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Comparison of Experiments and Calculations of Void Fraction Distributions in Randomly Stacked Pebble Beds

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ABSTRACT

In pebble bed reactors the fuel forms a randomly stacked pebble bed with non-uniform fuel densities, affecting neutronics (streaming) and thermodynamics (wall channeling). To investigate these effects, computational tools are needed capable of generating realistic pebble beds, and experimental results to validate these tools. Using gamma-ray scanning the absolute ϵ_0 and radial void fraction profile $\epsilon_r(r)$ of a randomly stacked pebble bed was measured. Results were used to validate three different methods: Discrete Elements Method (DEM), Monte Carlo (MC) rejection method, and expanding system method. The bed consisted of 5457 acrylic pebbles with a diameter $d = 12.7$ mm in an acrylic cylinder with diameter $D = 229$ mm ($D/d = 18.0$), and had an average void fraction $\epsilon_0 = 0.395$. The radial void fraction profile showed large, dampened oscillations near the wall extending up to five pebble diameters into the pebble bed, with a minimum void fraction of 0.22 half a pebble diameter away from the wall. The MC rejection method resulted in a ϵ_0 much higher than measured, and could not reproduce well the oscillations in ϵ_r observed in the experiment. Both the DEM and expanding system method showed excellent agreement with the experiment for both ϵ_0 and ϵ_r, with the expanding system method having the benefit of creating pebble beds with no overlapping pebbles, suitable for exact pebble bed models in other codes.

Key Words: Pebble bed, void fraction, HTR, DEM

1. INTRODUCTION

In pebble bed type HTR's the fuel is contained within graphite pebbles, which form a randomly packed bed inside a graphite-walled cylindrical cavity. As a result there is no a priori knowledge of the exact location of the pebbles, and thus of the fuel. It has been shown that such a random distribution will exhibit non-uniform fuel densities, especially near the reflector wall [1]. The effect of the non-uniform pebble distribution can be significant for both neutronics, due to neutron streaming for example [2], as well as thermodynamics, for example due to the wall channeling effect of the coolant flow [3]. To facilitate research on these effects, computational tools capable of generating randomly stacked beds of hard spheres are needed, and experimental results to validate these tools.

Over the years several experiments have been performed to measure void fractions in packed beds. Benenati and Brosilow [4] poored uniformly sized spherical lead shot into a container and then filled up the interstices with a liquid epoxy resin. Upon curing of the resin, the solid cylinder was machined in stages to successively smaller diameters and the weight and diameter of the cylinder was measured after each machining. In this manner the mean density of each annular ring removed could be determined and from that the void fraction. They showed that the radial void fraction profile shows large fluctuations near the cylinder wall that dampen out at about 5 ball diameters from the wall, and that for packed beds the average void fraction goes to 0.39 for very large D/d ratios. Goodling et. al. [5] used a similar method, filling a cylinder with polystyrene spheres and then epoxy to fill the void. Finely ground iron was mixed with the epoxy in order to increase its density well above that of the spheres. After hardening of the epoxy, the resulting cylinder was machined and weighted, and the void fraction determined from the density of the removed annulus. Mueller [6] used a non-destructive method by filling cylinders with specially prepared plexiglas spheres with a small steel sphere at their center. The coordinates of the spheres were determined using X-ray radiography and the radial void fraction distribution was determined from these center coordinates.

In more recent years computational methods to generate randomly stacked pebble beds got more attention. du Toit [7] applied a Discrete Elements Method (DEM) to generate void fraction profiles in pebble beds for use in reactor thermal-hydraulics studies. Both Cogliati [8] and Rycroft [9] used DEM to simulate pebble flow in pebble bed reactors, and Kloosterman [10] applied a Monte Carlo rejection method to generated pebble bed stackings for the calculation of spatially-dependent Dancoff factors.

In this paper a new non-destructive method to measure radial void fractions of pebble beds is presented, and used to measure the radial void fraction profile of a randomly stacked pebble bed. Subsequently, the results are used to evaluate three different computational methods to generate randomly stacked pebble beds: the Discrete Elements Method (DEM), a Monte Carlo (MC) rejection method, and an expanding system method. Pebble beds with identical pebble and vessel dimensions as in the experiment are generated by the three methods, and the average void fraction ϵ_0 and radial void fraction ϵ_r of the generated pebble beds are compared with each other and with the experimental results. Additionally the axial void fractions ϵ_z of the computationally generated beds are compared with each other.

The following section outlines the PebBEx (Pebble Bed Experiment) facility used to perform the void fraction measurements. Section 3 details the three computational methods investigated. The results of the measurements and computations are in section 4 together with their discussion, followed in section 5 by the conclusions and recommendations for further work .

2. THE PEBBEX FACILITY

The PebBeX facility is a Pebble Bed Experimental setup at the Reactor Institute Delft (RID) of the Delft University of Technology and has been developed to measure void fractions of packed beds of pebbles using gamma-ray scanning [11]. See figure 1 for a schematic overview and photograph of the setup. The setup consists of a cylindrical vessel of acrylic plastic, with a height of 235 mm and an inner diameter of $D = 229$ mm. The vessel can be filled with acrylic pebbles of various sizes. For this experiment pebbles of $d = 12.7$ mm were used, resulting in a D/d ratio of 18.0.

The radial void fraction of the pebble bed is measured using an Am-241 source with an activity of 11.1 GBq on 01-01-1968. The main gamma peak at 59.5 keV was used by applying single channel analysers. The attenuation coefficient of the used acrylic (PMMA) for this energy was experimentally determined to be 0.2288 ± 0.004 cm^{-1}. The source is placed above the experiment, followed by a collimator with a diameter of 1 mm, creating a narrow beam downwards through the pebble bed. Below the pebble bed the intensity of the beam is measured using a NaI(TI) scintillation detector, topped by a second collimator. From the measured intensity of the beam the amount of acrylic in the path of the gamma beam can be calculated. The vessel itself can be rotated and moved sideways using two motors. By measuring the void fraction while rotating the vessel the (average) radial void fraction at a certain distance from the wall can be measured. Moving the vessel sideways in between the radial void fraction measurements in small steps allows measuring the void fraction at various radial positions.

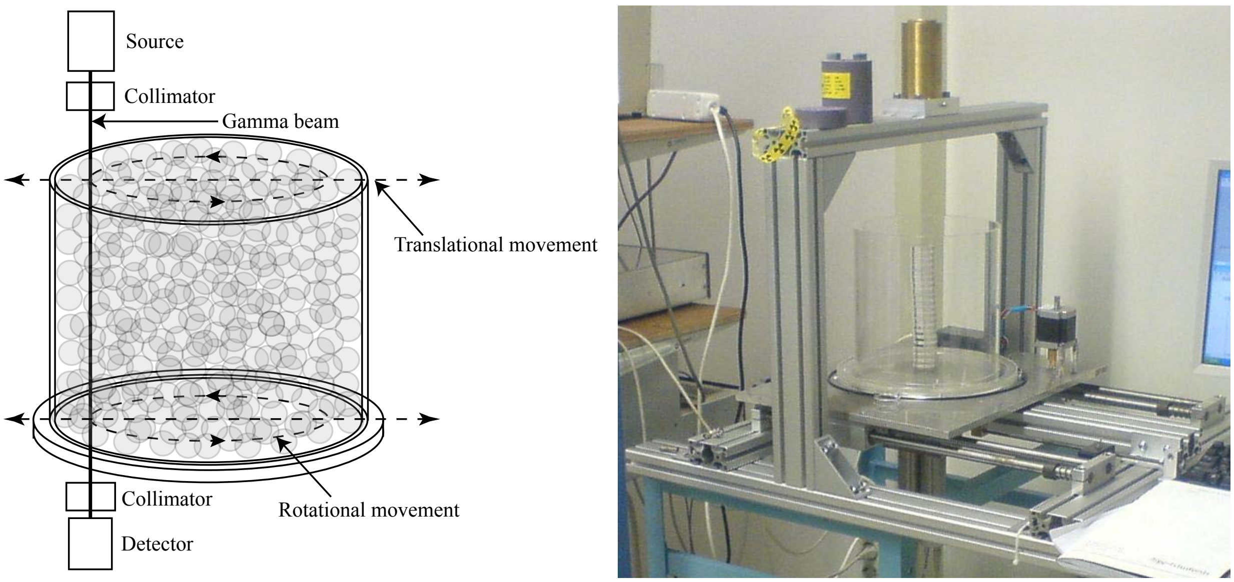

Figure 1. Schematic overview and photograph of the PebBEx facility.

To fill the vessel, pebbles were quickly poured in until it was filled almost to the top, after which the last pebbles were carefully placed at the top. To make sure the pebble bed height was as uniform as possible a plate was slowly pushed over the top of the pebble bed. The surplus of spheres which could not find a place were removed from the pebble bed. Care was taken to keep the pressure at a minimum to maintain a pebble bed stacking with a free upper surface. Filling the cylinder in this way required 5457 ± 10 pebbles [12].

3. COMPUTATIONAL METHODS

The literature on the computational generation of randomly packed pebble beds can be divided in two approaches. One approach is to use rigorous algorithms that simulate pebble flow as accurately as possible based on physics laws [7, 13, 14]. The other approach is based on synthetic techniques [14–16], such as a rain model in which a pebble is randomly dropped in the vessel until it reaches another pebble, after which a Monte Carlo shaking routine is used to increase the packing fraction of the bed, or a method in which pebbles are randomly extracted from a regularly packed bed. The first approach is expected to give realistic packing fractions and porosity profiles, while the second is not. However, in the second category of methods overlap of pebbles is easily avoided, whereas for the rigorous methods this is much more difficult. For example, in a packed bed of 5-cm pebbles within a nuclear reactor, it is reported [7] that the average overlap for the rigorous method is 1%, with a maximum of 20%.

To computationally generate randomly stacked pebble beds, three simulation methods were investigated. The first method, the Discrete Elements Method (DEM), is a rigorous method. The other two methods, a Monte Carlo rejection method, and an expanding system method in which the pebble size was increased in several steps, are synthetic methods.

3.1. Discrete Elements Method

The Discrete Elements Method (DEM) is a family of numerical methods for computing the motion of a large number of particles like molecules or grains of sand. It consists essentially of integrating the equations of motion of the system numerically. The fundamental assumption of the method is that the material consists of discrete particles whose trajectories are studied separately. At each time step all the forces working on each particle are calculated, from which the resulting acceleration of each particles is calculated using Newton's second law, which is then time-integrated to find the new particle positions. This process is repeated until the end of the simulation time is reached.

The DEM code used in the current work was written by Abreu [17]. The model takes into account rotational and translational motions of the particles and uses the gravitational force on the particles as well as inter-pebble and pebble-wall contact forces to simulate particle motion. Friction is taken into account through Coulomb's law, using coefficients of friction for pebble-pebble and pebble-wall interactions. The magnitude of the forces pebbles exert on each other depends on their relative velocities and the amount of overlap they have. The magnitude of the normal force between particles in contact depends on the amount of overlap through a spring-like force based on the stiffness of the particles. The energy dissipated during collisions is taken into account by means of normal and tangential coefficients of restitution. After calculating the resulting accelerations, using the initial speed and acceleration of the particles, the equations of motion are solved using the Adams-Bashforth-Moulton predictor-corrector model.

3.2. Monte Carlo Rejection Method

The Monte Carlo Rejection Method used by Kloosterman [10] is a synthetic technique for creating a pebble bed. First a large collection of random points is generated, up to 100,000 times the number of pebbles that fit into the vessel. Then, starting at the bottom of the vessel, each random point is checked as to whether it is suitable as a pebble center coordinate. If a pebble at that coordinate would overlap with other pebbles or structures in the core, it is rejected; otherwise it is accepted, and a pebble is located at that position. Besides some problems that need to be avoided, such as integer overflows, this algorithm is extremely simple to program. Furthermore, overlap of pebbles is easily avoided, whereas for the rigorous methods this is much more difficult. However, as may be expected from the discussion above, no physics are simulated in the model, and the resultant pebble-bed packing does not necessarily reflect all characteristics of a real packed bed.

3.3. Expanding System Code

The third method is based on a method described by Mrafko [18] to generate a random close packing of hard spheres. After randomly generating the initial coordinates of the pebbles, the pebble radius is increased in N steps to its desired radius R_{peb}, while in each step the algorithm eliminates overlap among the spheres by moving them apart.

In the initialization step the pebble coordinates of the N_{peb} pebbles are generated randomly inside the cylinder containing the pebble bed, disregarding overlap. The volume in which the pebbles are initialized has a diameter equal to that of the cylinder, and is located at its bottom, but the height is chosen such that the volume in which the pebbles are initialized is equal to that of the N_{peb} pebbles at their initial radius R_{ini}.

The pebble radius is increased in N steps from its initial value R_{ini} to the desired final pebble radius R_{peb}. The initial radius R_{ini} is typically chosen to be $\frac{2}{3}$ of R_{peb}. The pebble radius is increased in ever smaller steps to increase the sensitivity of the method in each step, following a logarithmic interpolation between initial and final radius

$$R_i = R_{ini} + (R_{peb} - R_{ini}) \log(1 + 9\frac{i-1}{N-1}) \quad (1)$$

with R_i the pebble radius in step i.

In each step overlaps between pebbles are removed by moving the pebbles apart. A loop is run over all pebbles, and for each pebble it is checked if it overlaps with a wall or the closest neighboring pebble. If the pebble intersects with a wall it is moved perpendicular to the wall until it touches the wall. If the pebble intersects with its nearest neighbor, both pebbles are moved an equal distance apart along their line of intersection, until they are touching. When moving the pebbles it is allowed to create new overlaps. If there are no more overlaps, the loop is exited and the pebble radius can be increased again, starting the next iteration.

4. RESULTS AND DISCUSSION

As was mentioned in section 2, the PebBEx facility was filled using 5457 ± 10 pebbles up to its full height of 235 mm, with a flattened horizontal top surface of the pebble bed.

The DEM code would normally create a pebble bed by letting the pebbles fall by gravity on top of each other. This would create an irregular upper surface with possibly a little 'bump' in the middle. To generate a flat upper surface of the pebble bed, additional pebbles were simulated, and after calculations were finished all pebbles (partly) above 235 mm were removed. In the DEM calculation 5700 pebbles were simulated for a total simulation time of 25 seconds. The density of the pebbles was set to 1.19 g/cm^3, the density of acrylic. The coefficient of friction for acrylic was not exactly known, and a value of 0.3 was chosen for the normal and tangential coefficients of friction based on values for polyethylene and polystyrene of 0.2 and 0.5 [19]. Although the value of the coefficients of friction can have an effect on the void fraction, this effect is small, up to 0.01, as was show by Webbe [20]. No significant effect on the packing fraction was observed for the normal and tangential coefficient of restitution. However, they do influence calculation times, as they are the only way of energy to leak away from the system. A lower coefficient of restitution will result in faster dampening of the system, thus reducing the time that has to be simulated before the pebbles stop moving. A value of 0.5 was taken for the coefficients of restitution. A realistic value for the stiffness of the acrylic pebbles would be of the order of 10^7 N/m. However, this would lead to extremely long computation times, as the time step of the DEM simulation is directly proportional to the stiffness of the materials. Also, when the stiffness is set to values of 10^5 and above, the probability of the simulations becoming unstable increases, leading to pebbles moving through walls or shooting away. Thus the stiffness was set to a relatively low value of 10^4 N/m.

As there is no gravity in the expanding system model, the 'pressure' of the pebbles near the top of the cylinder on those below have to take on this role. To make sure the upper part of the pebble bed is still well packed and does not contain any 'floating' pebbles balancing on only one or two other pebbles, a significant amount of extra pebbles have to be simulated to interact downwards. In the expanding system model 8500 pebbles were simulated for $N = 5$ number of steps. Just as with the DEM code, all pebbles not completely below 235 mm were removed.

The MC rejection method always puts the pebbles at the lowest available point, so no tricks with extra pebbles were needed. The simulation terminated as soon as no more points were available below 228.65 mm (235 minus the pebble radius). The simulation was run with a density for the random points of 50,000 points per cm^3.

4.1. Average Void Fraction ϵ_0

The number of pebbles in a cylinder of 229 mm diameter and 235 mm height for both the experiment and the three calculational methods are shown in table I together with the resulting average void fractions ϵ_0. Also given is the calculation time on a desktop computer with an Intel Core Duo 2.0 GHz processor. Besides ϵ_0 for the entire cylinder, the void fraction for the central part of the pebble bed was calculated, representing the void fraction of an infinite packing. This inner void fraction was calculated by calculating the average void fraction in a cylinder with diameter $\frac{4}{9}D$ and height between 0.3 and 0.8 of the height of the larger cylinder containing the bed. These values were chosen such that the borders of the volume were far enough away from the wall not to have any wall effects.

Table I. Measured and calculated average void fractions ϵ_0.

Method of Generation	Number of Pebbles	Void Fraction	Inner Void Fraction	Calculation Time (min)
Experiment	5457	0.3953	—	—
DEM	5424	0.3990	0.3613	348
MC Rejection	4935	0.4532	0.4142	147
Expanding System	5440	0.3972	0.3685	197

The experimental void fraction for the PebBEx setup is $\epsilon_0 = 0.3953 \pm 0.11$, which is in excellent agreement with other experimental results. Benenati [4] found for $D/d = 14.1$ an average void fraction of $\epsilon_0 = 0.395$ and for the HTR-10 pebble bed reactor with a D/d ratio of 30 an average void fraction of $\epsilon_0 = 0.391$ is reported [21].

The MC rejection method generated a pebble bed with a void fraction over 10% larger than the experimental value. Generating the random points for placement of the pebbles at a higher density did not result in a significantly higher packing fraction, $\epsilon_0 = 0.4499$ for $300,000$ points per cm^3, but did increase the calculation time to 807 minutes. Both the DEM and the expanding system method generated pebble beds with void fractions in good agreement with the experimental value. One should consider however, that these packing fractions are for a stacking with exactly touching pebbles in the expanding system method, while the stacking generated by DEM did include overlaps of the pebbles. On average the overlap of the pebbles with the walls or each other was $\sim 1\%$ of the pebble radius, with a maximum overlap of 0.12 mm on a pebble radius of 6.35 mm. This overlap could be reduced by increasing the stiffness of the pebbles in the input, but this causes a large increase in computation time. The presence of these overlaps not only causes an artificial decrease in void fraction, it also results in problems in using DEM created stackings to generate exact models of pebble beds for other computer simulations, such as Monte Carlo type neutronics calculations, due to multiple defined volumes.

The inner void fraction is a representation of the void fraction for an infinite randomly stacked pebble bed without boundary effects. Scott [22] found for the void fraction of an infinite randomly stacked pebble bed a value of 0.3634 by extrapolating experimental results. Comparing this value with those in table I, we see excellent agreement with the inner void fractions for the DEM and Expanding System method. Again the MC Rejection method shows a larger void fraction, although the difference is slightly smaller than for the average void fraction of the entire cylinder.

Calculation times were of comparable order for all three methods, with the DEM method roughly twice as slow as the other two methods. For the generation of larger pebble beds, calculation times for the MC rejection method scale linearly with the number of pebbles. For DEM calculations the increase in calculation time is slightly higher than linear, but still far from quadratic, due to the fact that only immediate neighbors interact with each other, and the usage of a neighboring list [8]. The expanding system method however scales quadratic with the number of pebbles, because overlaps near the bottom of the pebble bed have to propagate through the entire bed before being removed from the system. Thus the number of overlaps that have to be removed in each step until no more overlaps remain increases quadratically with the size of the pebble bed, making the expanding system method unsuitable for the generation of pebble beds of large reactors with hundreds of thousands of pebbles.

4.2. Radial Void Fraction ϵ_r

The radial void fraction $\epsilon_r(r)$ of the PebBeX setup was measured in steps of 0.5 mm. At each position the vessel was rotated two to four times during the measurement. The number of rotations depended on the count rate at the detector, with count rates ranging from 3.1 counts per second half a pebble diameter from the wall to 8 cps just next to the wall. At low count rates, measurement times were increased to make sure the uncertainty was kept uniform, and thus the vessel was rotated more often. Measurements were corrected for background, with a background of 2.51 ± 0.02 cps. As calibration measurements for the empty and full cylinder measurements outside the cylinder for a void fraction of $\epsilon_r = 1$ and through the wall of the vessel for a void fraction of $\epsilon_r = 0$ were used. The final uncertainty in the measurements of the void fraction at each point was between 0.5% and 3%, depending on the local count rate, with higher uncertainty at positions with a lower void fraction. Due to the width of the gamma beam, locating the exact position and boundaries of the cylinder wall from the measured results is difficult. Instead, the center of the pebble bed was located by continuing measuring the void fraction profile after reaching the center of the pebble bed, and mirroring the profile at the center. The center was chosen at the point for which the mirrored measurements had the highest correlation with the measurements just before the center. The measured $\epsilon_r(r)$ profile including uncertainty bars is plotted in figure 2. The uncertainty in the distance from the wall is negligible due to the high precision of the step motor used to move the cylinder.

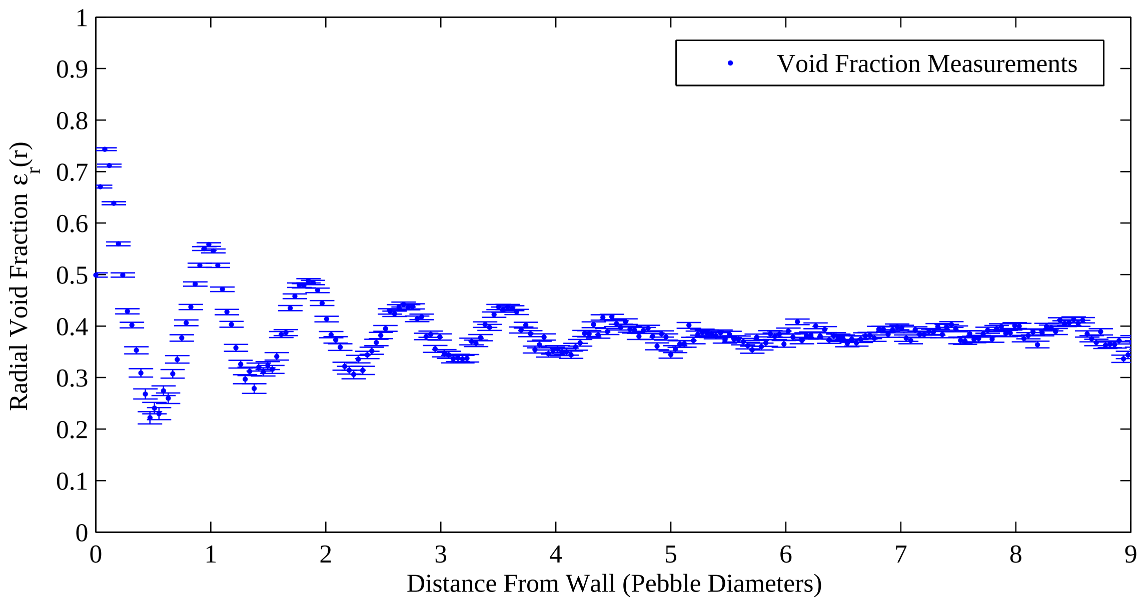

Figure 2. Measured radial void fraction profile $\epsilon_r(r)$ with uncertainty bars.

Although the uncertainty per point is significant, the oscillating behavior of $\epsilon_0 r$ is very clear due to the large number of measuring points. The oscillations are quite large near the wall, with a minimum void fraction of 0.22 half a pebble diameter from the wall. The oscillations dampen out further away from the wall and disappear at about 5 pebble diameters from the wall, just as was observed in previous experiments [4–6]. At the wall one would expect the void fraction to go to unity, instead a slight drop is observed in the measurements less than 0.5 mm away from the wall. This is caused by the finite width of the gamma beam used to measure the void fraction, created by the 1 mm wide collimator. Near the wall, part of the beam will go through the wall itself, causing additional attenuation and a lower measured void fraction. At the other end of the measured range, at the center, a drop in void fraction can be observed. This is caused by the stochastic nature of the experiment itself. Near the center of the pebble bed, the path length over which the void fraction is measured becomes very small, and thus ϵ_r is measured over a small surface. Thus the measurements approach that of a local point, causing larger fluctuations due to local variations in void fraction in the pebble bed. Other measurements showed a slight rise in void fraction, or any other form of irregular behavior near the center of the pebble bed. Averaging the void fraction near the center over multiple experiments using different realizations of the pebble bed would result in a smooth behavior of ϵ_r.

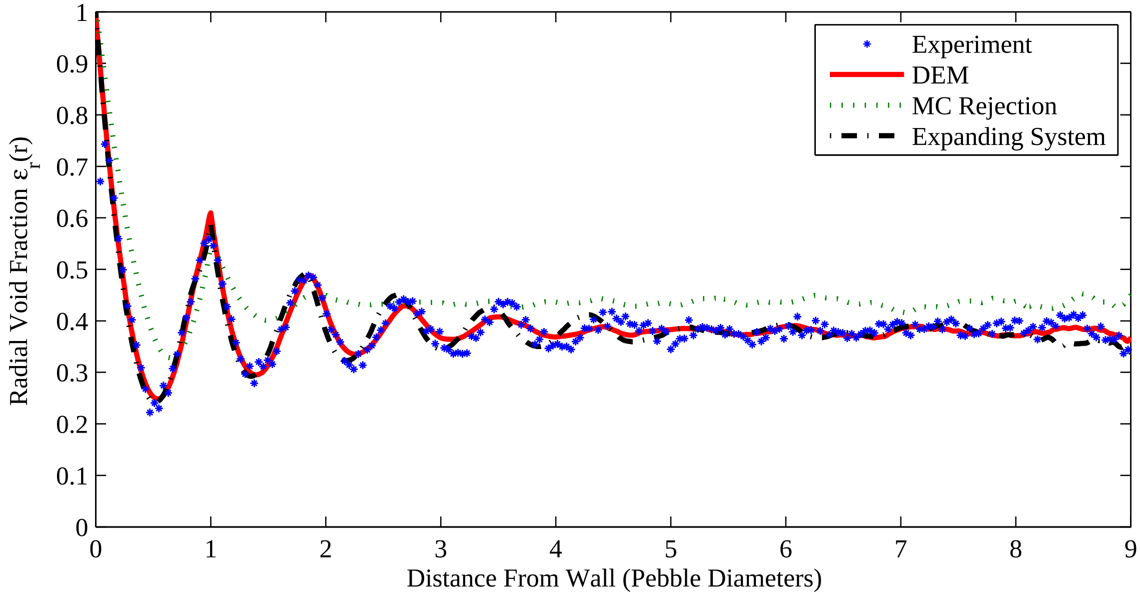

Figure 3. Measured and calculated radial void fraction profile $\epsilon_r(r)$.

The radial void fractions of the three computationally generated pebble beds were calculated from the pebble coordinates and are, together with the experimental results, plotted in figure 3. The ϵ_r profile of the MC rejection method compares poorly with the experimental results. As was expected from the results in table I, the void fraction is too high. Besides this, already next to the wall the profile shows a significantly lower amplitude in the peak in ϵ_r, and after only two pebble diameters from the wall, ϵ_r has flattened out and shows no more oscillations. It is clear from this radial void fraction profile that the MC rejection method, due to the lack of physical or other inter pebble interaction mechanisms, it is not capable of simulating the effect of the wall throughout the pebble bed.

When examining the radial void fraction generated by the DEM, the period of the oscillations in the void fraction profile correspond well with the experimental results, but the amplitude shows a small deviation. After two pebble diameters, the amplitude of the oscillations dampens out faster than in the experiment. A cause could be the overlap of pebbles in the pebble bed. As the sizes of the overlaps depend on the forces on the pebbles, and the forces are larger near the bottom of the pebble bed due to the pressure of the pebbles on top, the overlaps are larger near the bottom. Indeed when looking to a slice of the cylinder between 0.3 and 0.6 of the cylinder height, an average packing fraction of 0.3801 ± 0.0002 was found, while for a slice between $0.6z_{max}$ and $0.9z_{max}$, the average packing fraction was 0.3831 ± 0.0003. Thus, due to a larger overlap, near the bottom the period of the oscillations will be shorter than near the top. This results in a slight variation in the period of the oscillations over the axial length of the cylinder, damping the oscillations in the ϵ_r profile averaged over the cylinder height, with the effect being more pronounced further away from the wall.

The profile generated using the expanding system method does not have this problem. The oscillations dampen out just as fast as those in the measured profile. However, the period of the oscillations is shorter than that of the experiment. Although for the first two oscillations, up to two pebble diameters from the wall, the difference is very small, after about five pebble diameters the shift in the radial position of the peaks is significant. The absence of gravity could be the cause of this effect. As the pebbles form a close packing, they are pressed together and against the walls with no bias to any direction. In reality, pebbles are also pulled downwards by gravity. Since the wall is solid, pebbles can only move down by moving away from the wall, thus slightly increasing the period of oscillations in ϵ_r in the radial direction.

4.3. Axial Void Fraction ϵ_z

Besides the radial void fraction ϵ_r, also the axial void fraction $\epsilon_z(z)$ was calculated for the three computationally generated pebble beds. The axial void fraction was calculated at 1000 intervals along the height of the pebble bed, by calculating at each interval for an horizontal slice through the pebble bed the fraction of surface area of the slice not occupied by pebbles. The resulting axial void fraction profiles are plotted in figure 4.

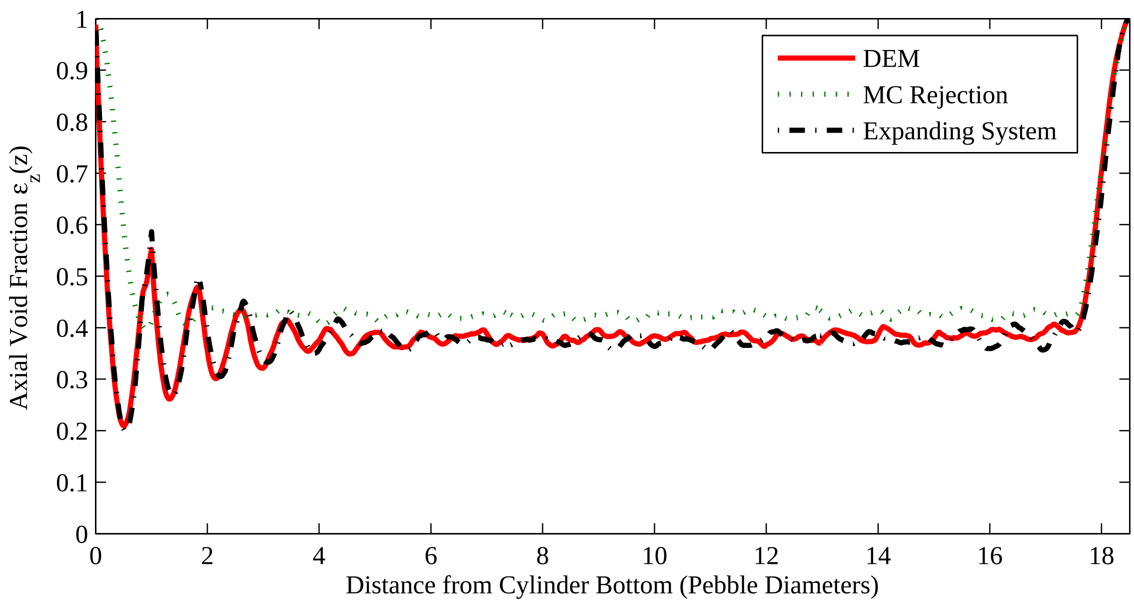

Figure 4. Axial void fraction profiles $\epsilon_z(z)$ for the computer generated pebble beds.

For all three methods, at the top of the pebble bed the void fraction rises towards unity in a distance of one pebble diameter. Here, no oscillations or boundary effects are seen in of the axial profile, as is expected, since the upper boundary is a free boundary, which imposes no restraints on the locations of the pebbles.

From the bottom of the cylinder upwards, the axial void fraction of the MC rejection method drops off much slower than for the other two methods. By placing the pebbles at random coordinates, pebbles are not pushed against each other, resulting in large gaps in between the pebbles forming the bottom layer of the bed. As a result the void fraction drops off a lot slower than for the other two cases. Additionally, as the bottom layer of pebbles has a loose packing, the next layer of pebbles is less restricted to certain heights as in reality, resulting in ϵ_z showing almost no periodic behavior.

The DEM and expanding system methods generated pebble beds with very similar ϵ_z profiles. Both show oscillations in the void fraction due to the wall comparable to those seen in ϵ_r, both in magnitude and period. Again after about 5 pebble diameters the oscillations due to the wall disappear and the void fraction profile stays almost flat, besides random fluctuations. In contrast with the ϵ_r profiles in figure 3, the oscillations in ϵ_z of the expanding system method show a slightly larger period than those of the DEM, starting to be noticeable three to four pebble diameters from the bottom of the pebble bed. The reason could be similar as to why the ϵ_r profile for the expanding system method showed a smaller period than in the experimental and DEM pebble beds. The DEM includes gravity, pushing pebbles tightly together in the axial direction. This force, and thus this bias in direction, is lacking in the expanding system method, and thus the packing is less tightly pushed together in the axial direction than for DEM, resulting in a slightly larger period over which the axial void fraction oscillates. The second contribution to the smaller period in DEM could be due to overlapping pebbles. As the forces on the pebbles are largest near the bottom of the cylinder, due to the pressure of the pebble bed above, here the overlap between pebbles would be largest, and pebbles are pressed into each other. This results in a smaller effective pebble radius, and thus a shorter oscillation period in the axial direction.

5. CONCLUSIONS AND FURTHER WORK

With the PebBEx facility an experimental setup is available with which precise and reliable radial void fraction measurements can be performed on pebble beds in a non-destructive manner. It was confirmed that the average void fraction ϵ_0 approaches 0.39 for randomly stacked pebble beds in a large cylinder, with $\epsilon_0 = 0.395$ for a pebble bed with $D/d = 18.0$. The radial and axial void fractions in such beds show large oscillations near the wall and floor of the cylinder, with a minimum void fraction of 0.22 half a pebble diameter away from the wall. The oscillations dampen out towards the center, extending up to 5 pebble diameters into the pebble bed.

The Monte Carlo rejection method was found to be unsuitable to create realistic randomly stacked pebble beds. The resulting pebble beds average void fraction $\epsilon_0 = 0.45$, significantly higher than in the experiment, and the oscillations in the radial and axial void fraction profiles damp out at two pebble diameters away from the wall. Both DEM and the expanding system method generate pebble beds with absolute and radial void fraction in good agreement with experimental values. Both show small differences in the radial void fraction profiles compared to measurements, starting a few pebble diameters away from the wall. But near the wall, where the oscillations in radial void fraction are large and their effects are most important, there is an excellent agreement with experimental values. Both models are well suited for the generation of density profiles in pebble beds. Additionally, DEM can be used to simulate pebble movement through a pebble bed. However, when an exact model of the pebbles in a pebble bed is needed for use in a subsequent code, the expanding system model is better suited, as pebble beds generated by DEM will include overlapping pebbles, which can cause errors in the geometry of such codes. For small pebble beds, up to ten thousand pebbles, the expanding system method is also faster than DEM. However, for large beds of hundreds of thousands of pebbles, calculation times using the expanding system method will become extremely long, and DEM is expected to be much faster.

Measurements have already been performed with the PebBEx facility on pebble beds with multiple pebble sizes, and on shaken beds [12]. Further experiments should include measurements of the axial void fraction profile for further validation of computer codes. Also the effect of different loading patterns on the void fraction should be investigated, as well as the effect of pressurizing the pebble bed. Another possibility with the PebBEx facility is measuring void fraction profiles on an annular pebble bed, using an already available special insert.

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REFERENCES

[1] D. Bedenig, “Experimentelle Untersuchungen in Stromungsverhalten eines Kugelhaufens im Hinblick auf den Brennelementkreislauf im Core eines Kugelhaufenreactor,” *Institut fur Reaktorentwickelung Kearnforschungsanlage*, Julich, Germany (1962).

[2] J. Lieberoth and A. Stojadinović, “Neutron Streaming in Pebble Beds,” *Nuclear Science and Engineering*, **76**, pp. 336-344 (1980).

[3] W. W. Schertz and K. B. Bischoff, “Thermal and Material Transport in Non-isothermal Packed Beds,” *AIChE Journal*, **15**, pp. 597 (1969).

[4] R. F. Benenati and C. B. Brosilow, “Void fraction distribution in beds of spheres,” *AIChE Journal*, **8**, pp. 359-361 (1962).

[5] J. S. Goodling et al., “Radial Porosity Distribution in Cylindrical Beds Packed with Spheres,” *Powder Technology*, **35**, pp. 23-29 (1983).

[6] G. E. Mueller, “Radial Void Fraction Distributions in Randomly Packed Fixed Beds of Uniformly Sized Spheres in Cylindrical Containers,” *Powder Technology*, **72**, pp. 269-275 (1992).

[7] C. G. Du Toit, “The Numerical Determination of the Variation in the Porosity of the Pebble-Bed Core,” *Proc. Int. Topl. Mtg. High Temperature Reactor Technology (HTR-TN 2002)*, Petten, The Netherlands, April 22-24, 2002, High Temperature Reactor Technology Network (2002).

[8] J. J. Cogliati and A. M. Ougouag, “Pebbles: a Computer Code for Modeling Packing, Flow and Re-circulation of Pebbles in a Pebble Bed Reactor,” *HTR2006, 3rd International Topical Meeting on High Temperature Reactor Technology*, Johannesburg, South-Africa, Oktober 1-4 (2006).

[9] C. H. Rycroft et al., “Analysis of granular flow in a pebble-bed nuclear reactor,” *Physical Review E*, **74** (2006).

[10] J. L. Kloosterman and A. M. Ougouag, “Comparison and Extension of Dancoff Factors for Pebble-Bed Reactors,” *Nuclear Science and Engineering*, **157**, pp. 16-29 (2007).

[11] V. van Dijk, “Radial Void Fraction Measurements of the Pebble-Bed inside a Pebble-Bed Reactor,” *Bsc. Thesis*, TU Delft, The Netherlands (2008).

[12] J. Groen, “Radial Void Fraction Measurement of a Random Multisized Pebble Stacking,” *Bsc. Thesis*, TU Delft, The Netherlands (2009).

[13] P. L. Spedding and R. M. Spencer, “Simulation of Packing Density and Liquid Flow in Fixed Beds,” *Comput. Chem. Eng.*, **19(1)**, pp. 43-73 (1995).

[14] H. Freund et al., “Numerical Simulations of Single Phase Reacting Flows in Randomly Packed Fixed-Bed Reactors and Experimental Validation,” *Chem. Eng. Sci.*, **58**, pp. 903 (2003).

[15] W. Soppe, “Computer Simulation of Random Packings of Hard Spheres,” *Powder Technology*, **62**, pp. 189-196 (1990).

[16] R. Julien, A. Pavlovitch and P. Meakin, “Random Packings of Spheres Build with Sequiential Models,” *J. Phys. A: Math. Gen.*, **25**, pp. 4103 (1992).

[17] C. R. A. Abreu, “Simulacao Computacional de Sistemas Granulares: Aplicacao dos Metodos de Monte Carlo e de Elementos Distintos,” *PhD thesis, Universidade Federal do Rio de Janeiro, UFRJ, Brasil*, (2004).

[18] P. Mrafko, “Homogeneous and Isotropic Hard Sphere Model of Amorphous Metals,” *Journal de Physique Colloques*, **41**, pp. 322-325 (1980).

[19] ”Coefficient of Friction”, in *CRC Handbook of Chemistry and Physics, 89th Edition (Internet Version 2009)*, David R. Lide, ed., CRC Press/Taylor and Francis, Boca Raton, Fl., USA (2009).

[20] E. Webbe, “Multi Sized Pebble Stacking,” *Bsc. Thesis*, TU Delft, The Netherlands (2009).

[21] Zongxin Wu, Dengcai Lin, Daxin Zhong, “The Design Features of the HTR-10,” *Nuclear Engineering and Design*, **218**, pp. 25-32 (2002).

[22] G. D. Scott and D. M. Kilgour, “The Density of Random Close Packing of Spheres,” *Journal of Physics D: Applied Physics*, **2**, pp. 863-866 (1969).