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Pebble bed nuclear reactor structure study: A comparison of the experimental and calculated void fraction distribution

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ABSTRACT

The structure of the pebbles in the pebble bed nuclear reactors plays an important role in their performance as it affects the neutron streaming and the wall channeling of the coolant flow. In this study, the structure of a one foot diameter pebble bed reactor that was measured experimentally by gamma ray computed tomography (CT) in our laboratory in terms of void cross-sectional distribution and radial profiles has been used to evaluate the predictions of the void fractions of the reported empirical and analytical correlations. It can be seen that there is an agreement between the experimental results and the exponential expression for the void fraction with the use of the smaller spherical pebbles diameter ($D/d_p = 24$) as compared to those of larger diameters.

1. Introduction

Pebble Bed Reactors are among the candidates for the new generation nuclear plants (NGNP). They are small modular reactors and inherently safe. The fuel pebbles are inserted in the core cavity to form a randomly packed pebble-bed with non-uniform fuel densities. This non-uniformity will significantly affect the core neutronic and the thermodynamics due to wall channeling. These reactors are cooled by gas (helium) that flows downward. The thermal-mechanical behavior of the pebble bed reactor core depends strongly on the spatial variation of the packing structure (void fraction) distribution inside the bed and in particular on the number of contacts between pebbles, and between the pebbles and the blanket walls. To understand the pebble bed structure, experimental data are needed to validate other numerical simulations and correlations to facilitate the advancement of these reactors.

In the core of the pebble-bed reactor there are two types of pebbles (6 cm diameter), namely graphite and fuel pebbles. The graphite balls fill the cylindrical center of the pebble bed and the fuel balls surround the graphite balls such as the Pebble Bed Modular Reactor (PBMR) of South Africa or the core is composed of mixture of pebbles containing fuel and pebbles containing graphite only such as the High Temperature Reactor (HTR-10) in China. Both the graphite and the fuel pebbles are extracted from the bottom and reinserted (or replaced in case of burn up) on the top of the pebble-bed. This extracting and reinserting gives rise to a pebble velocity of about 4.5 (mm/h) (Cogliati and Ougouag, 2006a). Since this flow is slow we can approximate the pebble bed as a fixed packed bed. This has been recently confirmed by Khane et al. (2017) using radioactive particle tracking (RPT) technique. It is noteworthy that the quantification of the void fraction distributions in pebble beds is highly important to the mechanisms of heat and mass transfer and also to the flow field and pressure drop of the coolant throughout the pebble bed. Because of the sensitivity of those mechanisms to the void fraction and its distribution, it becomes important to know the void distribution inside the pebble-bed and the knowledge of the porosity is necessary for any rigorous analysis of the transport phenomena in the bed (Zhang et al., 2006). The geometry in the packing of a pebble-bed is interrupted at the wall and this gives rise to large void fraction variations near the wall. The flow through a medium depends on this porosity and because of the wall disturbance in the void fraction profile of the pebble-bed, the velocity profile of the cooling gas is also disturbed. This phenomenon is called wall-channeling (Roblee et al., 1958). Understanding the bed structure and the extent of the wall channeling and their effects of how structure of pebbles and gas and heat transfer can lead to better and more efficient and safe design of the pebble bed reactors.

Al Falahi and Al-Dahhan (2016) investigated experimentally the bed structure of various sizes of pebbles using gamma ray computed tomography (CT) technique. Their results were presented in the forms of the cross-sectional distributions of the voids and solids and their radial profiles. However, in the open literature, a number of empirical

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correlations were proposed to predict the average bed void and the radial profiles of the bed void. Also, Discrete Element Method (DEM) and Monte Carlo simulation were used to predict the bed void structure. Therefore, in this study the experimental data of Al Falahi and Al-Dahhan (2016) obtained by Gamma Ray Tomography (CT) has been used to evaluate the prediction of the literature reported correlations of the average void fraction and the void fraction profiles as discussed in the following sections.

1.1. Correlations for estimating the average void fraction in packed and pebble beds

The average void fraction for spheres in cylindrical packed beds has been investigated in the open literature and correlations have been proposed to estimate the average void fraction of packed beds. The average void fraction in a pebble bed (or a packed bed) reactor is a statistical characteristic of the bed which is required for thermal-hydraulic parameters quantification. It depends on many factors such as the method of charging/discharging, the shape of particles, the aspect ratio (cylinder to particle diameter ratio or D/d_p), the surface of the particles, and others. The void fraction of a fixed bed can be determined experimentally from the total density of the bed (ρ_T) and the density of packed particles (ρ_s):

$$\varepsilon = 1 - \left(\frac{\rho_T}{\rho_s}\right) \tag{1}$$

The proposed correlations for the average void fraction estimation as a function of the aspect ratio (D/d_p) yield considerable differences in the void even for the same cylinder to particle diameter ratio due to the random and disordering nature of the packing in the packed bed structure. These correlations were developed to estimate the void fractions of packed beds that are packed with small to large diameter particles.

Jeschar (1964) and Kugeler and Schulten (1989) both estimated the average bed porosity using the following formula:

$$\varepsilon = 0.375 + 0.34\frac{d_p}{D} \tag{2}$$

A standard correlation for predicting the overall void fraction in a packed bed of spheres was developed by Dixon (1988) and is reproduced by Theuerkaut et al. (2008):

$$\varepsilon = 0.4 + 0.05\frac{d_p}{D} + 0.412\left(\frac{d_p}{D}\right)^2 \tag{3}$$

De Klerk (2003) proposed the following equation to describe the void fraction in a packed bed with small aspect ratio:

$$\varepsilon = 0.41 + 0.35e^{-0.39\frac{D}{d_p}} \tag{4}$$

Pushnov (2006) derived an empirical expression to estimate the void fraction of a bed of spherical particles for ratios D/d_p less than 2.4:

$$\varepsilon = 12.6(D/d_p)^{6.1}e^{-3.6(D/d_p)} \tag{5}$$

$$\varepsilon = \frac{1}{(D/d_p)^2} + 0.375 \quad \text{for } D/d_p > 2 \text{ and } \text{h} > 20\ \text{d}_\text{p} \tag{6}$$

Another correlation is proposed by Zou and Yu (1995)

$$\varepsilon = 0.372 + 0.002\left[e^{\left(\frac{15.306}{D/d_p}\right)} - 1\right] \tag{7}$$

Mueller (1992) proposed an empirical correlation to calculate the bed porosity (ε_b) in a cylinder packed bed of spheres:

$$\varepsilon_b = 0.365 + \frac{0.22}{D/d_p} \tag{8}$$

Sodr¨e and Parise (1998) proposed that the value of average porosity for an annular bed (at annulus) is given by:

$$\bar{\varepsilon} = 0.3517 + 0.387\frac{d_p}{2(R_o - R_i)} \tag{9}$$

where R_o is outer radius of annulus and R_i is the inner radius of the annulus.

Finally, an exponential expression to determine the average bed porosity in packed beds of monosized spheres was proposed by Rbeiro et al. (2010). This expression is suitable for random dense packing and for $2 \le \frac{D}{d_p} \le 19$ and is given by:

$$\varepsilon = 0.373 + 0.917e^{\left(-0.824\frac{D}{d_p}\right)} \tag{10}$$

1.2. Correlations for estimating the radial voidage variation in packed and pebble beds

Many empirical and analytical correlations and computational methods have been proposed in the literature to describe the packing structure in packed bed and pebble bed reactors in terms of void radial profiles. The void fraction data of Benenati and Brosilow (1962) for uniform spherical particles have the typical oscillatory variation in void fraction in the region of the wall. Different spheres diameters were studied in their experiment with a tube diameter of 1.624 inch and D/d_p 2.61, 5.6, 14.1, and 20.3 for d_p = 0.62, 0.29, 0.115 and 0.08 inch, respectively. They fitted their data empirically to the following formula:

$$\varepsilon(x) = 0.38 + 0.62e^{-1.7x^{0.434}}\cos(6.67x^{1.13}) \tag{11}$$

where x is the number of d_p from the wall and equal to (1-ξ)δ/2. ξ is a dimensionless radial coordinate (r/R) and δ is radial aspect ratio (R/R_p). They presented the results for a number of cases with D/d varying from 2.6, 5.6 and larger.

Martin (1978) proposed the following correlation based on experimental data of Benenati and Brosilow (1962):

$$\varepsilon(z) = \begin{cases} \varepsilon_{min} + (1 - \varepsilon_{min})z^2, & -1 \le z \le 0 \\ \varepsilon_b + (\varepsilon_{min} - \varepsilon_b)e^{-\frac{x}{4}}\cos\left(\frac{\pi}{C}z\right), & z \ge 0 \end{cases} \tag{12}$$

With $z = 2\dfrac{R - r}{d_p} - 1$ as a dimensionless coordinate (13)

$$C = \begin{cases} 0.816 & \frac{D}{d_p} = \infty \\ 0.876 & \frac{D}{d_p} = 20.3 \end{cases} \tag{14}$$

The ε_{min} is the minimum void fraction in the range of ε_{min} = 0.20–0.26 and ε_b is the bulk void fraction and is not affected by wall near the bed center.

Cohen and Metzner (1981) used a quantitative description of void variations reported in the literature to describe the oscillatory variation of void away from the wall using the following set of correlations:

$$\frac{1 - \varepsilon(\tau)}{1 - \varepsilon_b} = 4.5\left[\tau - \frac{7}{9}\tau^2\right] \qquad \textit{for } \tau \le 0.25 \tag{15}$$

$$\frac{\varepsilon(\tau) - \varepsilon_b}{1 - \varepsilon_b} = a_1 e^{(-a_2\tau)} cos\,[a_3\tau - a_4]\pi \qquad \textit{for } 0.25 < \tau < 8 \tag{16}$$

$$\varepsilon(\tau) = \varepsilon_b \qquad \textit{for } 8 \le \tau \le \infty \tag{17}$$

where τ is the distance from the wall nondimensionalized with respect to the particle diameter,

$$\tau = \frac{R - r}{d_p} \tag{18}$$

The constants are (a_1 = 0.3463; a_2 = 0.4273; a_3 = 2.4509 and a_4 = 2.2011) with D/d_p range from 7 to 60.