Theoretical calculation and analysis modeling for the effective thermal conductivity of Li$_4$SiO$_4$ pebble bed

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ABSTRACT

The effective thermal conductivity of Li$_4$SiO$_4$ pebble bed is an important design parameter and must be known for the thermo-mechanical design of solid breeder blankets. The theoretical calculation and modeling analysis for the effective thermal conductivity of Li$_4$SiO$_4$ pebble bed are performed in this paper. The 2D and 3D theoretical equations for the thermal conductivity of Li$_4$SiO$_4$ pebble bed are given, moreover compared with the modeling results and other experimental data. The results show that the effective thermal conductivity of Li$_4$SiO$_4$ pebble bed can be preliminarily obtained by analysis modeling or theoretical calculation under the lack of experimental set-up at present.

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1. Introduction

ITER is a joint international research and development project that aims to demonstrate the scientific and technical feasibility of fusion power. A main function of ITER is to test the tritium producing TBM (Test Blanket Module). CN HCSB (Chinese Helium Cooled Solid Breeder) TBM to be tested on ITER is designed to check and validate the technologies of breeding tritium, which is important for the development of China DEMO fusion reactor in the future. CN HCSB TBM consists of U-shaped FW (first wall), caps, backplate, stiffening grids, breeding sub-modules and support plates, etc., as shown in Fig. 1. And CN TBM considers RAFMs (reduced activation ferritic/martensitic steel) as structure material, lithium orthosilicate (Li$_4$SiO$_4$) as tritium breeder in a form of pebble with the diameter of about 0.5–1 mm, beryllium as neutron multiplier also in pebble form, helium as coolant and purge gas, respectively.

For the thermo-mechanical design of solid breeder blankets, the effective thermal conductivity of pebble bed is an important design parameter and must be known. In China, the construction of experimental set-up for the pebble bed is still being planned and prepared now, so it might be a feasible choice to firstly calculate and model the thermal conductivity of pebble bed based on the heat transfer law of Fourier and other experimental results.

As far as the pebble bed bulk region is concerned, conduction is the dominant mechanism of the macroscopic thermal behavior. The velocity of the purge gas was so low (∼1 mm/s) that the convection does not affect the effective thermal conductivity of the pebble bed, i.e. the pebble bed can be considered under a stagnant condition [1]. The radiative heat transfer also seems to be negligible due to the relatively low temperature (<1000 K) envisaged within the pebble bed [2].

And for the Li$_4$SiO$_4$ pebble bed, Dalle Donne et al. [3] measured its effective thermal conductivity using the experimental device PEHTRA; and gave a linear function depending on the mean temperature of pebble bed; subsequently, Reimann and Herrmsmeyer [4] investigated the thermal conductivity of compressed ceramic breeder pebble bed in the uniaxial compression tests (UCTs) combined with the pulsed hot wire method (HWM), and the experimental results show that the effect of thermal conductivity increase with bed deformation is quite small and might be neglected at high temperatures because of the small conductivity ratio of pebble material to gas atmosphere.

Therefore, the model adopted in this paper for the calculation of thermal conductivity of Li$_4$SiO$_4$ pebble bed is a simple thermal conduction model, which only depends on the model shape (packing factor $\gamma$) of pebble bed and the thermal conductivity of purge gas helium and solid pebble material. In the following Sections 2 and 3, 2D and 3D models will be described in detail, respectively.

2. 2D calculation and modeling

Fig. 2 shows the 2D schematic array of pebble with the theoretical packing factor of 78.5%, the green color is the type of Li$_4$SiO$_4$ pebbles with the diameter of 0.5 mm, the yellow is the typical purge