MA (kg / fpy)	-33.07	-126.49	-79.93

* LL TRU (Long-lived TRU) : half-life > 100 years

* SL TRU (Short-lived TRU) : 10 years < half-life ≤ 100 years

3.2 Check of online-refueling cycle effect

In this chapter, effect of refueling cycle was checked to optimization of transmutation with low required fusion power. Comparison models are three: 400 day, 600 day and 1200 day (35 L/day model). Reactivity swing is in inverse proportion to length of the refuel cycle. Especially, reactivity swing with 400 day reaches equilibrium state during operation period. Since the FP that interrupt the fission reaction are removed frequently. However, transmutation performance shows some different results. The amount of the fresh MS is increased as the number of refueling increases. Most of the fresh MS is plutonium nuclides, as a results, most of reaction with neutrons are come from plutonium. Therefore, transmutation performance with plutonium nuclides is increased while with MA is degraded as the refuel cycle reduced. Moreover, transmutation of SL TRU with 400 day model comes from ^{241}Pu.

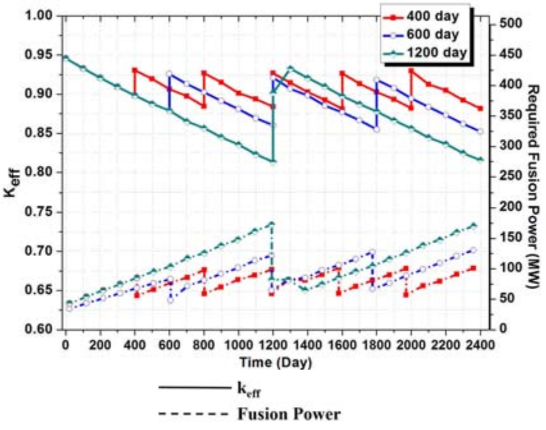

Fig. 4. k_{eff} and required fusion with time function for online-refueling cycles.

Table III: Tritium breeding ratio (TBR) and mass variation of TRU nuclides for online-refueling cycles.

Refuel Cycle	400 day	600 day	1200 day
TBR	2.07	1.81	1.58
TRU (kg / fpy)	-1015.98	-1001.35	-1002.99
LL TRU (kg / fpy)	-943.59	-935.20	-952.19
SL TRU (kg / fpy)	-98.41	-86.41	-63.90
Pu (kg / fpy)	-957.32	-934.07	-923.06
MA (kg / fpy)	-58.68	-67.28	-79.93

3.3 Check of Blanket Geometry Effect

Change of blanket geometry impacts on transmutation performance considerably since neutron spectrum is sensitive to the boundary. Therefore, effect of blanket geometry was check on aspect ratio (R/a). Comparison model has same 'a' (70 cm) and then aspect ratio is reduced as soon as possible under the design constraint as listed in Table IV. The online-refueling cycle is 1200 day to high MA transmutation.

Table IV: Design Parameters of low aspect ratio (2.5) dual fluid fusion-fission hybrid system for waste transmutation.

Major Radius (R)	1.75 m
Minor Radius (a)	0.7 m
b	1.26 m
Total Operation Period	2400 day
Maximum Fusion Power	300 MW
Thermal Fission Power	3000 MW
Molten-Salt Fuel	NaCl + $TRUCl_3$ (66/34 mole %)
Fuel Tube Inner Radius	0.725 cm
Fuel Tube Outer Radius	0.825 cm
SiC Coating Thickness	0.1 cm
Fuel Pin Pitch	2.02 cm
Coolant	PbBi (44.5/ 55.5 w/o)
Tritium Breeder	Li_4SiO_4 + Be (60/20 %, pebble) ^{6}Li is enriched to 90 w/o

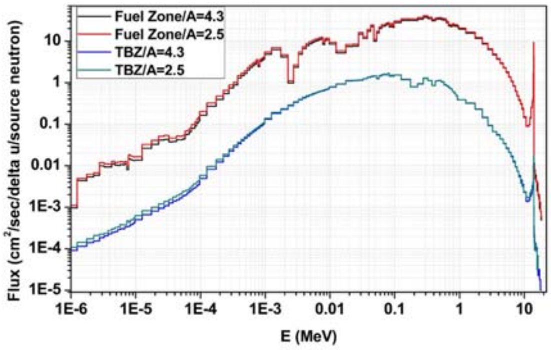

Fig. 5. Neutron flux over total volume in the molten-salt fuel zone for aspect ratio.

Table V: Tritium breeding ratio (TBR) and mass variation of TRU nuclides for aspect ratio.

Aspect Ratio	4.3 (Reference)	2.5 (low aspect ratio)
TBR	1.58	1.08
TRU (kg / fpy)	-1002.99	-986.53
LL TRU (kg / fpy)	-952.19	-962.92
SL TRU (kg / fpy)	-63.90	-36.72
Pu (kg / fpy)	-923.06	-894.74
MA (kg / fpy)	-79.93	-91.79

The blanket geometry is closed to spherical as the aspect ratio reduced. In addition, in this section, low aspect model has more compact geometry compared to reference design because 'R' was reduced. As a result, the flux with low aspect ratio is increased compared to reference model (1200 day model in Ch 3.2). Since the impact of increased flux is remarkable in the fast energy region, transmutation performance with MA is improved rather than fissile materials as listed in Table Ⅴ. Transmutation with SL TRU and plutonium nuclides are degraded. Since transmutation with MA are considerably improved, it is more suitable for FFHS for WT. However, reactivity swing is increased by maintaining the same fission power in spite of reduced blanket size.

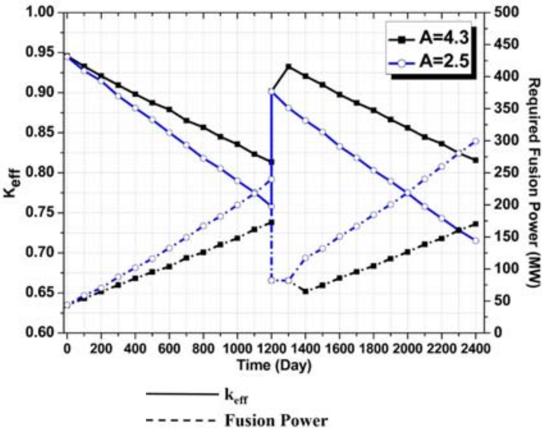

Fig. 6. k_{eff} and required fusion with time function for aspect ratio.

4. Conclusions

In this paper, transmutation performance was checked on various design options as a preliminary nuclear design of FFHS with DF concept. By using DF concept, reactivity swing is significantly reduced through online-refueling. And then it is possible that long cycle operation with low fusion power. Transmutation performance with MA is improved as online-refueling cycle length is increased. Also, blanket geometry is more suitable for transmutation with MA as the aspect ratio is smaller and more compact size due to flux increased.

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