Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang, Korea, October 30-31, 2014

Neutronic Analysis on Coolant Options in a Hybrid Reactor System for High Level Waste Transmutation

Seong-Hee HONG and Myung Hyun KIM*
Department of Nuclear Engineering, Kyung Hee University, 446-701, Rep. of Korea
mhkim@khu.ac.kr

1. Introduction

At present, nuclear industry is facing one of the biggest obstacles which how to dispose high level radioactive waste (HLW) from current power plants. Therefore, investigation of nuclear waste incineration became a major research issue. Some candidates burning HLW in fast reactors or accelerator driven subcritical reactor (ADSR) have been studied worldwide with technical feasibility shown in many literatures.

A fusion-fission hybrid reactor (FFHR) which is a combination of plasma fusion tokamak as a fast neutron source and a fission reactor as of fusion blanket is another potential candidate. In FFHR, fusion plasma machine can supply high neutron-rich and energetic 14.1MeV (D, T) neutrons compared to other options. Therefore it has better capability in HLW incineration. While, it has lower requirements compared to pure fusion. Much smaller-sized tokamak can be achievable in a near term because it needs relatively low plasma condition. FFHR has also higher safety potential than fast reactors just as ADSR because it is subcritical reactor system.

FFHR proposed upto this time has many design concepts depending on the design purpose. FFHR may also satisfy many design requirement such as energy multiplication, tritium production, radiation shielding for magnets, fissile breeding for self-sustainability also waste transmutation. Many types of fuel compositions and coolant options have been studied. Effect of choices for fuel and coolant was studied for the transmutation purpose FFHR by our team [1]. In this study LiPb coolant was better than pure Li coolant both for neutron multiplication and tritium breeding. However, performance of waste transmutation was reduced with increased neutron absorption at coolant caused by tritium breeding. Also, LiPb as metal coolant has a problem of massive MHD pressure drop in coolant channels. Therefore, in a previous study, waste transmutation performance was evaluated with light water coolant option which may be a realistic choice [2].

In this study, a neutronic analysis was done for the various coolant options with a detailed computation.

2. Characteristics of Various Coolants

2.1 Water Coolants

Water coolants such as H_2O and D_2O have more operational database because they have been used widely for nuclear reactors. One of the driving attraction points is escape from MHD pressure drop problem.

On the other hand, if they are used as coolant in FFHR operating at high temperature range, departure from nucleate boiling (DNB) problem may occur because of low boiling temperature and vapor pressure of water. Therefore pressurization should be applied to coolant system which brings high burden to system; additional pressure to the first wall and structure wall under the high DPA condition. One of solutions suggested is to use the pressure tubes inside of first wall and second wall [3], [4].

2.2 Metal Coolants

Metal coolants such as Na and LBE are used in both fast reactors and ADSR. Because they have high boiling temperature, they can be used at the ambient pressure. Coolant LBE is known to be better than Na in neuron economy but worse in cooling capability.

LBE coolant produces Po-210 from neutron activation from Bi. On the other hand Na coolant reacts actively with air and water. MHD pressure drop can be partly mitigated by coating on the coolant channel surface but still has some problems not solved yet.

2.3 Molten Salt Coolants

Molten salt coolants such as FLiBe, FNaBe have low reactivity with air and water. Also, it is possible to operate at very low pressure. They also have very low MHD pressure drop expected, almost negligible because of its high electrical resistivity of about 10^{-2} Ω m [5].

On the other hand, they have low compatibility with structural materials. Because they have some possibility that TF can be formed which is very corrosive to most structural materials. However this problem can be neutralized or resolved by using Be ($Be + 2TF = BeF_2 + T_2$) and MoF_6 ($MoF_6 + 3T_2 = 6TF + Mo$).

3. Methods and Results

3.1 Blanket Design

Hybrid reactor for waste transmutation (Hyb-WT) using LiPb coolant was designed to incinerate the high level waste of transuranic isotopes (TRU) and fission products (FP) from PWR spent fuel [6]. The compositions of TRU nuclides are adopted from PWR spent fuel. And the compositions of FP nuclides are Tc-99, I-129 and Cs-135 which have high radioactivity and long half life. The design concept of this previous study is now a reference model for the test of different coolants. Fig. 1 shows geometrical design of Hyb-WT modeled in MCNPX and Table I shows data for material specification of Hyb-WT [6], [7]. MCNPX 2.6.0 with ENDF/B-VII.0 neutron cross section library is used for computational analysis.

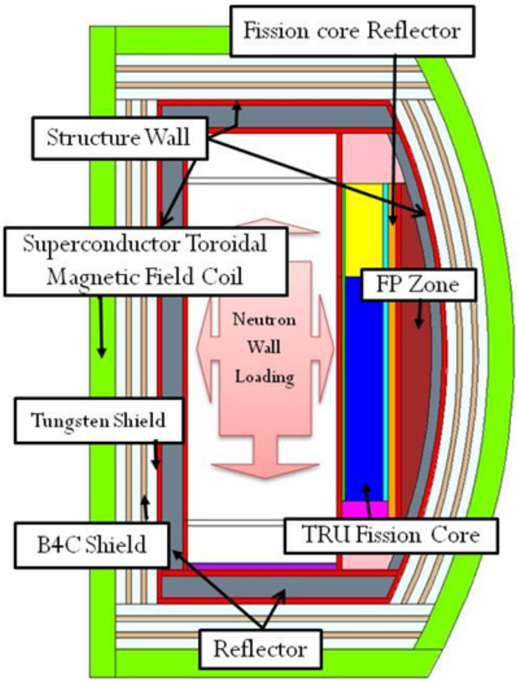

Fig. 1. Geometrical Configuration of Hyb-WT

Table I: Material Specification of Hyb-WT

Region	Thicknes s (cm)	Composition (%)
TRU Fission Core	45	TRU: 4.25(Np237, Am241, Am243, Cm244, Pu); Zr: 8.42; Coolant: 54.53; SiC: 4.91; Clad ODS steel: 11.05; Na-Bond: 16.84
Structure Wall	5	ODS Steel(MA957):70; He-gas:30
FP Zone	30	CsI (129I: 0.42; 135Cs: 1.76); 99Tc: 0.82; SiC: 2.5; C: 78; He-gas:16.5
Tungsten Shield	10	W (W182:26.5; W183:14.3 W184:30.7; W186:28.5)
B_4C Shield	5	Be(Be10:16; Be11:64; C:20)
Superconductor Toroidal MF Coil	20	Nb93:70; Sn116:5; Sn117:2.6; Sn118:8.3; Sn119:2.9; Sn120:1.1; He:10.1
Reflector	20	C:90; He-gas:10
Fission core Reflector	4	Li6:0.14; Li7:0.54; Pb204:24; Pb206:22; Pb208:52

3.2 Comparison for Performances

Table II shows performance parameters of Hyb-WT for various coolant options.

Table II: Performance Parameters of Hyb-WT for Coolant Options

Coolant / Vol. %	LiPb / Reference	H_2O / 54.53	D_2O/ 54.53	Na / 54.53	LBE/ 54.53	FLiBe/ 54.53	FNaBe/ 54.53
Fission Power (MW_{th})	2000	2000	2000	2000	2000	2000	2000
K_{eff} [BOC / EOC]	0.96949 /0.83392	1.07509 /0.98496	1.15246 /0.97685	1.01726 /0.86567	1.08281 /0.92509	0.90226 /0.77904	1.11022 /0.9422 3
Fusion Power (MW_{th})	15.8 ~99.7	0 ~7.48	0 ~11.6	0 ~77.7	0 ~40.4	53.8 ~141	0 ~30.4
Irradiation Time (days)	1100	1100	1100	1100	1100	1100	1100
TBR	1.84					2.26	
TRU inventory (kg)	14000	14000	14000	14000	14000	14000	14000
Total TRU mass-burned (kg)	2250	2250	2251	2250	2250	2250	2250
TRU mass-burned/yr (kg/fpy)	746.6	746.6	747.0	744.6	746.6	746.6	476.6
% TRU mass burned/yr	5.35	5.34	5.36	5.35	5.35	5.35	5.34
Support Ratio for 75% availability	2.24	2.24	2.24	2.24	2.24	2.24	2.24
fis/cap	2.95	0.76	1.04	2.3	2.76	1.52	1.41
Total FP loaded in FP zone (kg)	2500	2500	2500	2500	2500	2500	2500

Total FP burned in FP zone (kg)	448	27.2	102.8	483.6	456.1	270.7	275.6
FP produced in TRU core (kg)	163.1	149	154.36	162.1	162.87	160.26	159.64
Net FP mass-burned (kg)	285	-121.8	-51.56	321.5	293.23	110.44	115.96
Net FP mass-burned/yr (kg/fpy)	94.57	-40.42	-17.11	106.68	97.30	36.65	38.48
% of Net FP mass burned/yr	3.78	-4.87	-0.68	4.26	3.89	1.46	1.54
FP support Ratio 75% availability	1.77			2.00	1.83	0.69	0.72

k_{eff} values with all coolants except for FLiBe are higher than with LiPb as shown in Fig.2. Therefore, required fusion powers with all coolants except for FLiBe are lower than with LiPb.

The decrement of k_{eff} with H_2O is the lowest compared to the others, therefore H_2O has long cycle length.

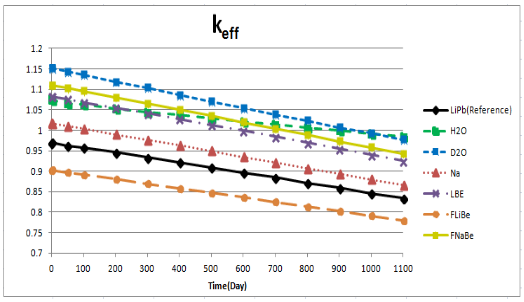

Fig. 2. keff value for coolant options.

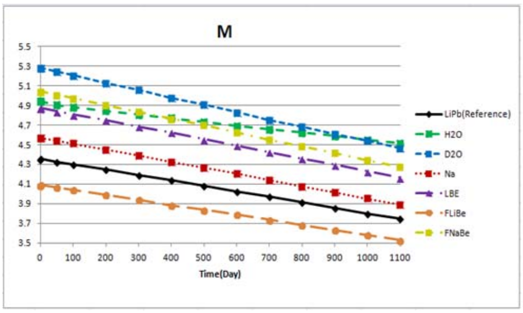

Fig. 3.Energy multiplication factor for coolant options.

Energy multiplication factor means the ratio of the total amount of nuclear energy release in the blanket to the incident fusion energy. This factor based on fission power, therefore it is proportional to the k_{eff} value.

Tritium breeding is possible only LiPb and FLiBe coolant contained Li. TBR with FLiBe is higher than with LiPb, because of contained high number density of Li-6.

In Table II there were no big differences in total TRU mass burned in cases of all coolants. However, there are big differences between long-lived transuranic isotopes (LL-TRU) and medium-lived transuranic isotopes (ML-TRU) in transmutation in Table III.

Table III: TRU Waste Transmutation Performance Parameters of Hyb-WT for Coolant Options

Coolant/ Vol. %	LiPb / Reference	H_2O / 54.53	D_2O/ 54.53	Na / 54.53	LBE/ 54.53	FLiBe/ 54.53	FNaBe/ 54.53
TRU inventory (kg)	14000	14000	14000	14000	14000	14000	14000
LL TRU mass-burned (kg,(%))	2107.75 (17%)	2995.59 (24%)	2483.17 (20%)	2156.29 (17%)	2117.86 (17%)	2267.82 (18%)	2295.84 (18%)
ML TRU mass-burned (kg,(%))	169.83 (13%)	-690.36 (-52%)	-181.23 (-14%)	126.52 (10%)	161.52 (12%)	-2.01 (-0.16%)	-3.75 (-0.28%)
Total TRU mass-burned (kg,(%))	2250 (5.35%)	2250 (5.34%)	2251.35 (5.36%)	2250 (5.35%)	2250 (5.35%)	2250 (5.35%)	2250 (5.34%)

* LL TRU : half-life of TRU nuclide ≥ 100years
* ML TRU : 10years ≤ half-life of TRU nuclide < 100years

Neutron flux with H_2O and D_2O coolant is excessively softened compared to LiPb, because of moderation effect of water coolants especially H_2O as shown in Fig. 4. Flux with Na and LBE coolant has higher thermal flux compared to LiPb, because LiPb absorbs thermal neutrons for tritium production. Thermal flux with Na is higher than with LBE because of slightly softened flux with Na. While, flux over 0.1~1 Mev with LBE is higher than with Na, because LBE has low neutrons slowing down capability and large inelastic scattering cross section compared to Na. High thermal flux with LBE is not softening effect but has more neutron population compared to LiPb. Flux with FLiBe and FNaBe coolant is rather than softened compared to LiPb. Also, thermal flux with FLiBe is lower than with LiPb. Because number density of Li in FLiBe is higher than one in LiPb, as a result more absorption of thermal neutrons is generated at FLiBe.

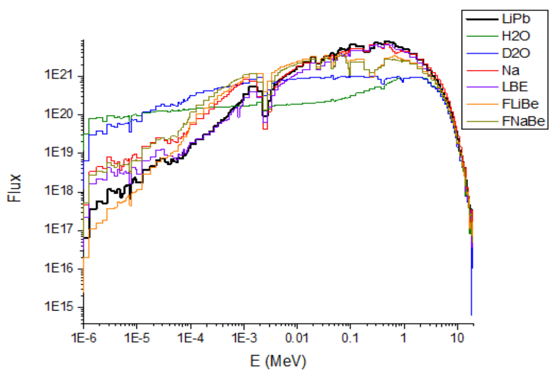

Fig. 4. Neutron flux for coolant options in TRU fission core in Hyb-WT.

Fission reaction of Pu-239 and Pu-241 is increased with all coolants, especially in H_2O and D_2O, because of flux softening as shown in Fig. 5. Fission reactions of all TRU nuclides with LBE are increased, because they have higher thermal flux compared to LiPb.

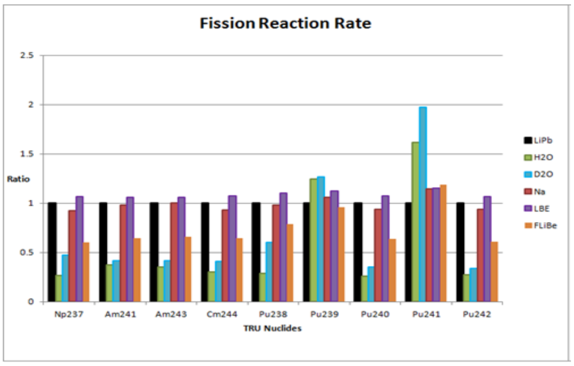

Fig. 5. Relative fission reaction rate in TRU fission core to LiPb.

Capture reactions of all TRU nuclides are increased with all coolants. They extremely are increased with H_2O and D_2O coolant because of softening flux. While, they with LBE coolant are increased the lowest.

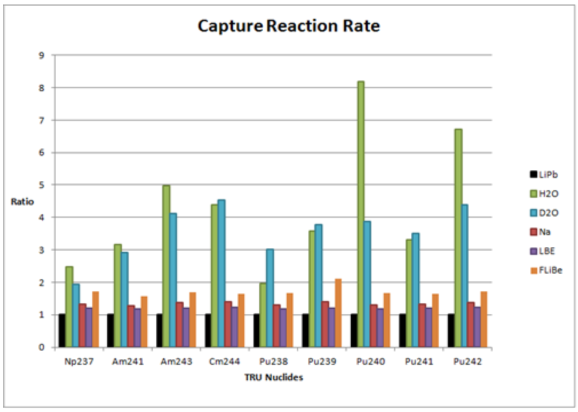

Fig. 6. Relative capture reaction rate in TRU fission core to LiPb.

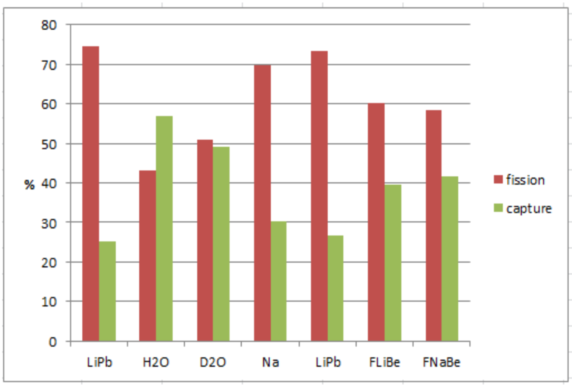

Fig. 7. Average distribution of fission and capture reactions subsequent to neutron absorption in TRU nuclides for coolant options.

LL-TRU mass burned with H_2O and D_2O coolant is very high, especially with H_2O compared to LiPb, because fission reaction of Pu-239 and Pu-241 and capture reaction of all TRU nuclides are extremely increased. However, waste transmutation performance of ML-TRU with H_2O and D_2O coolant is poor, even ML-TRU with H_2O is more generated about 50% of loaded ML-TRU mass. This result means that LL-TRUs are not incinerated using fission but transformed to other TRU nuclides because of higher capture reaction than fission as shown Fig.7. TRU waste transmutation performance with Na and LBE coolant has not big difference compared to with LiPb. LL-TRU mass burned is slight high, while ML-TRU mass burned is slight low. Waste transmutation performance of LL-TRU with FLiBe and FNaBe coolant is higher than with LiPb, however ML-TRU mass burned decreases as much as increasing LL-TRU mass.

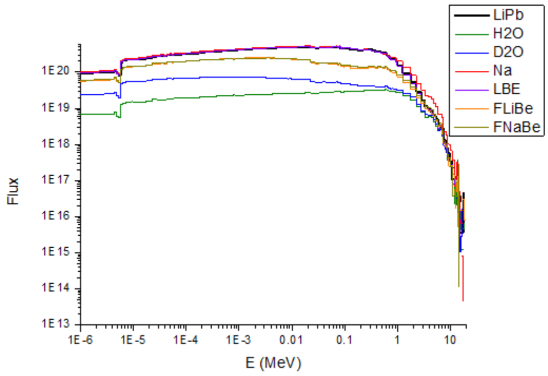

Fig. 8. Neutron flux for coolant options in FP zone in Hyb-WT.

Fig. 8 shows neutron flux spectrum in FP zone for coolant options. Neutron flux with H_2O and D_2O coolant is lower than with the others, because of low fast flux in TRU fission core by extremely softening. While, flux with Na and LBE coolant especially Na is slightly higher compared to LiPb, because of low softening effect compared to water and molten salt coolant options in TRU fission core.

As a result, capture reactions of long-lived fission products (LLFP) with Na and LBE coolant are the highest as shown in Fig. 9.

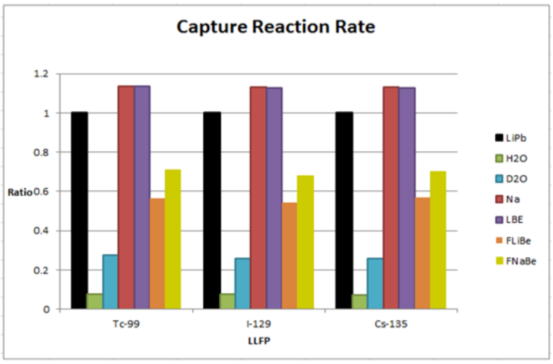

Fig. 9. Relative capture reaction rate in FP zone to LiPb.

Fig. 10 shows mass variation of LLFP for coolant options. There is no big difference in LLFP produced in

TRU fission core by TRU fission reaction depending on coolant options. However, there is big difference in FP burned by capture reaction in FP zone. LLFP transmutation with H_2O and D_2O coolant is very poor, because of low flux in FP zone. While, LLFP transmutation with Na and LBE coolant is better than with LiPb, because of high flux in FP zone. Therefore, net LLFP mass burned with Na and LBE coolant is higher than with LiPb, on the other hand LLFP with H_2O and D_2O coolant is generated.

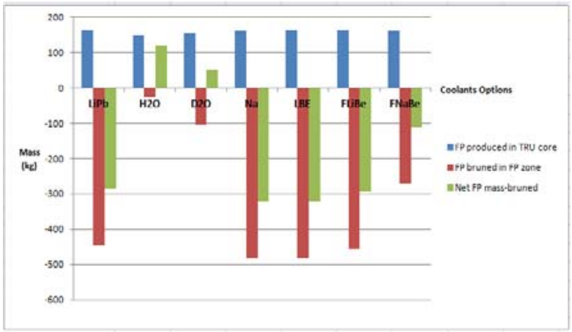

Fig. 10. Mass variation of LLFP for coolant options.

4. Conclusions

In this work, performance of radioactive waste transmutation was compared with various coolant options. On the whole, k_{eff} increases with all coolants except for FLiBe, therefore required fusion power is decreased.

In cases of H_2O and D_2O coolant, TRU is not incinerated using fission but transformed to other TRU nuclides using capture, because of extremely softening flux. Therefore, using H_2O and D_2O coolant are not good for FFHR for waste transmutation. While, H_2O and D_2O coolant are suited to FFHR for energy production, because of high k_{eff} and energy multiplication factor.

There are no big differences in TRU transmutation performance between Na, LBE and LiPb coolant. ML-TRU transmutation performance with Na is worse than with LiPb, because fission reaction of Pu-239 and Pu-241 and capture reactions of all TRU nuclides increase by softening flux. TRU transmutation performance with LBE is similar with LiPb, because LBE just has high thermal flux compared to LiPb. Moreover, LLFP transmutation performances with Na and LBE coolant better compared to LiPb. However, Na and LBE coolant like LiPb also have big MHD pressure drop problem which main issues in magnetic field.

TRU transmutation performances with FLiBe and FNaBe coolant worse compared to LiPb. TRU is not incinerated using fission but transformed to other TRU nuclides using capture, because of rather softening flux. TRU and LLFP transmutation performances with FLiBe and FNaBe coolant is rather lower than with Na and LBE coolant, however they are not inefficient like H_2O and D_2O coolant. Also, Tritium production capability with FLiBe is better than with LiPb. Moreover, MHD pressure drop is not a problem in cases of FLiBe and FNaBe coolants. Therefore, it is believed that FLiBe and FNaBe coolants have high potential for FFHR for waste transmutation.

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