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FEASIBILITY INVESTIGATION OF DELETING MODERATORS IN A FUSION-FISSION HYBRID REACTOR

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The possibility of removing the moderators of the typical Fusion-Fission Hybrid Reactors is investigated, regarding the latest changes in the technical issues of hybrid reactors. For this purpose, tritium production flux and released fission energy parameters were analyzed using the MCNPX for the hybrid reactors without a moderator and compared with the previous results of another study. According to the implemented data validation, the results showed that removing the moderators can have some advantages, leading to better neutronic efficiencies, which is effective in the neutronic economy of reactors. Besides, removing the moderators reduces the reactor building costs and problems related to the moderators. Therefore, modern designs based on removing moderators are strongly assumable and recommended.

Keywords: Fusion-Fission Hybrid Reactors, MCNPX 2.7.0, Fertile, Fissile

1. Introduction

Fusion-fission hybrid reactors are based on the new version of an old idea [1] accompanying the new technologies, which can have more sufficiency rather than pure-fusion or pure-fission reactors. In the case of hybrid reactors, the inherent safety of fusion reactors [2] alongside their more power gain than the pure-fusion reactors (as a result of being combined with fission reactors), makes them interesting to work with [3–5].

High energy neutron produced from the deuterium-tritium fusion reaction can be used to burn the remaining transuranic elements (TRUs) [6] of a light-water reactor (LWR). These TRUs are actually the burned-up products [7], and the mentioned neutrons can cause fertile fuels to experience a fission reaction.

Increasing incident neutron energies to more than 1 keV, the fission cross-section increases and reaches smoothly to the fissile fuel cross-section. Therefore, the fission reaction can be triggered by fusion neutrons [8] with energies of >1 MeV [9, 10]. The most important fusion reactions are as follow [11]:

$$ {}_{1}^{2}d + {}_{1}^{2}d \rightarrow {}_{1}^{3}t(1.01MeV) + {}_{1}^{1}p(3.03MeV) \quad (1)$$

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$$ {}_1^2d + {}_1^2d \to {}_2^3He(0.82MeV) + {}_0^1n(2.45MeV) \quad (2)$$

$$ {}_1^2d + {}_1^3t \to {}_2^4\alpha(3.52MeV) + {}_0^1n(14.06MeV) \quad (3)$$

$$ {}_1^2d + {}_1^3He \to {}_2^4\alpha(3.67MeV) + {}_1^1p(14.67MeV) \quad (4)$$

As can be seen in the reaction (3), the neutron produced by a d-t reaction has 14.06 MeV energy, which is in the range of fast neutron energies [12–14]. These fast neutrons can be used as accelerated particles for some further goals [15, 16] because they can cause fertile fuels to undergo fission reactions. Besides, since d-t fusion reaction has the most fusion cross-section [17, 18], the first generation of the Fusion Power Reactors will use this reaction with high probability.

The other aspects of using fertile fuels are their capability of producing fissile fuels through absorbing neutrons, and transmutation of fertile materials into fissionable ones through β-decay reaction [19], according to the following reactions.

$$ {}_0^1n + \begin{cases} {}^{232}Th \\ {}^{238}U \end{cases} \longrightarrow \begin{cases} {}^{233}Th \\ {}^{239}U \end{cases} \xrightarrow{\beta^-} \begin{cases} {}^{233}Pa \\ {}^{239}Np \end{cases} \xrightarrow{\beta^-} \begin{cases} {}^{233}U \\ {}^{239}Pu \end{cases} \quad (5)$$

Therefore, for fast or even thermal neutron fluxes, the optimization action of the amounts of fertile and fissile fuels can be used to gain the highest fission energy and the most amount of fissile fuel breeding ratio (*FFBR*), which should be higher than 1 [20–24].

As a fusible fuel, tritium has a short half-life [25, 26], hence, there is a little amount of natural tritium [27–29]. Regarding the mentioned reason, so as to have a self-sufficient d-t fusion reactor [30–35], tritium must be produced artificially.

On the other hand, Lithium, which has two major isotopes, can be a tritium breeder in special conditions. The two different isotopes of lithium with mass numbers of 6 and 7 can breed tritium through interactions with thermal and fast neutrons, respectively [36]. In order to produce 14.1 MeV fast neutrons through d-t reaction, ^{7}Li isotope can be used, and since the natural abundance of ^{7}Li is more than ^{6}Li [37, 38], enrichment of ^{6}Li will not be needed [39]

$$ {}_0^1n(thermal) + {}_3^6Li \to {}_1^3t + {}_2^4\alpha + 4.78(MeV) \quad (6)$$

$$ {}_0^1n(fast) + {}_3^7Li \to {}_1^3t + {}_2^4\alpha + {}_0^1n - 2.47(MeV) \quad (7)$$

Regarding the above points, to achieve the best neutronic performance, optimization of moderator amount can lead us to have the best amount of each fertile and fissile fuels and actual tritium breeders.

In this work, a typical Subcritical Advanced Burner Reactor (*SABR*) [40] is used as a fusion-fission hybrid reactor. SABR is a conceptual reactor design, developed by the Georgia Institute of Technology and driven by a tokamak D-T fusion neutron core, which is based on ITER physics and technology. SABR is a modular sodium pool-type fast reactor with 3000-MW nominal power.

SABR is the sixth one in the series of fast transmutation reactor concepts that have been developed in design projects by academic students at Georgia Tech. The selection reason for the SABR on this study is the wide possibility of investigation on the parameters of this reactor, which in turn is due to SABR design and materials.

All the required parameters were taken from Stacey et al.'s work [41], otherwise were referred properly.

2. Measurements and Methods

The main purpose of the research is to investigate the effects of removing the moderator of a fusion-fission hybrid reactor on its performance. Hence, in this study, the *MCNPX 2.7.0* calculation code is used for neutronic calculations, and the reactor geometry on this research is visualized by *MCNPX VISUAL EDITOR* [42]. Using the MCNPX, neutronic parameters, including the produced tritium flux and tritium production parameters are calculated for hybrid reactors without a moderator (i.e. void or air as a moderator), then the results were compared with the previous results (from another study) for the reactors that have light or heavy water and liquid sodium as their moderators. This comparison proves the final conclusions of this study. Furthermore, another simulated experiment was performed for the neutronic parameters of different moderators, which will be mentioned later.

For the simulation, the F4 tally and MT=205 numbers were used as tritium production calculations and MT=19 number was used for released fission energy. The materials used in the reactor design are defined using the "Mn" card (cell parameter on MCNPX), and the geometry of the reactor was simulated using surface cards so that the surfaces were called to form the occupied space.

Also, the "FILL, U" and "LAT" cards have been used to define the lattice geometry, and "LIKE n BUT TRCL n" and "TRn" cards have been used for the rotation of the cells [43]. The above parameters are calculated for different cases of with and without a moderator.

3. SABR Design

The geometry depicted by MCNPX Visual Editor for SABR reactor is shown in Fig. 1, and the dimensions of the reactor parts have been shown in Table 1. Different parts and blankets are identified using different numbers, which have been addressed on the right side of Fig. 1.

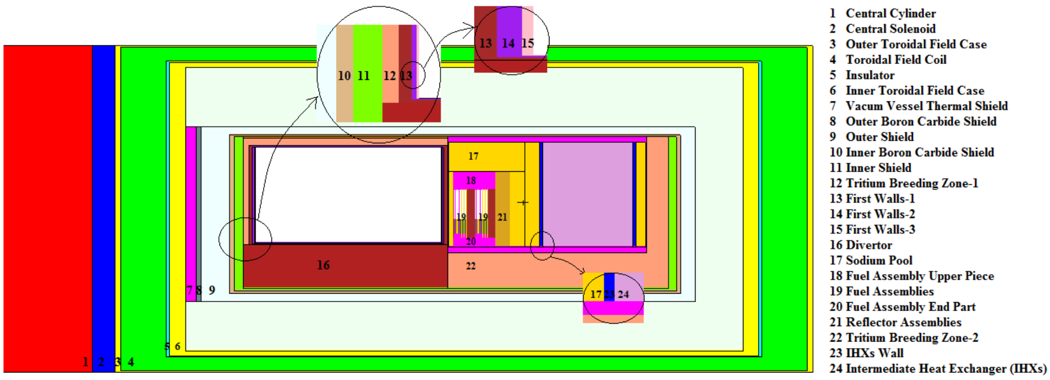

Fig. 1. Fusion-fission hybrid reactor different parts, depicted by MCNPX Visual Editor.

3.1. Pool

The pool is made of three different parts: assemblies, intermediate heat exchangers (IHXs), and the pool.

The dominant percentage of the pool volume consists of a moderator. In the SABR design, the material of the moderator is Sodium. In this work, five different cases are investigated as the materials to fill the pool and the related neutronic parameters of the material. Moderator fills all the empty areas of the pool, hence flowing in the gaps of fuel assemblies and the fuel rods.

3.2. Fuel Pins and Fuel Assemblies

There are four parts in the assemblies, in turn: fuel rods, insulator, gap, and the duct. The gap consists of a void. Also, there is an insulator layer, consisting of SiC, which is located after the fuel rods part and controls the function of loops. The middle layer is the gap, which controls stresses between the duct and the insulator, while the outermost layer is the duct.

Fuel rods have six different parts: 1- *Upper endcap*, 2- *Lower endcap*, at the two ends of both sides of the fuel pin. 3- *Fission fuel part* (the main part of the pin), which in turn consists of different parts: fertile and fissile materials. 4- *Fission gas plenum*, which keeps gases created from the fission reaction. 5- *The gap*, which controls the stresses between the clad and the fission part, and 6- *The clad*, which is the outermost layer of the fuel rod, and encloses the fuel rod and prevents radioactive fission fragments to escape from the fuel into the moderator and to prevent the contaminating it.

Dimensions and materials used in the studied reactor are shown in Tables 1 and 2.

Table 1

Materials and Some Other Dimensions of the studied reactor [41]

Parameters	Values
Materials—fuel/ tritium breeder/ clad and structure	ThO_2/ Li_2O/ ODS MA957
Shield Materials	Graphite, tungsten carbide, boron carbide, Na
Divertor Materials	Tungsten, CuCrZr, Na cooled
First wall Materials	Be, CuCrZr, ODS steel
Materials—reflector assembly in-core (vol %)	ODS steel (58.1%), SiC (6.6%), Na (35.3%)
Materials—graphite reflectors (vol %)	Graphite (90%), Na (10%)
Fuel/clad/bond/insulator/duct/coolant/wire (vol %)	22.3/17.6/7.4/6.5/9.3/35.3/1.5%
Number of fuel assemblies/fuel rods/ modular pools	800/469 per assembly, 375200 total/10
Height—fusion core/pin/duct/assembly	65.0/204.415/215.135/274.901 cm
Thickness—first walls	8.1 cm (1 cm Be, 2.2 cm CuCrZr, 4.9 cm ODS steel)
Thickness—cladding/duct/pin/fuel	0.0559/0.394/0.539/0.370 cm
Pitch—pin/ assembly	0.6346/16.142 cm

3.3. Shields and Tritium Breeding Blankets

There are four shielding parts around the cores: the inner shield, the boron carbide shield, the outer shield, and the vacuum vessel shield. These shields prevent exiting of the radiations or hazardous fission products to the outside of the reactor [44]. The materials and thickness of the shields are mentioned in Table 2.

Table 2

Materials and Thickness of Shields [41]

Name	Materials	Thickness (cm)
Ins (organic insulator)	An effective layer of glass-filled Polyamide	4.42
TF case	SS316LN-IG (stainless steel)	
	Outer side	7.08
	The inner side (next to plasma)	20.48
VV (Vacuum Vessel)	50 vol % ODS steel, 50 vol % He	14.35
Graphite	Graphite with 10 vol % Na	7
FW (first wall) part 1	Beryllium	1
FW part 2	A mix. of ODS steel, Na, and CuCrZr	2.2
FW part 3	80 vol % ODS steel, 20 vol % Na	4.9
OB_4C	B_4C with 5 vol % Na	6.35
OShield-1	WC (Tungsten carbide) with 5 vol % Na	36
Oshield-2	WC with 5 vol % Na	32.4
Oshield-3	WC with 5 vol % Na	18

Oshield-4	WC with 5 vol % Na	33
IB4C-1	B_4C with 10 vol % Na	6.5
IB4C-2	B_4C with 10 vol % Na	7
IB4C-3	B_4C with 10 vol % Na	6
IB4C-4	B_4C with 10 vol % Na	10
Ishield-1	WC with 10 vol % Na	12
Ishield-2	WC with 10 vol % Na	n/a
Ishield-3	WC with 10 vol % Na	10
Ishield-4	WC with 10 vol % Na	10
Trit-1 (Tritium Breeding)	Li_2O	6.7
Trit-2	Li_2O	31.9
Trit-3	Li_2O	The volume under the pool except for the diverter part
Trit-4	Li_2O	28

Ins: Insulator, SS: Stainless Steel, VV: Vacuum Vessel, FW: First Wall, WC: Tungsten Carbide, OB_4C: Outer Boron Carbide, Oshield: Outer Shield, Ishield: Inner Shield, Trit: Tritium Breeding.

4. Results

In order to validate the results, the experiment was performed for the neutron flux of the fission part in the manner of Liu et al.'s work in the China Academy of Engineering Physics [45]. The results are shown in Fig. 2, which shows a good agreement compared to the results of the previous experiments.

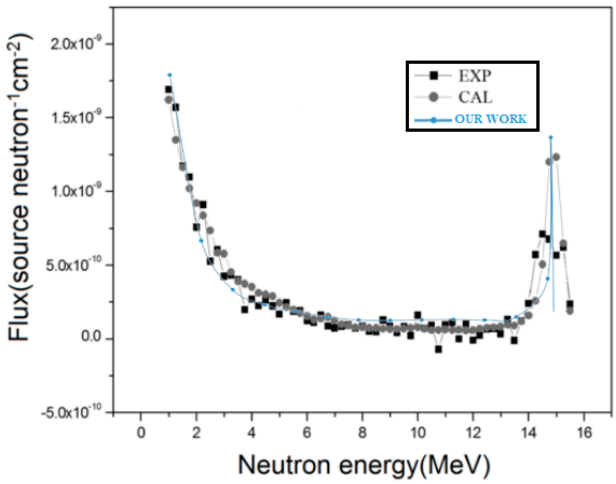

Fig. 2. Comparison of the previous measured and calculated results [45] with the results of this study.

The results of this study were validated by comparing them with the previous research. These results show a high adaptation to the experimental and calculated results of the published manuscript that strongly confirms the accuracy of the obtained results.

On the next step, the experiment was performed for the neutronic parameters of different moderators: heavy water, light water, liquid sodium, normal air, and void as the moderators of the reactor.

4.1. Released Fission Energy

Released fission energies for different moderators and different incident neutron energies were calculated and analyzed. The results are shown in Fig. 3.

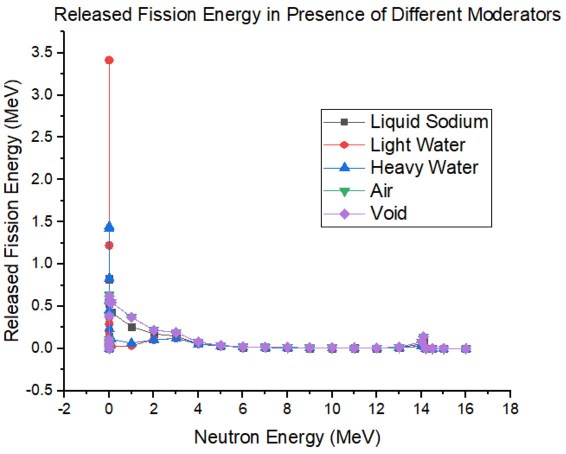

Fig. 3. Released fission energy in the presence of different moderators with different incident neutron energies.

The results showed that for the low-energy neutrons, light and heavy water have better performances, and for the high-energy neutrons, air and void leaded to better performances. Fig. 4 shows the released fission energy for high-energy neutrons.

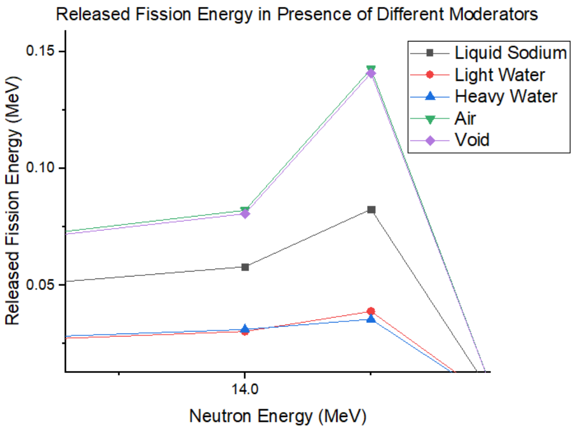

Fig. 4. Released fission energy in the presence of different moderators for high-energy neutrons.

The results show that increasing the fast neutron flux, the absence of the moderators leads to better performance.

4.2. Tritium Production

As mentioned before, tritium production is such an important parameter for fusion reactors that the tritium breeding ratio should be more than unity to satisfy the self-sufficiency condition of the reactor (TBR>1).

Tritium production in the presence of different moderators was examined and the results are shown in Fig 5.

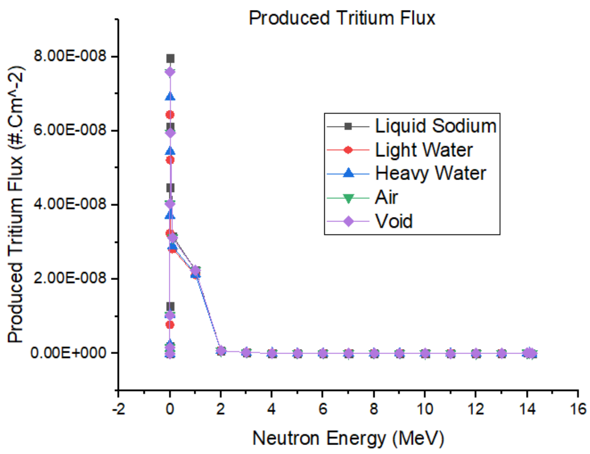

Fig. 5. Produced tritium flux for different incident neutron energies.

As it is obvious in Fig. 5, the results do not show an impressive difference, but some differences can be seen in the low-energy neutron ranges. Fig. 6 shows the results of the same simulation of Fig. 5, but for a low-energy neutron range.

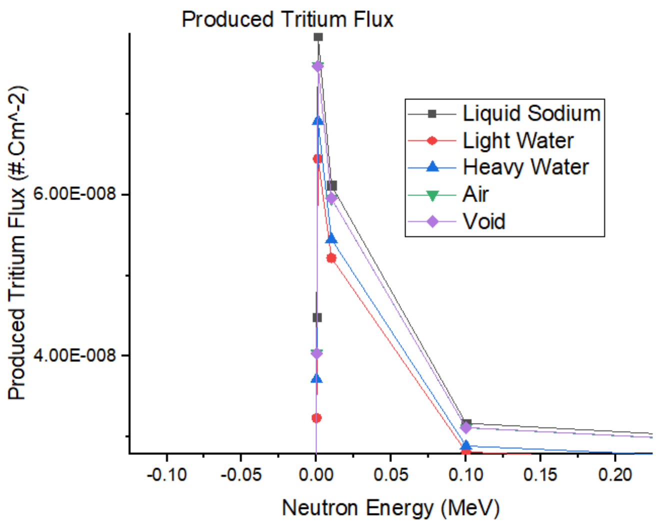

Fig. 6. Produced tritium flux for low-energy neutron range.

The tritium production rate increased in the case of removing the moderators. The results for released fission energy also showed that for low-energy neutrons, light or heavy water have better performance, while for the high-energy neutrons, removing the moderator would lead to better performance. Hence, using air or void as the moderator causes considerably better results and can have a better tritium production rate than moderators such as light or heavy water.

5. Conclusion

In this study, the effects of removing the moderators of the SABR hybrid reactor on its performance have been investigated, and then the results have been compared with the status of using light or heavy water and liquid sodium as the moderator. For this, an experiment was simulated using void or air as moderators (for the case of a removed moderator) using the MCNPX 2.7.0, and neutronic parameters of tritium production flux, and released fission energy parameters were analyzed. The final results were compared with the previous results of another study on the SABR reactor. The results showed that removing the moderator can be considered in order to optimize the performance of a typical fusion-fission hybrid reactor. The results of the released fission energy parameter showed that in the case of using light or heavy water against the low-energy neutrons, the hybrid reactor would have better performance, while in the case of high-energy neutrons, removing the moderator leads to better performance. Removing the moderators can also have a positive effect on the tritium production rate, having a better tritium production rate than using moderators with light or heavy water.

It could be concluded from the results that the status of removing the moderators can cause to an increment for neutronic flux and the related neutronic parameters, which are effective parameters for the neutronic economy of a reactor. Hence, this deletion is acceptable according to the enrichment of fissile or fertile fuels mentioned in the introduction. Besides, removing the moderators reduces the technologic problems and failures related to the moderators, and decreases the costs of the reactor designation and building, as well, so that the modern designs, which are based on the deletion of the moderators of hybrid reactors, are strongly assumable and recommended.

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