Neutronic Assessment of He-Cooled Molten Li Fusion Blanket

Beomseok Han*[1], Yonghee Kim[2] and Chang Hyo Kim[1]
[1]*Nuclear Engineering Department, Seoul National University, San 56-1, Shinlim-dong, Kwanak-gu, Seoul, Korea*
[2]*Korea Atomic Energy Research Institute, 150, Deokjin-dong, Yuseong-gu, Daejeon, Korea*

Abstract

This study is intended to assess overall neutronic performances of He-cooled molten Li (HCML) blanket with a reflector and investigate the impact of ^{6}Li enrichment on tritium breeding ratio (TBR). To precisely evaluate the neutronic performances of the reflected HCML blanket, three-dimensional D-shape torus model is utilized and Monte-Carlo calculations are performed. In this study, the neutroic characteristics of five potential reflector candidates are compared and the reflected blanket is also optimized from the neutronic point of view. Taking into account the material availability and potential safety features, a high-density graphite reflector can be a practical choice for a high-performance HCML blanket. The graphite-reflected HCML blanket shows the best performances when the reflector is placed such that the blanket is divided into a thick front region and a thin back region. The HCML blanket with a slightly-enriched Li (8-10 wt% ^{6}Li) breeder shows the highest TBR.

KEYWORDS: Neutronic Assessment, He-cooled Molten Li Blanket, TBR, Graphite Reflector, ^{6}Li Enrichment

1. Introduction

Among the liquid breeder blankets, separately cooled options typically use He or H_2O as a coolant and the Li breeder circulates at a very low speed for tritium extraction. Besides favorable features of the liquid metal blankets [1], a He-cooled molten Li (HCML) blanket is considered to be attractive for reasons of virtually no concern about tritium permeation into coolant system, potential of the efficient high-temperature direct cycle, low possibility of Li fire in an inert gas environment, alleviated material compatibility issues, and marginal MHD effects due to a very slow Li flow [2-3].

In the majority of fusion breeding blankets, beryllium (Be) is usually utilized as a neutron multiplier to enhance the TBR since Be has a very good neutron multiplication performance and a low absorption cross-section. Nevertheless, Be has a limited natural resource and moreover is highly toxic, and is subject to the properties degradation during neutron irradiation. In a previous study, an HCML blanket without a Be multiplier was proposed, in which a graphite reflector was introduced to improve the neutronic performances of the blanket [4]. In this study, the neutronic characteristics of potential reflector candidates are compared and the reflected HCML blanket is

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* Corresponding author: Tel. 82-2-880-7211, Fax. 82-2-889-2688, E-mail: beomseok@snu.ac.kr

optimized more thoroughly with three-dimensional D-shape torus model. In addition, the TBR values are analyzed with respect to several ^{6}Li enrichments.

2. Model Description of HCML Blankets

Figure 1 shows the radial builds of the reflected HCML blanket, in which a neutron reflector is incorporated into the breeding zone for the spectral softening and the inner shield thickness is changed according to the reflector thickness. In order to enhance the shielding performances, WC and B_4C are utilized in the LT (Low Temperature) shield. The neutrons leaking from the breeder zone are moderated and absorbed in the shields. Since the neutron spectrum in the breeder zone is determined by the blanket configuration, it is essential to find out an optimal reflector configuration. For a parametric optimization of the reflector configuration, thicknesses of the reflector and the breeder 2, denoted as x and y, respectively, are treated as variables.

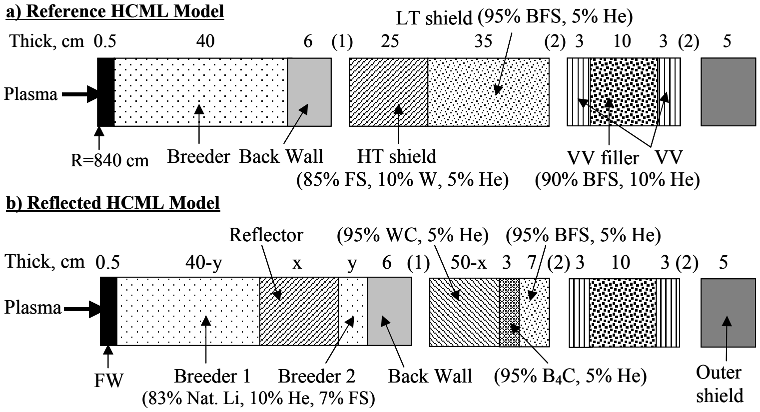

Figure 1. Reflected HCML blanket models.

In general, the blanket modules are divided into two parts; inboard and outboard, as shown in Fig. 2. In all neutronic analyses of this study, both inboard (IB) and outboard (OB) blankets are modeled simultaneously and source neutrons with 14.06MeV energy are generated isotropically from the volumetric source of a 3D ellipsoidal torus. Fig. 2 represents a schematic view of the 3D D-shape torus geometry.

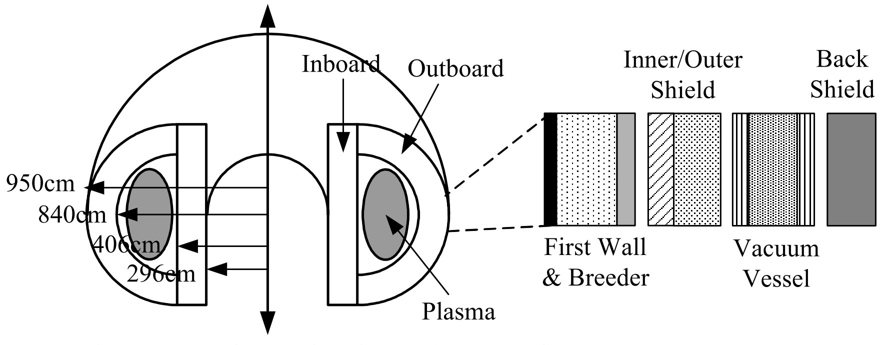

Figure 2. Schematic view of 3D D-shape torus geometry.

This D-shape torus is a simplified model of the ITER tokamak [5]. It is assumed that the major radius of the torus is 623cm and the minor radius is 217cm. In the D-shape torus geometry, the vertical rectangular region and the half-circle region correspond to the inboard and the outboard respectively. The gray region represents the volumetric source of fusion neutrons. In the next sections, the neutronic performances will be evaluated with the 3D D-shape torus model.

3. Neutronic Performance of Reflected Blankets

3.1 Comparison of Potential Reflector Candidates

In order to enhance the neutronic performance of the reflected blanket, the neutron leakage from the breeder zone should be minimized and a reflector must moderate the neutrons without an excessive neutron loss. To compare the neutronic performances of five potential reflector candidates (Be, $^{11}B_4C$, graphite, TiC, and ZrH_2), TBR of the blankets are evaluated for the configuration b) of Fig. 1, in which the breeder 2 thickness (x) is fixed at 5cm and an increase of the reflector thickness (x) is compensated by a decrease of the WC shield thickness.

Table 1. TBR and NMF of potential reflector candidates.

x(cm)*	Tritium Breeding Ratio (TBR)				
	Be	$^{11}B_4C$	Graphite	TiC	ZrH_2
20.0	1.554	1.332	1.254	1.141	0.971
25.0	1.601	1.346	1.284	1.123	0.956
30.0	1.623	1.349	1.305	1.105	0.949
40.0	1.629	1.337	1.326	1.078	0.943
50.0	1.604	1.320	1.327	1.065	0.942
x(cm)	Neutron Multiplication Factor (NMF)				
	Be	$^{11}B_4C$	Graphite	TiC	ZrH_2
20.0	1.460	1.133	1.142	1.162	1.193
25.0	1.484	1.131	1.137	1.160	1.192
30.0	1.501	1.129	1.133	1.160	1.192
40.0	1.521	1.129	1.129	1.159	1.191
50.0	1.529	1.128	1.127	1.159	1.191
x(cm)	Energy Multiplication Factor (EMF)				
	Be	$^{11}B_4C$	Graphite	TiC	ZrH_2
20.0	1.262	1.146	1.146	1.210	1.142
25.0	1.268	1.141	1.139	1.219	1.140
30.0	1.272	1.138	1.134	1.226	1.139
40.0	1.279	1.134	1.127	1.236	1.138
50.0	1.284	1.132	1.121	1.240	1.138

*x=Reflector Thickness, y=Breeder 2 Thickness (5cm)

In Table 1, several neutronic parameters of the reflected blankets are evaluated with different reflector thicknesses. In all cases, Be shows the best TBR and ZrH_2 has the worst TBR. The neutron multiplication factor (NMF) of Be is the best and increases with respect to the reflector thickness. It is also shown that the blankets with Be and TiC reflector show a higher energy multiplication factor (EMF), which slightly increases with respect to the reflector thickness.

Although the TBR values of Be and $^{11}B_4C$ are better than those of graphite and TiC, Be and $^{11}B_4C$ have some drawbacks. As previously mentioned, Be is very toxic and expensive, and has the properties degradation under neutron irradiation [6,7]. In addition, the maximum allowable temperature of a Be multiplier is rather limited, usually less than 900 °C. In the case of $^{11}B_4C$, an extremely high enrichment of ^{11}B (more than 99.99%) would be required due to the high neutron absorption of the ^{10}B impurity.

Material properties of graphite are rather moderate and it is relatively cheap. A potential advantage of the graphite reflector is that it can play a role of heat sink in the case of a coolant loss accident since its heat capacity is very high, so improving the safety features of the reflected HCML blanket. In addition, a graphite reflector can be utilized safely in the severe irradiation environment. For these reasons, a further optimization is performed for the graphite reflector in the following sections.

3.2 Impact on TBR of ^{10}B Impurity

As mentioned above, although $^{11}B_4C$ reflector shows a better TBR than the graphite and TiC reflector, it cannot be a practical choice due to high neutron absorption of the ^{10}B impurity. In this section, to investigate an impact on TBR of the ^{10}B impurity, ^{11}B enrichment of the $^{11}B_4C$ reflector is changed from 99% to 99.99999% with different reflector thicknesses.

Table 2. Impact on TBR of ^{10}B impurity.

^{11}B Fraction (wt%)	Tritium Breeding Ratio				
	x=20cm	x=25cm	x=30cm	x=40cm	x=50cm
99	0.909	0.900	0.896	0.892	0.890
99.9	1.048	1.025	1.012	1.000	0.996
99.99	1.159	1.124	1.099	1.074	1.065
99.999	1.277	1.259	1.234	1.192	1.167
99.9999	1.325	1.334	1.330	1.309	1.286
99.99999	1.332	1.345	1.347	1.334	1.316
^{11}B 100%	1.332	1.347	1.349	1.337	1.320

*x=Reflector Thickness, y=Breeder 2 Thickness (5cm)

Table 2 shows the TBR values of the $^{11}B_4C$-reflected blanket according to the variation of the ^{11}B fraction. It is shown that almost ^{11}B enrichment greater than 99.9999% is essential to achieve the TBR comparable to the 100% ^{11}B enrichment. Taking into account the cost of ^{11}B enrichment, the $^{11}B_4C$ reflector would be impractical.

4. Parametric Optimization of Reflected Blankets

4.1 Optimal Reflector Configuration

In general, TBR is sensitive to the neutron spectrum since ^{6}Li favors a soft spectrum and ^{7}Li a hard one. To find out an optimal configuration providing the best neutron spectrum, an optimization study is performed for thickness and position of the graphite reflector. Total thickness of the breeder zones was kept constant (40cm), and variation of the reflector thickness is accompanied with a change of the shield thickness to maintain the total thickness of the blanket/shield constant (106.5cm). In all analyses, total volume of the blanket also remains almost constant. The optimization results are shown in the Fig. 3.

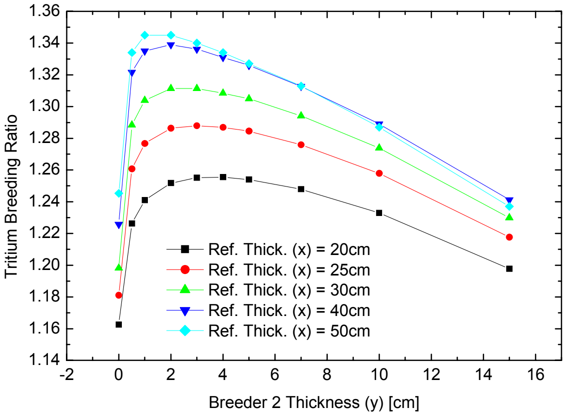

Figure 3. TBR vs. thickness of breeder 2 and reflector.

The TBR values are improved with an increase of the reflector thickness, and there exists an optimal thickness of the breeder 2 for a given reflector thickness. This optimal thickness of breeder 2 is quite small, i.e., 3~4cm and smaller for a thicker reflector. If the thickness of the breeder 2 is greater than the optimal one, TBR starts to decrease gradually due to a reduced contribution of ^{7}Li by the spectral softening. The TBR curves show an asymptotic behavior for the reflector thickness above 40cm.

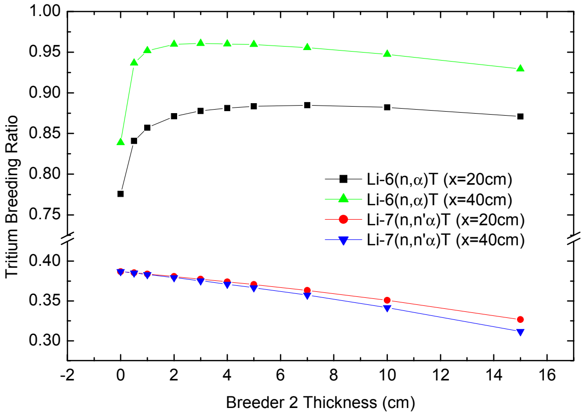

Figure 4. Tritium production by ^{6}Li and ^{7}Li reactions.

Figure 4 represents the tritium production rates of ^{6}Li and ^{7}Li separately for two reflector configurations. As the breeder 2 becomes thicker, the tritium production of ^{7}Li decreases gradually while that of ^{6}Li increases rapidly and then saturates. When the breeder 2 is thin (below 3cm), the total tritium production is rather sensitive to the of ^{6}Li contribution to the TBR. On the other hand, when the breeder 2 is thicker, the total TBR becomes smaller due to decrease of the tritium production of ^{7}Li. In addition, this figure shows that the difference of TBR between the two blankets results from the difference of ^{6}Li-6 contributions to total tritium production.

4.2 Impact on TBR of ^{6}Li Enrichment

To investigate an impact of the Li breeder composition, TBR is evaluated as a function of the ^{6}Li enrichment for several blanket configurations. Figs. 5 and 6 indicate that the maximum TBR occurs when ^{6}Li enrichment is in 8~10 wt%. Interestingly, the optimal ^{6}Li enrichment is close to the natural composition, i.e., 6.58 wt%, and TBR is rather insensitive to the ^{6}Li enrichment in the range of 8~10 wt%. The results imply that a slightly enriched Li breeder can be used for a very long time without any adjustment of the composition [8].

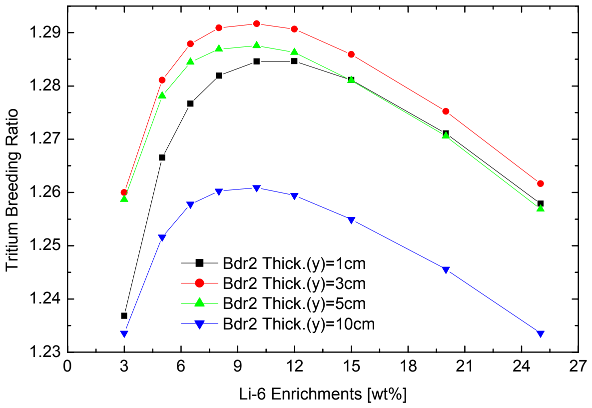

Figure 5. TBR vs. ^{6}Li enrichment and blanket 2 thickness.

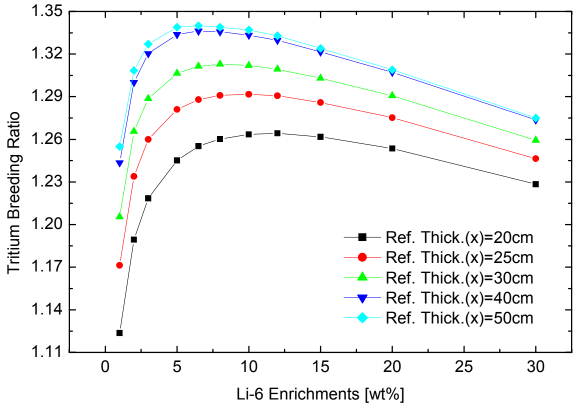

Figure 6. TBR vs. ^{6}Li enrichment and reflector thickness.

It is also worthwhile to note that the TBR curves of Figs. 5 and 6 agree well with that of Fig. 3. In the Fig. 5, the blanket model with the breeder 2 thickness of 3cm shows the best TBR performance. In the Fig. 6, when the reflector thickness is greater than 40cm, the TBR is not noticeably improved such as the result of Fig. 3.

4.3 Impact on TBR of Graphite Reflector Density

In the above parametric optimization, nuclear-grade graphite (density=1.76gm/cm^3) is used as the reflector material. In order to obtain the optimal neutron spectrum and minimize the blanket volume, it is desirable to utilize the reflector with a density as high as possible. In this study, the TBR behaviors are investigated along with the graphite reflector density, which varies from 1.64gm/cm^3 to 2.00gm/cm^3.

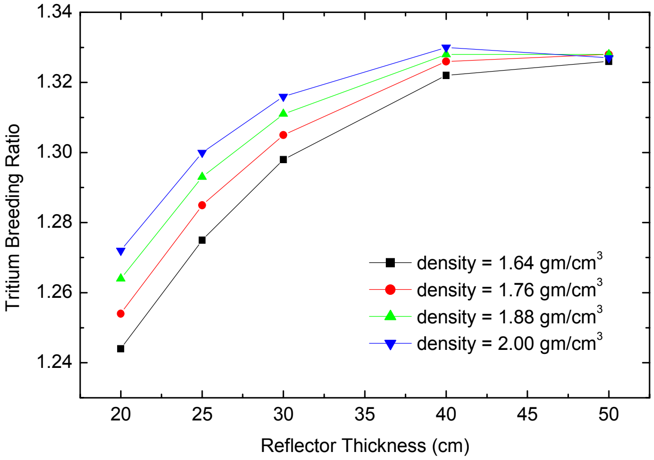

Figure 7. Impact on TBR of Graphite Reflector Density.

Fig. 7 shows that the blanket with a high-density and thick reflector can improve the TBR. As expected, the high-density reflector has a positive effect on the TBR. However, in case of the blanket with a 50cm thick reflector, a higher-density reflector does not improve the total TBR any more. If the higher-density reflector can be utilized, tritium self-sufficiency of the reflected blanket will be satisfied with the breeder of a smaller volume.

5. Conclusion

In this study, the HCML blanket configuration with a graphite reflector is optimized from the neutronic point of view with 3D D-shape torus model, and the neutroic characteristics are analyzed with the Monte-Carlo calculations. Taking into account the material availability and potential safety features, a high-density graphite reflector can be a practical choice for a high-performance HCML blanket. The HCML blanket shows the best performance when the reflector is placed such that the blanket region is divided into a thick front region and a thin back region. It is also observed that the blanket with a slightly-enriched Li (8-10 wt% ^{6}Li) shows the highest TBR.

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