

EFFECT OF NON-UNIFORM POROSITY DISTRIBUTION ON THERMALHYDRAULICS IN A PEBBLE BED REACTOR

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Abstract

In pebble bed reactors, the porosity profile shows strong fluctuations near the wall. These changes in fuel density affect local power density, coolant velocity, and temperature distribution. This paper describes the pebFoam code, capable of calculating pebble bed thermohydraulics including non-uniform porosity distributions for arbitrary geometries, and investigates the changes in velocity, pressure drop, and helium and pebble temperatures when using a non-uniform porosity distribution instead of a uniform distribution. Results show only minor changes in temperature profiles and pressure drop for full power steady state calculations, though the velocity profile shows a clear increase in velocity near the wall.

1. Introduction

The pebble bed nuclear reactor, a high temperature gas cooled reactor design, is one of the main candidates for next generation nuclear power plants. In these reactors the fuel is contained within graphite spheres, which form a randomly packed bed in the graphite-walled core region. Key features include the passive safety of the reactor, higher thermal efficiency due to higher coolant outlet temperatures, and the possibility of on-line refuelling by extracting pebbles at the bottom of the bed and adding pebbles to the top. It is well known that the porosity distribution of the randomly stacked bed formed by the pebbles in the core is not uniform, but shows large fluctuations near the wall [1]. Besides, due to the stochastic nature of the bed, locally the pebble stacking can vary, resulting in possible hot-spots due to tightly packed clusters of pebbles. Still, most thermohydraulics and neutronics calculations assume a uniform porosity distribution, both because it is easier and because the local porosity fluctuations are assumed to have only minor influence on the resulting pebble temperatures.

However, a safety study in the German pebble bed Arbeitsgemeinschaft Versuchsreaktor (AVR) found that pebbles fed into the radial outer zone of the AVR could experience up to 200 K higher surface temperatures than predicted by reactor analysis calculations [2]. Possible causes include higher core power peaking due to specific clustering of pebbles, and coolant flow disturbances due to local pebble packing conditions, possibly in combination with more complicated core geometry elements. To answer these questions, computational tools, capable of calculating the thermohydraulics in a pebble bed HTR, including the effects of non-uniform porosity distributions and able to handle complicated geometries are required.

For these computational tools two possible approaches exist. The first is to consider the individual pebbles and use CFD to resolve all flow details. However, this method is limited to small sections of the bed, due to the large computational power required [3], making it unsuitable for reactor core calculations. Thus this paper uses the second approach, the porous model, in which volume averaged values of the velocity and other quantities of interest are calculated, and a porosity value is used to represent the local packing structure [4].

This paper describes pebFoam, a program capable of calculating thermohydraulics in a pebble bed reactor taking into account non-uniform porosity distributions for arbitrary geometries in 1D, 2D and 3D. For the Chinese High Temperature gas-cooled Reactor-Pebble-bed Module (HTR-PM), resulting velocity distribution, pressure drop, and fluid and pebble temperatures are compared with results from pebFoam using a uniform and a non-uniform porosity distribution, and with results from the THERMIX code [5]. Additionally, the sensitivity of the results on the models used for momentum and thermal diffusion in the fluid is investigated.

2. The pebFoam program

The pebFoam solver is an OpenFOAM [6] application we created to solve the steady state heat and mass transfer in the core of a pebble bed for the gas and pebble phases, and is capable of handling non-uniform porosity distributions and complicated geometries. The equations that are solved by pebFoam are given below. They were derived from the two-phase flow equations for a fluidized bed described in [7], using the porosity ε of the bed as the phase fraction in the two-phase flow equations. The resulting equations were implemented in OpenFOAM, an open source set of general tools for solving continuum physics problems, based on finite volume discretization and supporting unstructured meshes of arbitrary shapes in 1D, 2D and 3D.

2.1 Coolant-phase transport equations

This section describes the equations used to calculate the helium phase pressure, velocity and temperature fields. As the equations are derived from two-phase flow models, the velocity $\mathbf{u}$ is the phase velocity or interstitial velocity, as opposed to the superficial velocity $\mathbf{u}_{sup} = \varepsilon\mathbf{u}$. Below, the coolant mass, momentum and energy equations as solved by pebFoam are given.

$$\nabla \cdot (\varepsilon \rho \mathbf{u}) = 0 \quad (1)$$

$$\nabla \cdot (\varepsilon \rho \mathbf{u} \mathbf{u}) = \nabla \cdot \varepsilon \mu_{eff} \nabla \mathbf{u} + \varepsilon \rho \mathbf{g} - \varepsilon \nabla p - B \mathbf{u} \quad (2)$$

$$\nabla \cdot (\varepsilon \rho \mathbf{u} h) = \nabla \cdot \varepsilon \alpha_{eff} \nabla h + H (T_{peb} - T) \quad (3)$$

Here ρ is the coolant density, h the coolant enthalpy, T the coolant temperature, T_{peb} the pebble surface temperature, p the pressure and $\mathbf{g}$ the gravitational acceleration. The momentum equation does not include a turbulent momentum flux, and the diffusion term is approximated as proposed by Vortmeyer and Schuster [8], including the momentum transport due to flow mixing as a result of the porous structure in an effective viscosity $\mu_{eff} = \eta\mu$, where μ is the coolant dynamic

viscosity. For lower Reynolds numbers some literature exists on values of η [9], however, for the high Reynolds flow in HTR pebble bed reactors, no literature could be found, and unless otherwise mentioned $\eta = 100$ was used in the remainder of this paper. For more on μ_{eff} see section 4.1. The momentum equation currently does not contain a turbulence model.

The last term in the momentum equation models the drag force on the flow due to the pebbles through a porous drag constant B . The pressure drop relation as given in the German safety guide KTA3102.3 [10] is used, resulting in the following relation for B , with d_{peb} the pebble diameter.

$$B = 160 \frac{\mu}{d_{peb}^2} \frac{(1-\varepsilon)^2}{\varepsilon} + 3 \frac{\mu^{0.1} \rho^{0.9}}{d_{peb}^{1.1}} \frac{(1-\varepsilon)^{1.1}}{\varepsilon^{0.1}} |\mathbf{u}|^{0.9} \quad (4)$$

The effective thermal diffusivity of the fluid α_{eff} [kg/m·s] includes the effect of mixing due to the porous structure of the bed, similar to μ_{eff} in the momentum equation. The relation found by Yagi and Wakao [11] is used, relating heat transfer due to porous mixing through the Péclet number Pe to the axial flow speed

$$\alpha_{eff} / \alpha = (\alpha\beta)_H Pe \quad (5)$$

Here $\alpha = \lambda/C_p$ is the thermal diffusivity of the fluid. $(\alpha\beta)_H$ is a parameter depending on the shape of the particles forming the bed, and is 0.11 for spheres in a bed with sufficiently large bed over pebble diameter. For the heat transfer coefficient at the wall the equation for turbulent flow parallel to a flat plate was used as suggested in [11], with $Re = \rho d_{peb} |\mathbf{u}| / \mu$.

$$Nu_{wall} = 0.036 Re^{0.8} Pr^{1/3} \quad (6)$$

The last term in equation (3) governs the heat transfer between the coolant and pebbles. H is here the heat transfer coefficient per unit volume of pebble bed and is given by

$$H = \frac{6(1-\varepsilon)}{d_{peb}} \frac{\lambda Nu}{d_{peb}} \quad (7)$$

The first part gives the amount of pebble surface area per unit volume of bed, and the second part is the heat transfer coefficient. Nu is calculated using the relation given by Gnielinski [12], as this was determined for a large range of porosity values ($0.26 < \varepsilon < 1.0$).

$$Nu = (1 + 1.5(1-\varepsilon)) \sqrt{2 + (0.664 Re^{0.5} Pr^{1/3})^2 + \left(\frac{0.037 Re^{0.9} Pr}{Re^{0.1} + 2.443 (Pr^{2/3} - 1)} \right)} \quad (8)$$

2.2 Pebble-phase transport equations

As the fuel pebbles are stationary, the pebble transport equations consist of only one equation describing the pebble surface temperature T_{peb} .

$$-\nabla \cdot (\lambda_{eff} \nabla T_{peb}) = H(T - T_{peb}) + Q \quad (9)$$

Here λ_{eff} denotes the effective thermal conductivity of the pebble phase, and Q is the fission or decay heat power density in W/m^3 . For λ_{eff} the Zehner-Bauer-Schlünder correlation is used as given in [13]. In this model λ_{eff} consists of three parts: $\lambda_{eff} = \lambda_{rad} + \lambda_{gas} + \lambda_{cont}$ where λ_{rad} , λ_{gas} and λ_{cont} describe the heat transfer between the pebbles through thermal radiation, gas conduction and contact conduction respectively. As in the ZBS model λ_{rad} goes to infinity in the near-wall region, where $\varepsilon \rightarrow 1$, for the region within $0.5d_{peb}$ of the wall it is replaced by the modified ZBS model as proposed by Tsotsas [14] with

$$\lambda_{rad} = \left(\frac{4\sigma T_{peb}^3 d_{peb}}{\frac{2}{e}-1} (1 - \sqrt{1-\varepsilon}) + \sqrt{1-\varepsilon} \right) \left(\frac{\frac{2}{e}-1}{4\sigma T_{peb}^3 d_{peb}} + \frac{1}{k_g} \right)^{-1} \quad (10)$$

Where σ is the Stefan-Boltzmann constant, $e = 0.8$ the emissivity of graphite and k_g the thermal conductivity of the pebble matrix graphite.

3. Geometry and boundary conditions

Calculations were performed on a core model of the HTR-PM reactor design with a total thermal power of 250 MW. The used geometric model is a subset of the core model used in [15]. Where the model in [15] consists of the entire core including reflectors, reactor pressure vessel and enclosing cavity concrete layer, the pebFoam geometric model consists of only the part containing the pebble bed and core top helium cavity. This resulted in a 2D cylindrical geometry model of 1.5 m radius and 11.78 m high, consisting of an 11 m high pebble bed, topped by the 78 cm high helium cavity. Although this core model makes no use of the capabilities of pebFoam to model the funnel at the bottom of the pebble bed, the geometric simplification allowed for easy comparison with THERMIX results, the pebble-bed reactor analysis software used in [15]. Furthermore the same power density distribution Q as used in THERMIX could be used as input for pebFoam. Figure 1 shows the pebble temperature distribution T_{peb} calculated by THERMIX and the Q used in pebFoam and THERMIX on the pebFoam calculation domain.

As boundary conditions for pebFoam results from THERMIX were used. For the helium temperature T and pebble temperature T_{peb} at the inflow ($z = 11.78$) and reflector wall ($r = 1.5$) the values calculated by THERMIX were used as fixed values. The velocity $\mathbf{u}$ used the velocity from THERMIX as fixed boundary condition at the inflow, and a no-slip ($\mathbf{u} = 0$) boundary condition at the reflector wall. The pressure p was fixed at 7 MPa at the core outlet ($z = 0$).

4. Results for uniform and non-uniform porosity profiles

Two calculations were performed with pebFoam. The first with a uniform porosity field with $\varepsilon = 0.39$, similar to THERMIX. The second calculation used a non-uniform porosity field, calculated from a computer generated pebble bed by the removing overlaps method described in [16,17]. The resulting porosity profile is shown in Figure 2, showing the expected oscillations near the

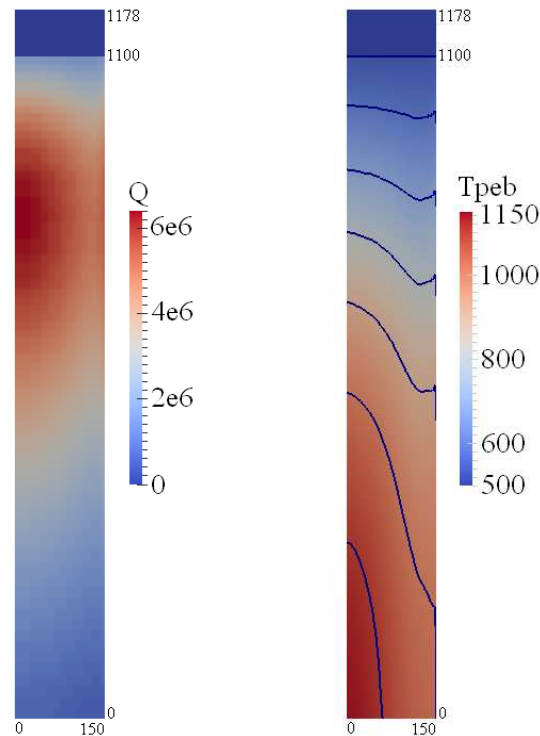


Figure 1 Left: Power density distribution Q in the pebble bed in W/m^3 . Right: Pebble surface temperature distribution in Kelvin calculated by THERMIX.

wall. For the non-uniform case the power density distribution Q was weighted by $(1 - \epsilon)$, as a lower porosity means a higher fuel density and thus a higher power density.

4.1 Velocity profile

The helium velocity $\mathbf{u}$ at the core outlet ($z = 0$) from THERMIX and as calculated by the pebFoam uniform and non-uniform models is shown in Figure 3. Although only the velocity profile at the bottom of the core is shown, for all three cases the profile in the rest of the core was similar, even if the velocity is lower at higher elevations in the core due to a lower gas temperature, and thus a higher gas density.

The velocity profiles from THERMIX and the pebFoam uniform model are very similar. For both cases the velocity is slightly higher near the centre, as here the density is lower due to a higher fluid temperature, which results in a slightly lower drag force on the fluid for equal flow speeds, see Equation (4). For the bulk of the bed, $\mathbf{u}$ is slightly ($\sim 1\%$) higher for pebFoam. This is to compensate for the lower velocity at the wall, as for pebFoam $\mathbf{u}$ goes to zero near the wall due to the no-slip boundary condition, while THERMIX imposes a no-normal-flow boundary condition on the flow near the wall.

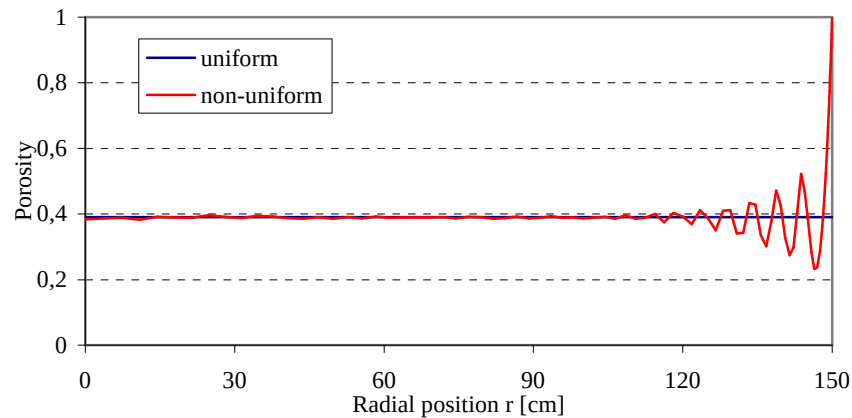


Figure 2 Uniform and non-uniform radial porosity profile as used in pebFoam.

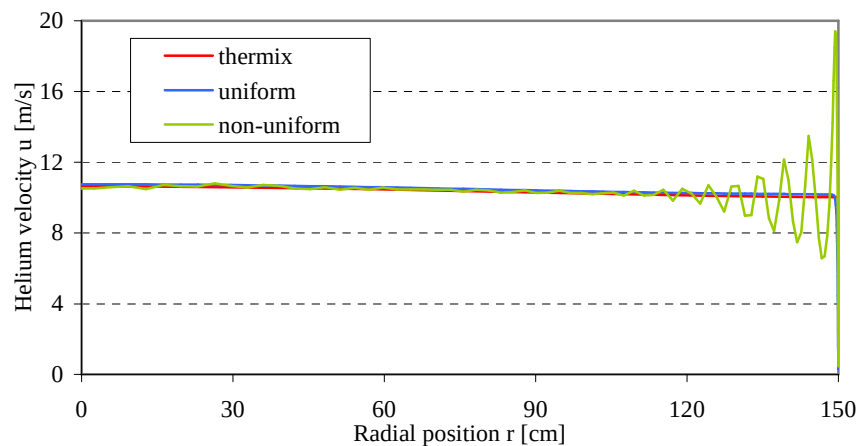


Figure 3 Helium velocity profile at core outlet calculated by THERMIX and by pebFoam uniform and non-uniform model.

For the pebFoam non-uniform model the velocity profile shows the expected oscillations near the wall due to the changes in porosity in this region. The wall channelling effect is clear with a peak velocity near the wall of almost twice the velocity in the bulk of the bed, which is in line with observations from previous studies [8,9]. Although the velocity in the near wall region is increased, u is not significantly lower in the bulk of the bed than for the pebFoam uniform model due to a higher outlet temperature for the non-uniform model (see Figure 4 and next paragraph), lowering the gas density and demanding an overall increase in u to satisfy continuity.

The pressure drop over the pebble bed for the pebFoam uniform model is 86.1 kPa, significantly higher than the 79 kPa from THERMIX. This is partly caused by the momentum interchange with the wall, but the main cause is that THERMIX uses a simplified version of the KTA pressure drop rule, instead of an exact implementation of Equation (4). For the non-uniform model the pressure drop is 83.9 kPa, slightly lower than for the uniform model due to the increased flow speed in the near wall region where flow resistance is low.

4.2 Temperature profiles

The helium and pebble surface radial temperature profiles are shown in Figures 4 and 5 respectively. The figures show the temperatures at three different axial positions in the core: at $z = 770$ cm around the peak in power density; at $z = 440$ cm where the power density is much lower; and at the outlet at $z = 0$ cm. The figures show the temperatures calculated by THERMIX and by the pebFoam uniform and non-uniform models. In all cases the helium inflow temperature at the top, at $z = -78$ cm, was a uniform 528 K. As the pebFoam calculations use the temperature results from THERMIX as boundary conditions at the reflector wall, all temperature profiles have identical values at the wall.

For all three axial core positions, the helium temperature profiles for the pebFoam uniform model are almost identical to those of THERMIX. The same is true for the pebble surface temperature profiles, except for $z = 770$ cm, where the T_{peb} calculated by pebFoam is slightly larger than that of THERMIX. This difference is due to the different models in THERMIX and pebFoam for the heat transfer between the helium and pebbles, see Equation (8). At the lower core positions this difference disappears, as here the power, and thus the difference between T and T_{peb} , is much lower.

Using a non-uniform porosity profile instead of a uniform has only a small effect on the helium and pebble temperatures. The higher helium velocity close to the wall results in a lower helium temperature here, creating a cooler blanket of helium along the wall, as can be seen in Figure 4 from the drop in T near the wall at $z = 770$ cm. This causes a lower heat flux to the wall, resulting in a higher helium temperature throughout most of the pebble bed. Further downstream the cooler layer near the wall disappears due to mixing of the helium and a lower power density.

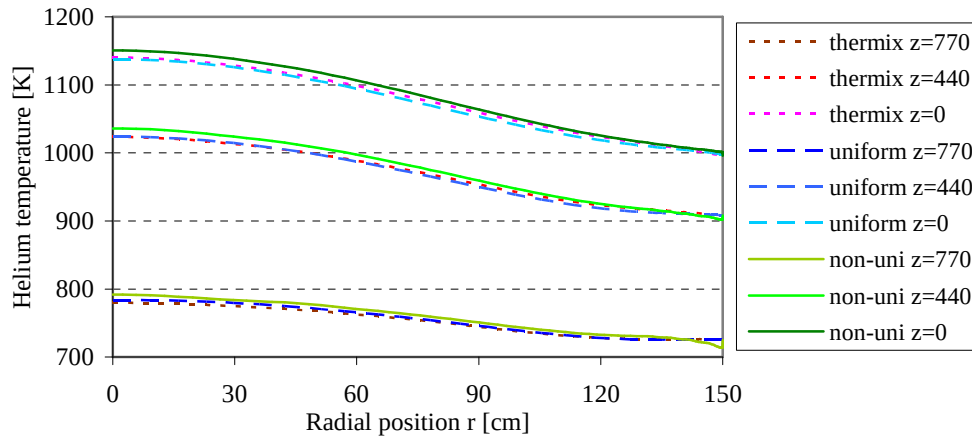


Figure 4 Helium radial temperature profiles at three different axial positions for THERMIX and for the pebFoam uniform and non-uniform models.

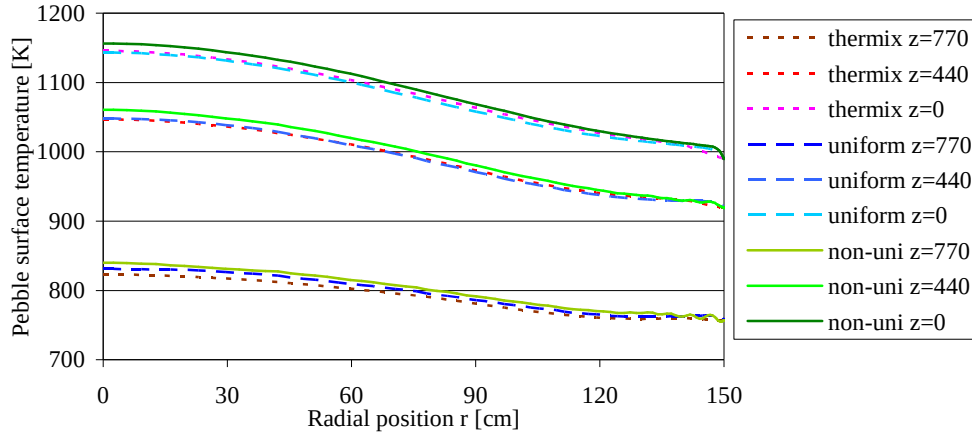


Figure 5 Pebble surface temperature profiles at three different axial positions for THERMIX and for the pebFoam uniform and non-uniform models.

The pebble surface temperature T_{peb} follows the helium temperature and is increased for most of the bed, see Figure 5. At $z = 770$ cm T_{peb} shows some small fluctuations near the wall. These are caused by the combination of higher helium velocity and lower power density in the regions of high void fraction, and visa-versa for the regions with low void fraction. These fluctuations disappear further down the bed, as there the power density is lower, and the pebble to pebble conductivity λ_{eff} is higher due to higher pebble temperatures, increasing λ_{rad} .

5. Model sensitivity

Due to the difficulties of obtaining experimental data regarding the local flow field and heat transfer inside packed beds, the validity of some of the models detailed in section 2 is questionable, specifically those for μ_{eff} and α_{eff} . In this section the sensitivity of the pebFoam to changes in these variables is investigated.

5.1 Sensitivity to changes in μ_{eff}

In Equation (2) μ_{eff} represents the effective diffusion of momentum in a pebble bed. This includes molecular diffusion plus the effect of flow mixing due to the porous structure of the bed. This effect is especially important near the wall, where the momentum transfer from the wall into the gas determines the velocity. Due to the difficulties of measuring detailed velocity patterns inside a porous bed few correlations exist for μ_{eff} . Based on measurements for laminar flow conditions with Reynolds numbers up to 500, Giese [9] gives the following relation for $\eta = \mu_{eff}/\mu = 2.0 \cdot \exp(3.5 \times 10^{-3} \cdot Re)$. However, in our case Reynolds is much higher, already $>26,000$ at inflow, and flow conditions are in the turbulent regime. The equation given by Giese is clearly not valid for these high Reynolds numbers. Lacking a better model we use a value of $\eta = 100$. In this section results for $\eta = 10$ and 1000 are compared with $\eta = 100$ to assess both the accuracy of the choice of $\eta = 100$, and the sensitivity of our model to μ_{eff} .

The helium velocity at the core outlet is shown in Figure 6 for the three values of η . Only the part closest to the wall is shown, as the velocity towards the centre of the core stays uniform. The

increase in momentum transfer with increasing η is clearly visible from the peak velocity. For $\eta = 1000$ the decreased velocity along the wall results in a small increase in the velocity in the bulk of the bed, while for $\eta = 10$ the reverse is true. This decrease of the velocity near the wall and increase in the bulk of the bed also causes an increased pressure drop across the bed, with pressure drop values being 80.7, 83.9 and 88.5 kPa for $\eta = 10$, 100 and 1000 respectively.

Literature [8,9] shows results for the superficial peak velocities $u_{sup,max}$ of 2 to 3 times the average velocity $\bar{u}_{sup}$, with a tendency for higher values at higher fluid velocities. Using the superficial velocity u_{sup} instead of the phase velocity u , we find for the peak velocities near the wall $u_{sup,max}/\bar{u}_{sup} = 1.4, 3.6$ and 7.3 for $\eta = 10, 100$ and 1000 respectively. From this we conclude that using $\eta = 10$ underestimates, and $\eta = 1000$ overestimates the velocity at the wall, giving confidence that the choice of $\eta = 100$ is at least the correct order of magnitude.

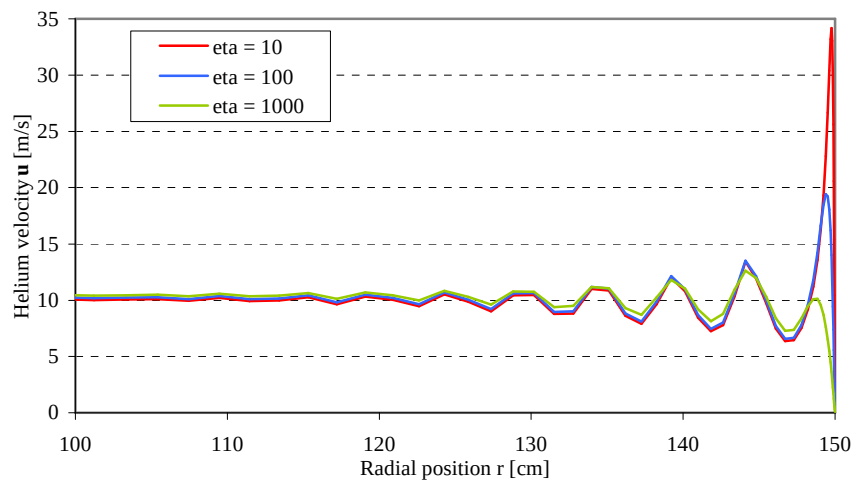


Figure 6 Radial velocity profile at core outlet for the pebFoam non-uniform model using values for $\eta = \mu_{eff}/\mu = 10, 100$ and 1000 .

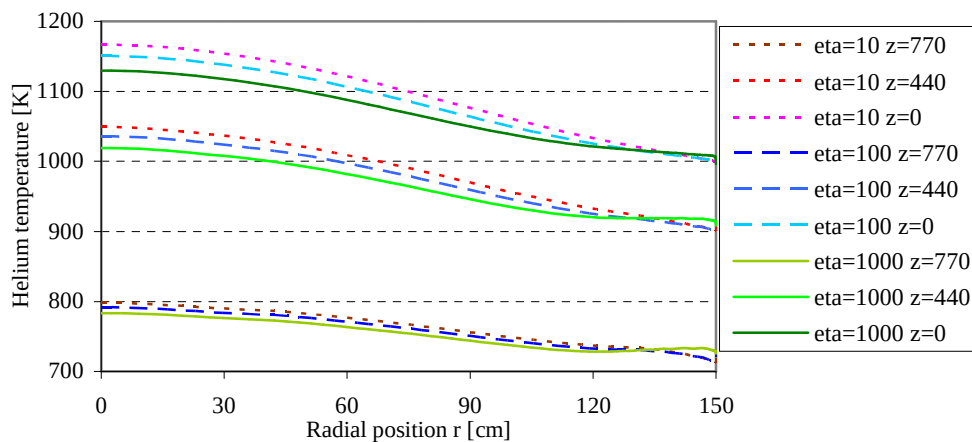


Figure 7 Helium radial temperature profiles at three different axial positions for the pebFoam non-uniform model using values for $\eta = \mu_{eff}/\mu = 10, 100$ and 1000 .

The helium temperature profiles for various core positions are given in Figure 7 for $\eta = 10, 100$ and 1000. The pebble surface temperature profiles are not given but show a similar behaviour. Compared to $\eta = 100$, for $\eta = 1000$ all profiles show an increase in temperature at the wall due to the lower helium velocity here, resulting in increased heat loss to the wall and a lower fluid temperature in the bulk of the bed. The reverse is true for $\eta = 10$. However, in spite of the large changes in μ_{eff} , the changes in temperatures are small, and we can conclude that for steady state full power operation, the temperature distribution in a HTR pebble-bed reactor depends only weakly on the momentum interchange with the wall, and thus on the value of μ_{eff} .

5.2 Sensitivity to changes in α_{eff}

Just as μ_{eff} includes the effect of fluid mixing due to the porous structure on the momentum transfer, so does α_{eff} describe the heat transfer in the fluid including mixing. Although α_{eff} is reasonably well known for the bulk of a pebble bed, this is not the case for the region near the wall with the sharp changes in porosity, and for the heat transfer to the wall. To investigate the sensitivity of our results to possible errors in the models for this heat transfer (Equations (5) and (6)), results for the pebFoam non-uniform model are compared with calculations where α_{eff} is halved or doubled.

The resulting helium temperature profiles are shown in Figure 9. As expected, lowering the thermal diffusion in the fluid lowers the heat transfer to the wall, increasing the fluid temperature further downstream, while the reverse is true when increasing the thermal diffusion. Still the changes in fluid temperatures are only minor, no larger than 37 K at the centre of the outflow, as heat transfer is dominated by convection for a pebble-bed reactor running at full power.

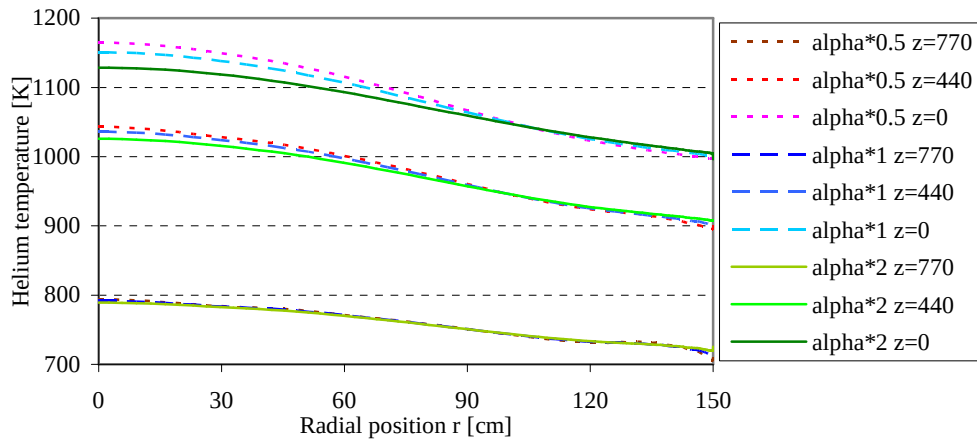


Figure 9 Helium radial temperature profiles at three different axial positions as calculated by pebFoam for half (*0.5), nominal or double (*2) the normal value of α_{eff} .

6. Conclusions and discussion

PebFoam is an OpenFOAM solver capable of calculating heat and mass transfer in a pebble bed including the effects of non-uniform porosity distributions and capable of handling complex geometries. Results for the uniform porosity distribution show excellent agreement with THERMIX results for the HTR-PM core design at steady state under full power operation. Including the non-uniform radial porosity distribution of the pebbles significantly increases the helium velocity near the wall. However, the helium and pebble surface temperatures show only a small increase, due to a reduction in heat transfer to the wall. Also, there is a small decrease in pressure drop over the bed due to the increased velocity along the wall where flow resistance is low. Investigating the sensitivity of the results to changes in the helium momentum and heat transfer, as these models contain many uncertainties in the near-wall region, showed that large changes in both μ_{eff} and α_{eff} result in only small changes in the helium and pebble surface temperature distributions, and the pressure drop increases slightly with increasing μ_{eff} . However, the velocity near the wall depends strongly on the value of μ_{eff} .

For transient cases and accident scenarios, the effects of a non-uniform porosity distribution might be more important. Also, for these cases a more detailed investigation of momentum and heat transfer models near the wall is of interest, as results might be much more sensitive to these models. To this end a turbulence model for the near-wall region of a packed is desirable. Beside transient cases, in the future the pebFoam code could be used to investigate temperature and velocity fields around hotspots, areas where are small number of pebbles form a densely packed cluster inside the core, as it is capable of doing 3D calculations. Another area of interest is including the effects of more complicated core geometries, such as the funnel at the core bottom, utilizing the benefit of using unstructured grids in pebFoam.

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