Neutronics Effect Study of Homogeneous Model on Solid Breeder Blanket

Nuclear performance evaluation is the core basis of tritium breeding blanket design and also the key input for thermo-hydraulic and thermo-mechanic numerical analysis. Whereas, the tritium breeding blankets have the features of complex structure, heterogeneous neutron flux distribution and a long energy span of neutron, which are considerable challenges for neutronic model description and transport calculation. Normally, the homogeneous blanket models, especially for the pebble bed of tritium breeder and neutron multiplier, are used worldwide for the neutronics calculation, however, the accuracy and applicability of this method need to be assessed considering the heterogeneous configuration of blanket. Referring to the blanket design of China Fusion Engineering Test Reactor (CFETR), the homogeneous model and high-fidelity model for neutronics calculation have been built. The neutronics effect of the homogeneous structure and the space self-shielding effect of pebble beds are studied separately considering two different types of coolant, helium and water. The calculation deviation of the homogeneous model comparing with the high-fidelity model is obtained, which will provide strong support for neutronics design and optimization of tritium breeding blankets, such as Chinese ITER helium cooled ceramic breeder test blanket module (HCCB TBM) and CFETR blanket.

Figure 1: Neutronics models of solid breeder blanket.

Firstly, the homogenous neutronics model (homogeneous both in structure and pebble beds, Model A), half-homogeneous neutronics model (homogenous only in pebble beds, Model B) and high-fidelity neutronics model (heterogenous, Model C) are performed by using the McCAD code individually. In the homogeneous model, different materials of the breeding blanket are mixed together according to their volume weights in each functional region. The reflecting boundaries are applied in these three models, including both toroidal and poloidal directions. Significantly, a packing fraction of 52.36% (simple cubic packing) in both the Li$_4$SiO$_4$ and Be pebble beds is assumed. A general neutron source is adopted and it is a Gaussian fusion energy spectrum which is added in the front of the first wall (FW). ODS steel is selected as the structure material, and Li$_4$SiO$_4$ as the breeding breeder in the pebble bed regions and Be is utilized as the neutron multiplier.
Secondly, Model A and B are considered for studying the neutronics effect of homogeneous structure on the solid breeder blanket. The MCNP code is applied for the 3D neutronics transport calculation for the solid breeder blanket, and FENDL2.1 is used. Nuclear performance evaluation, including the TBR (Tritium Breeding Ratio), neutron flux and neutron energy spectrum of each tritium breeding region is performed. Also, the neutron mean-free paths of Li in each tritium breeder regions are calculated. The results indicate that the homogeneous structure has small impacts (~0.30% TBR overestimation from 1.2162 to 1.2194) on the performance of the helium-cooled blanket concept, but makes the TBR overestimated by ~2.48% (from 1.0173 to 1.0425) in the water-cooled blanket concept due to the moderation of water towards neutrons.

Thirdly, the diameter of the pellet is assumed to be 0.8-1.2mm and there are more than one hundred million (~1E8) pellets in a single solid breeder blanket module and the MCNP input file will exceed ~3GB, which demands a huge amount of computer memories making it difficult to get solution. Therefore, two simplified models, Model D1 (homogeneous in structure, but real structure for pebbles) and Model D2 (homogeneous both in structure and pebble beds), are adopted. The space self-shielding effect is assessed in Model C and Model D1 with pellets of 1cm in diameter individually. Results show that the TBR overestimations are ~0.33% and ~0.30% in helium-cooled concept and ~4.02% and ~3.78% in water-cooled concept separately, which indicates that these two results are in good coincidence with each other. Therefore, simplified models are verified to be rational for performing space self-shielding neutronics analysis with pellets of real size.

Finally, nuclear performance evaluation with pellets of real size is performed and results indicate that the space self-shielding effect caused by the pebble beds has little influence on the neutronics performance if it is helium-cooled, yet ~1.28% overestimation for the TBR if it is water-cooled with 1mm diameter pellets. Based on Model D1, the TBR vs the diameter of pellets is also studied which implies that the overestimation could be omitted if the pellet diameter gets smaller to ~0.1mm for water-cooled blanket concept.

In conclusion, the homogeneous model is rational for neutronic analyses if the coolant is helium. Yet, there is non-negligible overestimation for the TBR of water-cooled blanket concept with more than 1mm diameter pellets, and high-fidelity model should be adopted during the neutronics transport calculation.

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