Neutronics Effect Study of Homogeneous Model on Solid Breeder Blanket

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INTRODUCTION

Background

- CFETR (China Fusion Engineering Test Reactor) is a new tokamak test reactor being designed in China aimed to bridge gaps between ITER (International Thermonuclear Experimental Reactor) and DEMO [1-2];
- Solid breeder blanket concept is considered for CFETR;

Motivations

- Homogeneous neutronics model is adopted internationally, but this may cause some concerns:
  - Different materials of the breeding blanket are mixed together according to their volume fractions in each functional region, but real neutron flux distribution in the real structure may be different, which may cause calculation error;
  - Space self-shielding effect caused by pebble beds is neglected in the regions of Li4SiO4 pebble beds and Be pebble beds;
  - The effects of neutron moderation, especially for water-cooled concept, are small in the homogenous model, which may lead to incorrect results of the neutron spectrum and the neutron flux distribution.

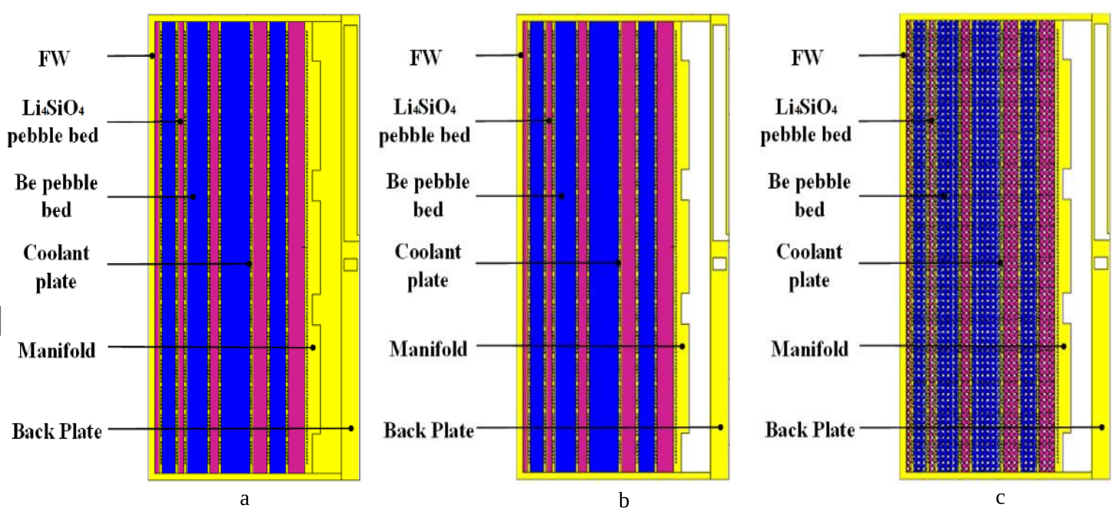
Research Significance

- Provide foundations for CFETR solid breeder blanket design.

HIGH-FIDELITY MODEL OF SOLID BREEDER BLANKET

Neutronics Models

- Model A
  Homogenous neutronics model
  homogenous in structure and pebble beds
- Model B
  Half homogeneous neutronics model
  homogenous only in pebble beds
- Model C
  High-fidelity neutronics model
  non-homogenous

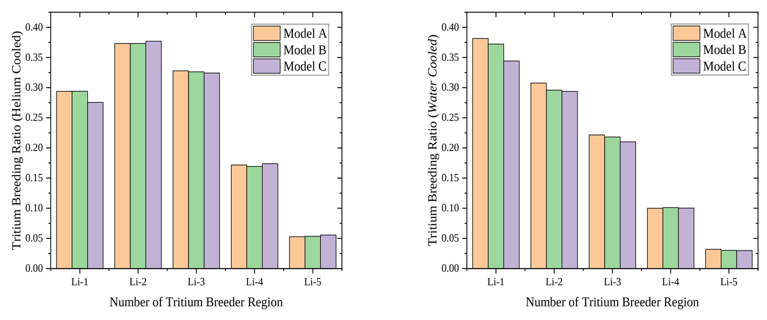


Neutronics models of solid breeder blanket [3-4]. (a: model A; b: model B; c: model C)

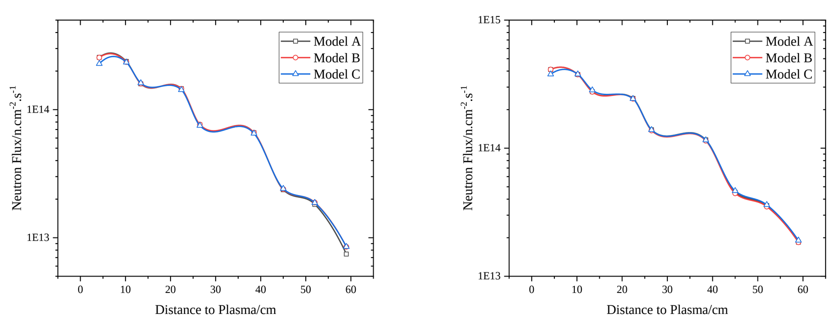
NEUTRONICS EFFECTS OF HOMOGENEOUS STRUCTURE

Neutronics Analyses

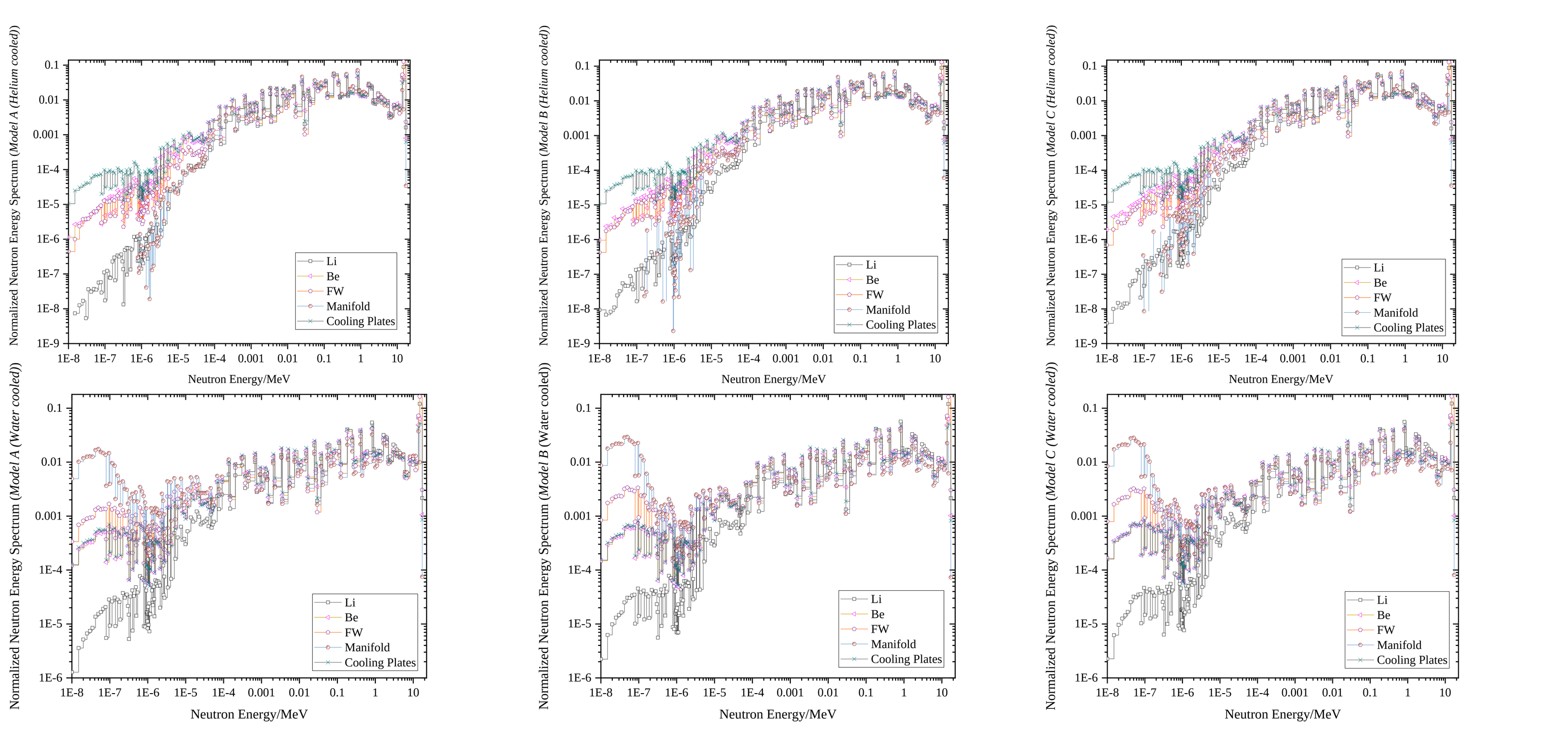
- Transport code: MCNP 4C;
- 10 million particles are simulated;
- A packing fraction of 52.36% in both the Li4SiO4 and Be pebble beds is assumed;
- A general neutron source of a Gaussian fusion energy spectrum is added in the front of FW;
- Reflecting boundaries in toroidal and poloidal;



Tritium breeding ratio of each neutron multiplier region. (left: Helium-cooled; right: Water-cooled)



Radial distribution of neutron flux



Normalized neutron energy spectrum of each region.

Tritium breeding ratio and relative difference of each model.

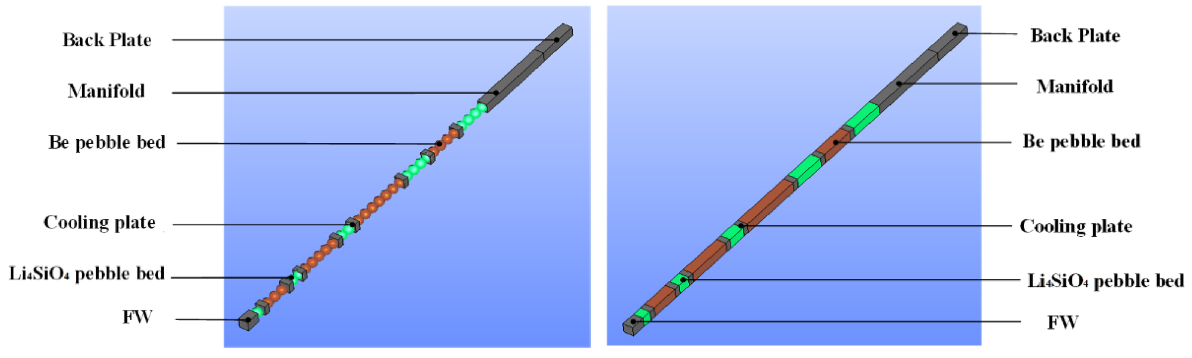
Coolant Type	Model	TBR	Relative difference
Helium	Model A	1.219	0.3% (Ref Model B)
	Model B	1.216	0.3% (Ref Model C)
	Model C	1.212	Ref
Water	Model A	1.042	2.5% (Ref Model B)
	Model B	1.017	4.0% (Ref Model C)
	Model C	0.978	Ref

- Helium-cooled condition: ~0.3% TBR overestimation;
- Water-cooled condition: ~2.5% increasement of the TBR due to the neutron moderation in H2O.

NEUTRONICS ANALYSIS OF SPACE SELF-SHIELDING EFFECT

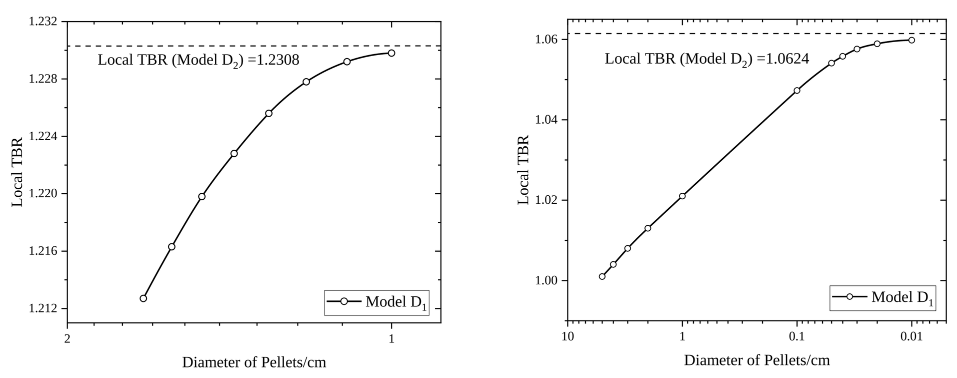
Simplified Neutronics Model

- Model D1
  Homogeneous in structure
- Model D2
  Homogeneous in structure and pebble beds



Simplified neutronics model of solid breeder blanket (left: model D1; right: model D2)

Space self-shielding effect analysis



Local TBR of model D1 vs the diameter of pellets (left: Helium-cooled; right: Water-cooled)

$$\nu_{^6Li} = \frac{4}{1-(1-\frac{1}{\varepsilon})\frac{M_{^6Li}}{M_{^7Li}}} \qquad \nu_{^7Li} = 4-\nu_{^6Li}$$

$$N_i = \nu_i \frac{\rho_{Li_4SiO_4} N_0}{M_{Li_4SiO_4}}$$

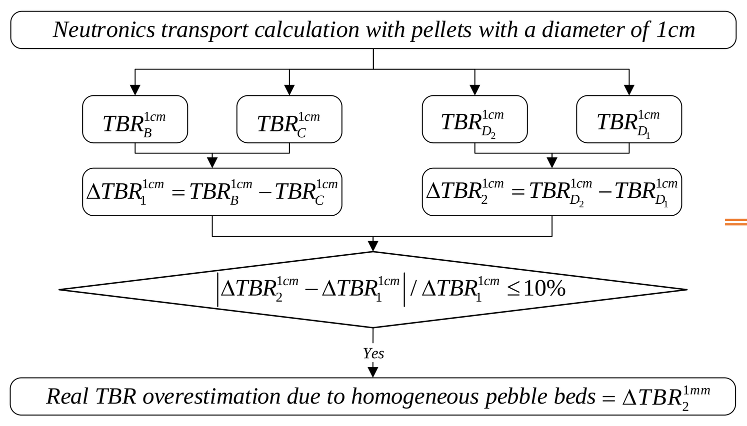
$$\lambda_{Li}^{(n,t)} = \frac{1}{N_{^6Li}\sum_{i=1}^{G}\sigma_{^6Li}^{i}\frac{\phi_i}{\sum_{i=1}^{G}\phi_i} + N_{^7Li}\sum_{i=1}^{G}\sigma_{^7Li}^{i}\frac{\phi_i}{\sum_{i=1}^{G}\phi_i}}$$

Neutron mean-free path of (n,T) reaction of Li in each tritium breeder region

Regions	(Helium-cooled) /cm	(Water-cooled) /cm
Li-1	5.20	4.14
Li-2	4.19	3.77
Li-3	3.80	3.59
Li-4	4.12	4.10
Li-5	4.96	4.35

- TBR shows an increasing trend if the diameter of pellets gets smaller and the local TBR of Model D1 is close to that of Model D2;
- Helium-cooled condition: TBR overestimation is ~0.1% if the diameter is 1mm.
- Water-cooled condition: TBR is larger by about ~1.3% if the pellet diameter is assumed to be 1mm;

Verification for space self-shielding effect



Flow chart of the verification of neutronics effect of space self-shielding

TBR increasement comparison

Coolant Type	ΔTBR_1^{1cm}	ΔTBR_2^{1cm}
Helium	0.3%	0.3%
Water	4.0%	3.8%

- Rational to use simplified neutronics models for space self-shielding effect analysis.

CONCLUSION

- The homogeneous model has small impacts on the performance of the helium-cooled condition, but the TBR will be overestimated by ~2.5% in the water-cooled one;
- The space self-shielding effect caused by the pebble beds has little influence on the neutronics performance if it is helium-cooled, yet ~1.3% overestimation for the TBR if it is water-cooled;
- Homogeneous model is rational for neutronic analyses of helium-cooled plan but not for water-cooled concept and high-fidelity model should be adopted in the neutronics transport calculation.

ACKNOWLEDGEMENTS / REFERENCES

Acknowledgements

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