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# Optimization of a radially cooled pebble bed reactor

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ABSTRACT

By altering the coolant flow direction in a pebble bed reactor from axial to radial, the pressure drop can be reduced tremendously. In this case the coolant flows from the outer reflector through the pebble bed and finally to flow paths in the inner reflector. As a consequence, the fuel temperatures are elevated due to the reduced heat transfer of the coolant. However, the power profile and pebble size in a radially cooled pebble bed reactor can be optimized to achieve lower fuel temperatures than current axially cooled designs, while the low pressure drop can be maintained.

The radial power profile in the core can be altered by adopting multi-pass fuel management using several radial fuel zones in the core. The optimal power profile yielding a flat temperature profile is derived analytically and is approximated by radial fuel zoning. In this case, the pebbles pass through the outer region of the core first and each consecutive pass is located in a fuel zone closer to the inner reflector. Thereby, the resulting radial distribution of the fissile material in the core is influenced and the temperature profile is close to optimal.

The fuel temperature in the pebbles can be further reduced by reducing the standard pebble diameter from 6 cm to a value as low as 1 cm. An analytical investigation is used to demonstrate the effects on the fuel temperature and pressure drop for both radial and axial cooling.

Finally, two-dimensional numerical calculations were performed, using codes for neutronics, thermal-hydraulics and fuel depletion analysis, in order to validate the results for the optimized design that were obtained from the analytical investigations. It was found that for a radially cooled design with an optimized power profile and reduced pebble diameter (below 3.5 cm) both a reduction in the pressure drop ($\Delta p = -2.6$ bar), which increases the reactor efficiency with several percent, and a reduction in the maximum fuel temperature ($\Delta T = -50\,^{\circ}$C) can be achieved compared to present axially cooled designs.



## 1. Introduction

In current high temperature reactor (HTR) designs of the pebble bed type, such as the Pebble Bed Modular Reactor (PBMR-400) (Koster et al., 2003) and the HTR-PM (Zhang et al., 2006), the helium coolant flows from top to bottom through the core. The pressure drop over the pebble bed is considerable, especially for HTR's that have a large core height, such as the PBMR-400 design. For the PBMR-400 with a core height of 11 m the pressure loss of the bed ($\Delta p \approx 2.8$ bar) results in a circulator power that is more than 7 % of the net power generated.

By altering the primary direction of the coolant flow from the axial to the radial direction, the pressure drop can be reduced theoretically with a factor 1000 (Muto and Kato, 2003). In that case the coolant flows from the outer reflector through the pebble bed and finally to flow paths in the inner reflector, through which the coolant exits the reactor. The cooling flow paths in the reactor for radial and axial cooling are shown in Fig. 1.

The reduction in the helium coolant velocity decreases the heat transfer between the pebble surface and the coolant, which results in a higher fuel temperature. However, the low pressure drop in the radially cooled reactor allows for a reduction in the pebble size that reduces the fuel temperature.

In this paper the effects of pebble size reduction on the pressure drop and the maximum fuel temperature are quantified. First, an analytical expression is derived to calculate the pressure drop and fuel temperature in a radially cooled reactor. In a second step a two-dimensional numerical model is used to calculate the effects.

Beside the possibility of smaller pebbles it is shown that the power profile can be modified by recycling the pebbles several times in 3 separated radial fuel zones (Muto et al., 2005). This reduces the fuel temperature significantly. A theoretical optimum for the radial profile can be derived analytically. In an attempt to achieve this optimal profile 3 or more radial fuel zones can be adopted.

The combined effect of pebble size reduction and adoption of radial fuel zones, up to 10 zones, is investigated in this paper for

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**Nomenclature**

| | |
|---|---|
| $c_p$ | helium thermal capacity (J/kg/K) |
| $d$ | pebble diameter (m) |
| $h$ | heat transfer coefficient (W/m$^2$/K) |
| $H$ | core height (m) |
| $k$ | pebble conductivity (W/m/K) |
| $k_{he}$ | helium conductivity (W/m/K) |
| $P$ | reactor power (W) |
| $Pr$ | Prandtl number |
| $q'''$ | power density (W/m$^3$) |
| $r$ | radial position in the core (m) |
| $i$ | inner |
| $o$ | outer |
| $Re$ | Reynolds number |
| $R_{fuel}$ | pebble fuel zone radius (m) |
| $R_{peb}$ | pebble radius (m) |
| $T$ | helium temperature (K) |
| $T_{max}$ | pebble center temperature (K) |
| $v$ | helium velocity (m/s) |
| $\Delta p$ | pressure difference (Pa) |
| $\varepsilon$ | pebble bed porosity |
| $\eta$ | helium viscosity (m·s/kg) |
| $\lambda_{tot}$ | total heat transfer coefficient (volumetric) (W/m$^3$/K) |
| $\rho$ | helium density (kg/m$^3$) |
| $\psi$ | friction factor |

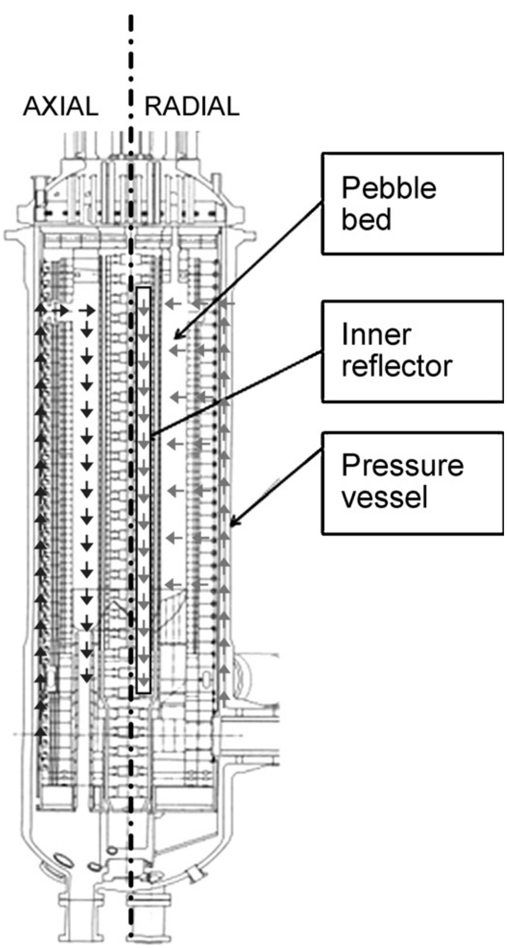


**Fig. 1.** Flow paths in an axially (left) and radially (right) cooled pebble bed reactor.

both normal and loss of forced cooling conditions (LOFC) using existing codes and methods for neutronics, thermal-hydraulics and fuel depletion analysis.

## 2. Optimization of the pebble size

In order to quantify the effect of the pebble diameter size on the pressure drop and the fuel temperature a simple analytical procedure is used first.

The maximum temperature at the pebble center, for a pebble located at a radial position $r$ in the core can be calculated from the helium temperature $T$ and the power density $q'''$ with the following equation (Kugeler and Schulten, 1989):

$$T_{max}(r) = T(r) + \frac{1}{\lambda_{tot}} q'''(r). \tag{1}$$

In the above equation $(1/\lambda_{tot})$ is the total thermal resistance (multiplied with the volume) between helium coolant and pebble center. An equation for the total thermal resistance can be derived from a heat balance for a single pebble (Kugeler and Schulten, 1989), assuming that heat is generated in the fuel region of the pebble only:

$$\frac{1}{\lambda_{tot}} = \frac{1}{(1-\varepsilon)} \left[ \frac{R_{peb}^3}{2kR_{fuel}} - \frac{R_{peb}^2}{3k} + \frac{R_{peb}}{3h} \right]. \tag{2}$$

The heat transfer coefficient $h$ between the helium coolant and the pebble surface can be calculated with (Kugeler and Schulten, 1989):

$$h = \frac{k_{he}}{2R_{peb}} \left( 1.27 \frac{Pr^{0.33}}{\varepsilon^{1.18}} Re^{0.36} + 0.033 \frac{Pr^{0.5}}{\varepsilon^{1.07}} Re^{0.86} \right). \tag{3}$$

The pressure difference by friction in a pebble bed depends on the Reynolds number and is derived from the following relation (Kugeler and Schulten, 1989):

$$\nabla p = -\psi \frac{1-\varepsilon}{\varepsilon} \frac{1}{2R_{peb}} \frac{\rho}{2} |\mathbf{v}|\mathbf{v} \tag{4}$$

$$\psi = \frac{320}{(Re/(1-\varepsilon))} + \frac{6}{(Re/(1-\varepsilon))^{1/10}}. \tag{5}$$

and the Reynolds number is defined as:

$$Re = \frac{\rho 2R_{peb}\varepsilon|\mathbf{v}|}{\eta}. \tag{6}$$

For the axially cooled core a straightforward integration of Eq. (4) over the core height results in a relation for the core pressure drop. For the radially cooled core the velocity depends on the radial position. From the continuity equation,

$$\frac{1}{r}\frac{\partial(\varepsilon r v_r)}{\partial r} = 0, \tag{7}$$

it follows that

$$v_r(r) = \frac{r_o v_r(r_o)}{r}, \tag{8}$$

by assuming that the helium flows inward with a certain velocity at the outer radius. It is assumed that the porosity profile of the pebble bed is flat.

The momentum equation in cylindrical coordinates for the radial direction is as follows:

$$\varepsilon \rho v_r \frac{\partial v_r}{\partial r} = -\varepsilon \frac{\partial p}{\partial r} + \varepsilon \psi \frac{1-\varepsilon}{\varepsilon} \frac{1}{2R_{peb}} \frac{\rho}{2} v_r^2. \tag{9}$$

Note that the constant porosity drops out of the above equation. Combining Eq. (9) with Eqs. (4) through (6) and integrating over the