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Effects of random pebble distribution on the multiplication factor in HTR pebble bed reactors

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ABSTRACT

In pebble bed reactors the pebbles have a random distribution within the core. The usual approach in modeling the bed is homogenizing the entire bed. To quantify the errors arising in such a model, this article investigates the effect on k_{eff} of three phenomena in random pebble distributions: non-uniform packing density, neutron streaming in between the pebbles, and variations in Dancoff factor. For a 100 cm high cylinder with reflective top and bottom boundary conditions 25 pebble beds were generated. Of each bed three core models were made: a homogeneous model, a zones model including density fluctuations, and an exact model with all pebbles modeled individually. The same was done for a model of the PROTEUS facility. k_{eff} calculations were performed with three codes: Monte Carlo, diffusion, and finite element transport. By comparing k_{eff} of the homogenized and zones model the effect of including density fluctuations in the pebble bed was found to increase k_{eff} by 71 pcm for the infinite cylinder and 649 pcm for PROTEUS. The large value for PROTEUS is due to the low packing fraction near the top of the pebble bed, causing a significant lower packing fraction for the bulk of the pebble bed in the homogenized model. The effect of neutron streaming was calculated by comparing the zones model with the exact model, and was found to decrease k_{eff} by 606 pcm for the infinite cylinder, and by 1240 pcm for PROTEUS. This was compared with the effect of using a streaming correction factor on the diffusion coefficient in the zones model, which resulted in $\Delta_{streaming}$ values of 340 and 1085 pcm. From this we conclude neutron streaming is an important effect in pebble bed reactors, and is not accurately described by the correction factor on the diffusion coefficient. Changing the Dancoff factor in the outer part of the pebble bed to compensate for the lower probability of neutrons to enter other fuel pebbles caused no significant changes in k_{eff}, showing that variations in Dancoff factor in pebble bed reactors can be ignored.

1. Introduction

The pebble bed nuclear reactor is one of the main candidates for the next generation nuclear power plants. In pebble bed type HTRs, the fuel is contained within graphite pebbles, which form a randomly packed bed inside a graphite-walled cylindrical cavity. Due to the stochastic nature of this bed, the location of the individual pebbles is not well defined.

The pebble bed in such a reactor is commonly modeled as a homogeneous mixture of the pebble and coolant materials, with a uniform density throughout the core. Unfortunately, such a model does not include all effects due to the heterogeneity of the pebble bed, resulting in possible errors. Three of these effects are the density fluctuations in the pebble bed near the wall, neutron streaming through the void space between the pebbles, and variations in the Dancoff factor near the edge of the pebble bed.

Benenati and Brosilow (1962) showed that the radial void fraction profile of a pebble bed shows large fluctuations near the cylinder wall that dampen out at about five ball diameters from the wall. See Fig. 1 for an example of the radial packing fraction profile in randomly stacked beds. These density fluctuations in the pebble bed can have a significant effect on the thermodynamics, for example due to wall channeling of the coolant flow (Schertz and Bischoff, 1969) or peaks in the power distribution. Assuming a radial density profile from Benenati and Brosilow, Terry and Ougouag (2003) found that including the radial density fluctuations leads to a small increase in k_{eff}.

Another effect neglected when homogenizing the pebble bed is neutron streaming. In a pebble bed, the space in between the pebbles is filled by helium. Neutrons can stream through this void space, increasing their migration length. The neglect of this in the homogenized model leads to an underestimation of neutron transport, resulting in less neutron leakage out of the pebble bed to the reflector and a lower k_{eff} of the system (Behrens, 1949).

To take into account the streaming effect in diffusion calculations, Lieberoth and Stojadinović (1980) proposed a streaming

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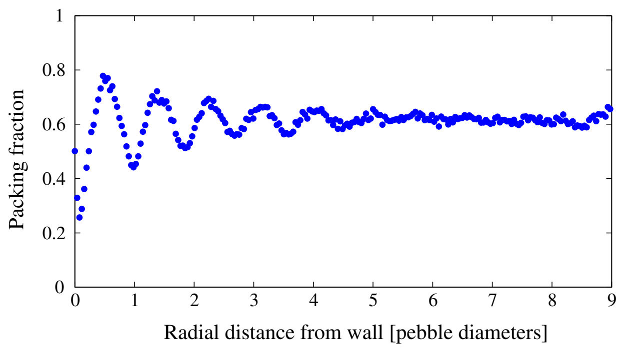

Fig. 1. Radial packing fraction profile of a randomly stacked packed bed of 5000 pebbles, measured using the PebBEx setup (Auwerda et al., 2010).

correction factor, increasing the diffusion coefficient to take into account the increased transport of neutrons. Wallerbos (1998) investigated the streaming effect for various core layouts of the LEU-HTR PROTEUS experimental facility at PSI, Switzerland (Williams et al., 2001). By comparing calculations using homogenized core models with calculations in which all pebbles were modeled individually, Wallerbos found significant reductions (1.5–3.3%) in k_{eff} due to neutron streaming. By similar means, Koberl and Seiler (2004) found reductions of 0.5–1.5% for various PROTEUS core loadings. Both investigated deterministic core loadings, with hexagonal close packed or columnar hexagonal (point-on-point) pebble stackings, in which the pebble locations were well defined. To our knowledge, the streaming effect in randomly packed pebble beds has not been quantified yet.

A third effect neglected in a homogenized pebble bed is related to the Dancoff factor. The Dancoff factor describes the probability of a neutron exiting a fuel kernel to enter another fuel kernel before interacting with other media and is an important parameter to calculate self-shielding parameters in the fuel. Near the edge of the pebble bed, pebbles are not completely surrounded by other pebbles, and a neutron exiting a fuel pebble will have a lower probability of entering a fuel kernel in another fuel pebble before scattering than in the center of the bed. This results in a lower Dancoff factor near the edge of the pebble bed, leading to lower resonance self-shielding and higher absorption cross sections for the fuel. However, the magnitude of this effect on k_{eff} is yet unknown.

To quantify the errors arising in homogenized pebble bed models, this article investigates the effect of three phenomena in random pebble distributions on k_{eff}: density fluctuations in the pebble bed, the neutron streaming effect, and a non-uniform Dancoff factor. The magnitude of the three effects was calculated for a simple model of an infinite cylinder, and for a model of the PROTEUS experimental facility (Mathews and Williams, 1995). For the cylindrical model 25 different pebble bed stackings were generated to investigate statistical effects of the random stacking.

For each pebble bed generated, three different core models were constructed: a homogeneous model, a zones model including the non-uniform packing fraction profile using homogenized zones, and a pebbles model with all pebbles modeled individually. For each core model, the k_{eff} was calculated using a Monte Carlo transport code. Additionally, the k_{eff} of the homogenized and zones models was calculated with a diffusion code and a finite element based neutron transport code.

The effect of the density fluctuations on k_{eff} was calculated by comparing results for the homogeneous model with the zones model. The streaming effect was calculated from the difference between the zones model and the pebbles model. The calculated streaming effect was compared with the change in k_{eff} when applying the streaming correction factor to the diffusion calculations. The effect of changes in the Dancoff factor was investigated by calculating the change in k_{eff} when using a lower Dancoff factor in the outer layer of the pebble bed.

Section 2 describes the geometry models, as well as the code developed to generate the randomly stacked pebble beds. Section 3 explains the methods used to calculate the Dancoff factor and to generate the cross sections. The calculation of the streaming correction factor on the diffusion coefficient is detailed in Section 4. Results for the calculations on the infinite cylinder model are in Section 5. Section 6 gives the geometry model for the PROTEUS facility as well as the results of the calculations. The last section contains the conclusions on the importance to k_{eff} calculations of the density fluctuations, the streaming effect and changes in the Dancoff factor in randomly stacked pebble beds.

2. Geometry model

A simple model of an infinite cylinder was used to study the effects of the pebble distribution on the multiplication factor in a controlled fashion. The model consisted of a cylindrical cavity with a radius of 62.71 cm containing the pebble bed, surrounded by a radial graphite reflector with an outer radius of 163.1 cm. The model was 100 cm high, and the top and bottom had reflective boundaries.

The pebble bed consisted of a 1:1 mixture of fuel and moderator pebbles with a diameter of 6 cm. The parameters of the model were taken from the LEU-HTR PROTEUS experiment (Williams, 1995). The moderator pebbles were made of pure graphite, while the fuel pebbles consisted of a central fuel zone of 2.35 cm radius in which the TRISO particles were dispersed in a graphite matrix, surrounded by a 0.65 cm thick outer graphite shell. Each fuel pebble contained 9394 TRISO particles. The TRISO particles consisted of a UO_2 fuel kernel (16.7% enriched) of 0.02510 cm radius, surrounded by a graphite buffer layer of 0.00915 cm thick, an inner pyrocarbon layer of 0.00399 cm, a silicium–carbon layer of 0.00353 cm, and an outer pyrocarbon layer of 0.00400 cm.

2.1. Generating the pebble bed

To generate the pebble coordinates, a numerical tool was developed based on the method described in Mrafko (1980). First N_{sph} points are chosen randomly within a reference space, representing the initial centers of the spheres, disregarding overlap. Next the sphere radius is set to its initial value $R_{sph,init}$ and this radius is increased in N steps to the desired final radius. In each step, a numerical loop is run over all spheres. If a sphere intersects with a wall the overlap is removed by moving the sphere a distance equal to the overlap away in a direction perpendicular to the wall. If the sphere intersects with its nearest neighbor, both spheres are moved an equal distance apart along their line of intersection until they are touching. When moving the spheres, the creation of new overlaps is allowed. This is repeated until no overlaps remain. Then the pebble radius is increased, after which the overlaps are removed again in another cycle.

The code was validated by comparing average and radial packing fractions of pebble beds generated by the code with experimental measurements performed on a perspex pebble bed model. Characteristics of the generated pebble bed compared well with measurements (Auwerda et al., 2010).

By using different random seeds to initialize the code, 25 different pebble beds were generated. Pebble beds were generated using 10,000 pebbles in a cylinder with a radius of 62.71 cm and a solid bottom, resulting in pebble beds approximately 155 cm high. To remove any influence in the pebble bed due to the bottom of the cylinder, the bottom 40 cm of the bed was discarded. The section