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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)
Δp	pressure difference (Pa)
ε	pebble bed porosity
η	helium viscosity (m·s/kg)
λ_{tot}	total heat transfer coefficient (volumetric) (W/m^3/K)
ρ	helium density (kg/m^3)
ψ	friction factor

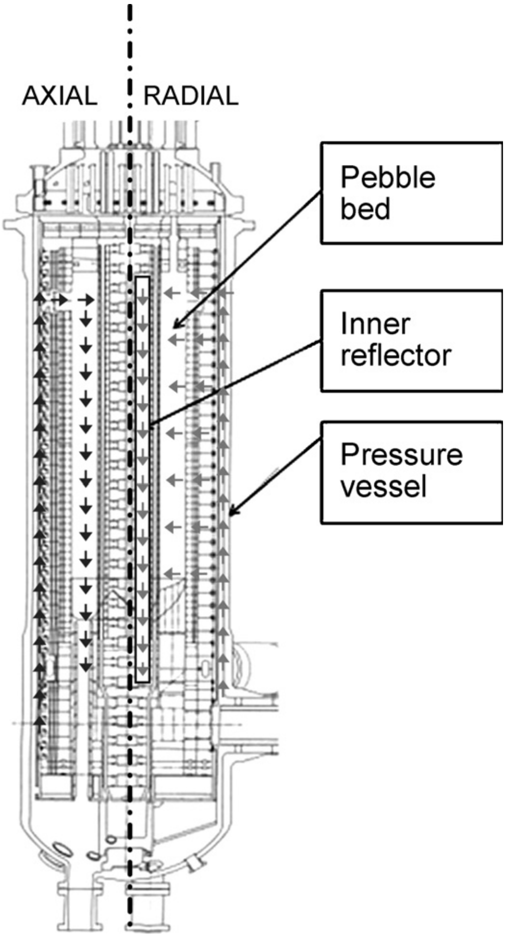

Fig. 1. Flow paths in an axially (left) and radially (right) cooled pebble bed reactor.

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

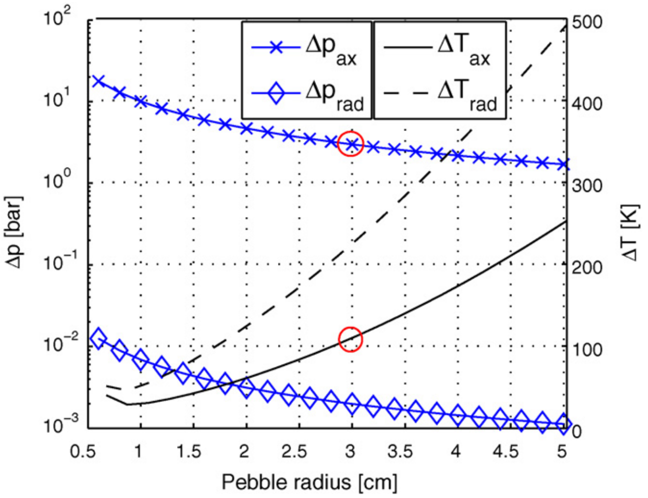

Fig. 2. Pressure drop (Δp) over the core and temperature difference (ΔT) between coolant and pebble center temperature for a radially (rad) and axially (ax) cooled pebble bed, as a function of the pebble radius. The circle shows the operating conditions of the PBMR-400 design.

radial direction results in the following expression for the pressure difference:

$$\Delta p = (r_o v_r(r_o))^2 \left[\frac{\rho}{2}(r_o^{-2} - r_i^{-2})\right] + (r_o v_r(r_o))^2 \left[A \cdot \ln(r_o/r_i) - B \cdot (r_o^{-9/10} - r_i^{-9/10})\right], \qquad (10)$$

in which A and B are defined as follows:

$$A = \frac{160(1-\varepsilon)^2 \eta}{r_o v_r(r_o) \varepsilon^2 d^2}, \qquad B = \frac{10}{3}\frac{\rho(1-\varepsilon)}{\varepsilon d}\left(\frac{1-\varepsilon}{r_o v_r(r_o) \varepsilon \rho d}\right)^{1/10} \qquad (11)$$

Note that the first term in Eq. (10) represents the pressure difference by convective flow, which is small compared to the pressure loss by friction for all cases considered.

The pressure and temperature have been calculated for various pebble diameters for both an axially and a radially cooled pebble bed based on the geometry of the PBMR-400 design. This design has a core height of 1100 cm, an inner reflector with a radius of 100 cm and a pebble bed with an outer radius of 185 cm. The standard pebble has a radius of 3 cm with a fuel-free (graphite) outer zone of 0.5 cm thickness. In the calculation for smaller pebble sizes, the fuel-free zone of 0.5 cm is kept, while the fuel zone size is varied. A case with pebbles of 0.5 cm radius without graphite shell is considered in Section 3.

The maximum temperature and pressure drop as a function of the pebble diameter for both radially and axially cooled pebble bed reactors are shown in Fig. 2. When radial cooling of the bed is adopted instead of axial cooling, both the coolant velocity and the length of the flow path through the core are reduced, which results in a large reduction of the pressure drop over the core. The reduction in coolant velocity causes a reduction in the heat transfer between coolant and pebble surface and therefore the pebble center temperature increases (Fig. 2).

For a given pebble diameter the temperature difference is higher for the radially cooled bed than for the axially cooled one. Reducing the pebble diameter, in an attempt to reduce this temperature difference, leads to a high pressure drop for the axially cooled pebble bed. In this case the pumping power is several percent of the power generated. For the radially cooled pebble bed however, the pressure drop remains small, even for very small pebble diameters. Therefore, by combining radial cooling with a reduced pebble size, a low pressure drop together with lower fuel temperatures, compared to an axially cooled core for a fixed helium outlet temperature, are theoretically achievable. For example, Fig. 2 shows that compared to the current PBMR-400 design the same temperature difference can be achieved for a 1.8 cm pebble radius with a pressure drop a factor 1000 lower (3 mbar).

3. Optimization of the power profile by radial fuel zoning

Besides reducing the pebble diameter, the power profile can also be optimized in order to reduce the fuel temperatures.

First, an analytical approach is used to derive the optimal radial power profile. In an attempt to realize this optimal profile the (radial) starting positions of the pebbles are altered. In a second step a more complex numerical calculation is used to determine the resulting power profile for several pebble loading patterns.

3.1. Derivation of the optimal power profile in a radially cooled reactor

The differential energy equation in the radial direction for the helium coolant, assuming that all the power generated is directly transferred to the helium coolant, is (Bird et al., 2002):

$$\rho c_p \varepsilon v_r \frac{dT}{dr} = q'''(r) \qquad (12)$$

Demanding that the maximum temperature described by Eq. (1) is constant over the radial direction of the core results in the following equation:

$$\frac{\partial T}{\partial r} + \frac{1}{\lambda_{tot}}\frac{\partial q'''}{\partial r} = 0 \qquad (13)$$

By combining Eq. (12) with Eq. (13) and the previous result (Eq. (8)) for v_r we arrive at the following differential equation for the radial power distribution:

$$\frac{\partial q'''}{\partial r} + \left(\frac{\lambda_{tot}}{\rho c_p v_r(r_o) r_o \varepsilon}\right) r q'''(r) = 0 \qquad (14)$$

Solving Eq. (14) results in the following optimal power profile:

$$q'''(r) = A e^{(-(1/2)(\lambda_{tot}/\rho c_p v_r(r_o) r_o \varepsilon) r^2)} \qquad (15)$$

in this equation A is a coefficient to be determined from the total reactor power, P, using:

$$\int_{r_i}^{r_0} 2\pi r H q'''(r) dr = P \qquad (16)$$

The resulting optimal power profile for a standard pebble size (R_{peb} = 3.0 cm) is presented in Fig. 3 and the resulting flat temperature profile in Fig. 4. A large difference exists between the power level at the inner surface and outer surface of the pebble bed. It follows from Eq. (15) that the profile depends on the total heat transfer (Eq. (2)) and is more flattened for large pebble size. In order to approximate the optimal power profile in practice the radial distribution of the fuel has to be optimized.

3.2. Modified in-core pebble recycling scheme using radial fuel zoning

The optimal power profile is approximated by dividing the core into several radial fuel zones. A multi-pass recycling scheme is adopted in which pebbles with a low burnup are placed in the outer core region and high burnup pebbles in the inner region. In the case that the total number of pebble passes through the core is larger than the number of fuel regions, a fuel zone can contain pebbles having different burnup levels.

Fig. 5 shows a pebble recycling scheme for a 3 zone core in which pebbles pass through the core 10 times. The first pass of the pebbles

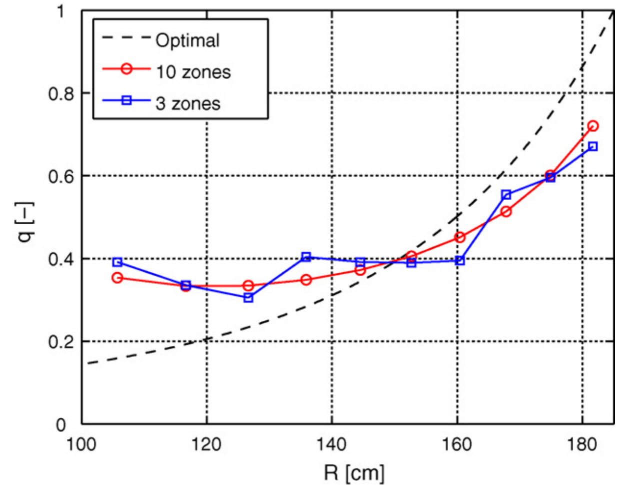

Fig. 3. The optimal (normalized) power profile yielding a radially flat temperature profile (R_{peb} = 3.0 cm) determined by an analytical derivation and two power profiles obtained numerically by applying 3 and 10 radial fuel zones.

is in the outer fuel zone and each consecutive pass is either in the same zone or in a zone closer to the inner reflector. Because fresh fuel is now present on the outside of the core and depleted fuel on the inside, the power level has increased on the outside and decreased on the inside.

After each time a pebble has passed through the core the burnup level is measured to determine its burnup level and consequent reloading position. The pebbles reach the target burnup of 95 MWd/kg after 10 passes.

3.3. Calculation procedure

The power profile for the proposed loading pattern is calculated with a numerical procedure that is also used in the analysis of HTR core optimization study (Boer et al., 2009). It consists of the coupled neutronics and thermal-hydraulics DALTON-THERMIX code system (Boer et al., 2010) which is linked to the depletion analysis and neutron cross-section generation routines of the SCALE-5 code system (SCALE-5, 2005). The codes are used consecutively until convergence is reached on the discharge burnup, neutron flux and k_{eff}.

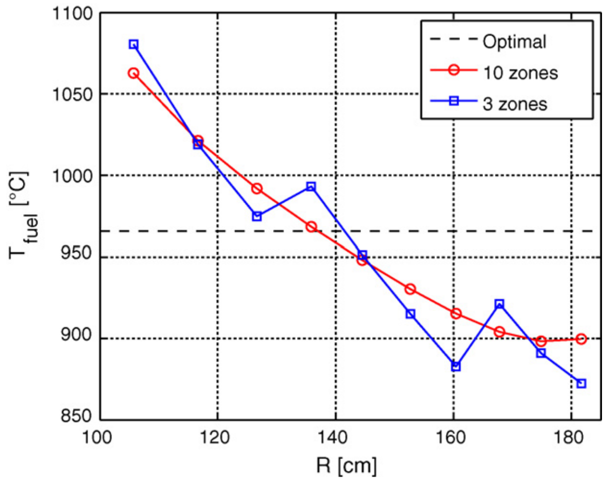

Fig. 4. The optimal fuel temperature profile (R_{peb} = 3.0 cm) determined by an analytical derivation and two power profiles obtained numerically by applying 3 and 10 radial fuel zones.

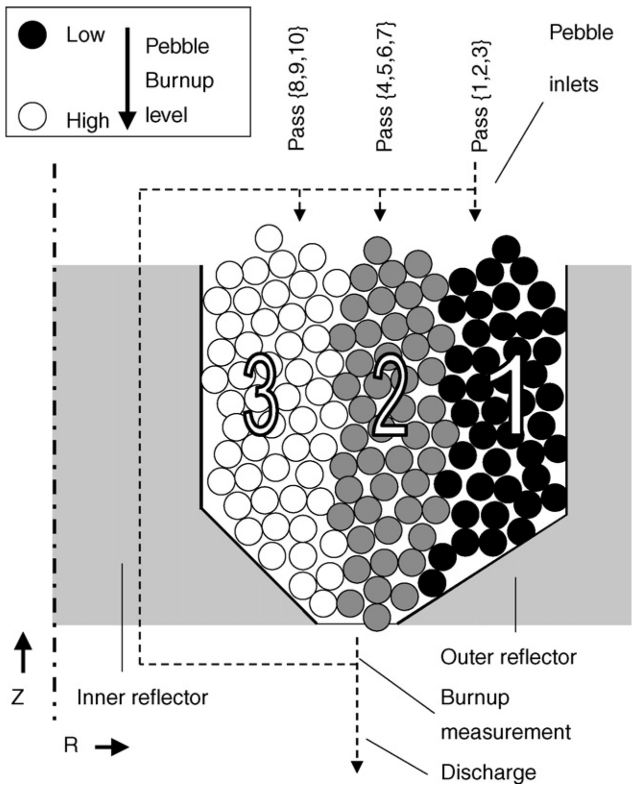

Fig. 5. Pebble loading pattern for a core with 3 radial fuel zones and 10 pebble passes, showing how the pebbles are recycled from the outside to the inside.

Several modules of the SCALE-5 are used to take into account the double heterogeneity of the fuel (TRISO and pebble) and the geometry of the reactor. The calculation steps are as follows:

1. First, the TRISO particles in the graphite matrix are modeled by using the CSASIX module of SCALE-5. In this module the evaluation of the resolved and unresolved resonances which are treated by the Nordheim Integral Method and the Bondarenko method, respectively. A one-dimensional discrete ordinates transport calculation is made of a fuel kernel surrounded by cladding (material from the carbon buffer, IPyC, SiC and OPyC layers) and moderator (graphite) material (see Fig. 6). The moderator volume having radius R_0 is equal to the volume of the fuel zone of the pebble divided by the number of TRISO's. From this last calculation homogenized neutron cross-sections are made for "TRISO material". For this purpose a 172 energy group (XMAS) library is used, based on the JEFF2.2/3.0 and JENDL3.3 libraries and pro-

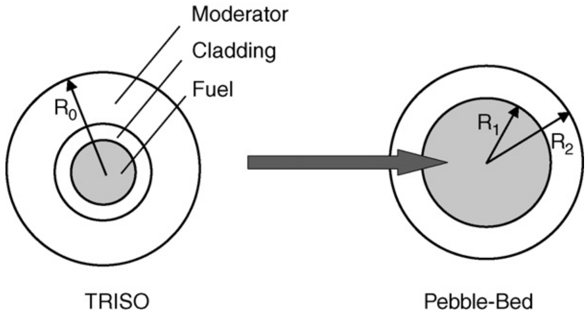

Fig. 6. TRISO and Pebble model used in calculation of homogenized cross-sections for the pebble bed region.

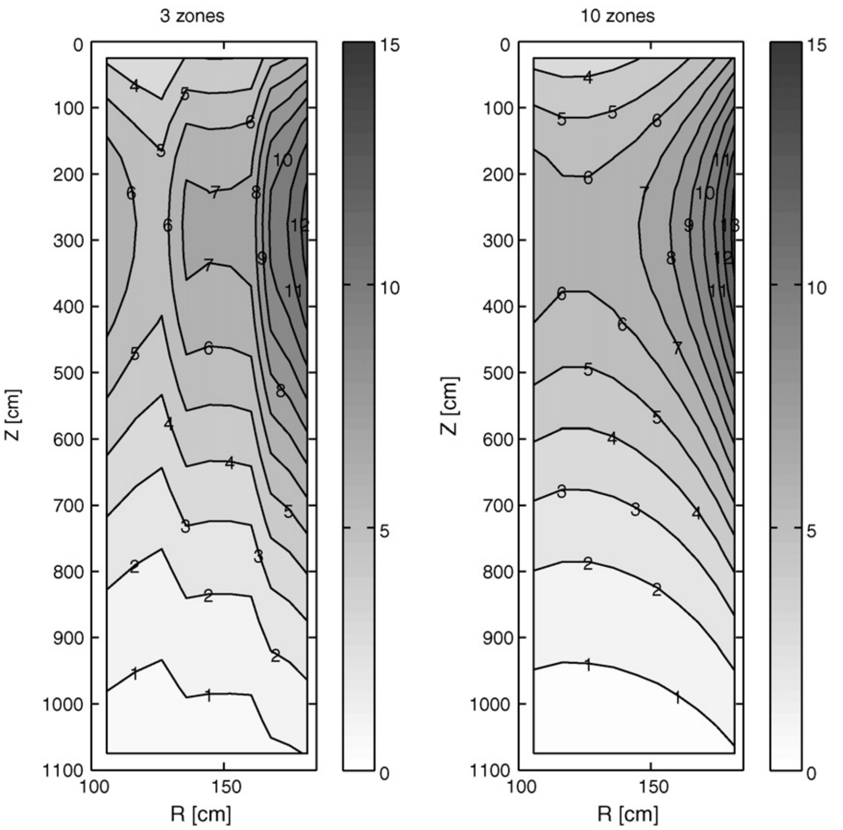

Fig. 7. Power profiles [MW/m^3] for both 3 (left) and 10 (right) radial fuel zones.

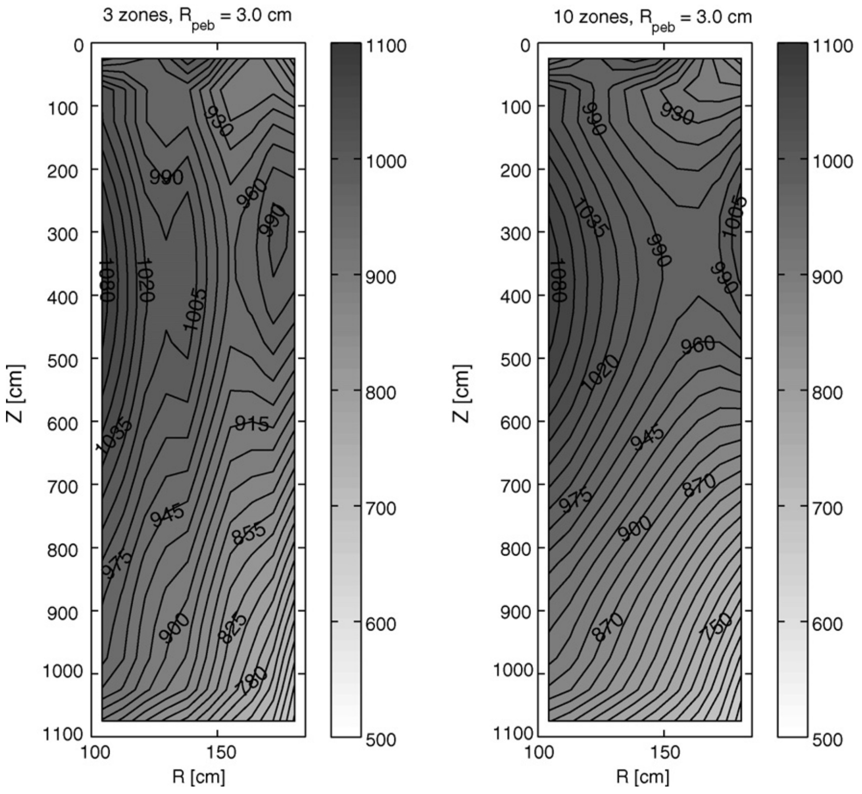

Fig. 8. Fuel temperature profiles [°C] in a core with 3 (left) and 10 (right) radial fuel zones for a pebble radius of 3.0 cm.

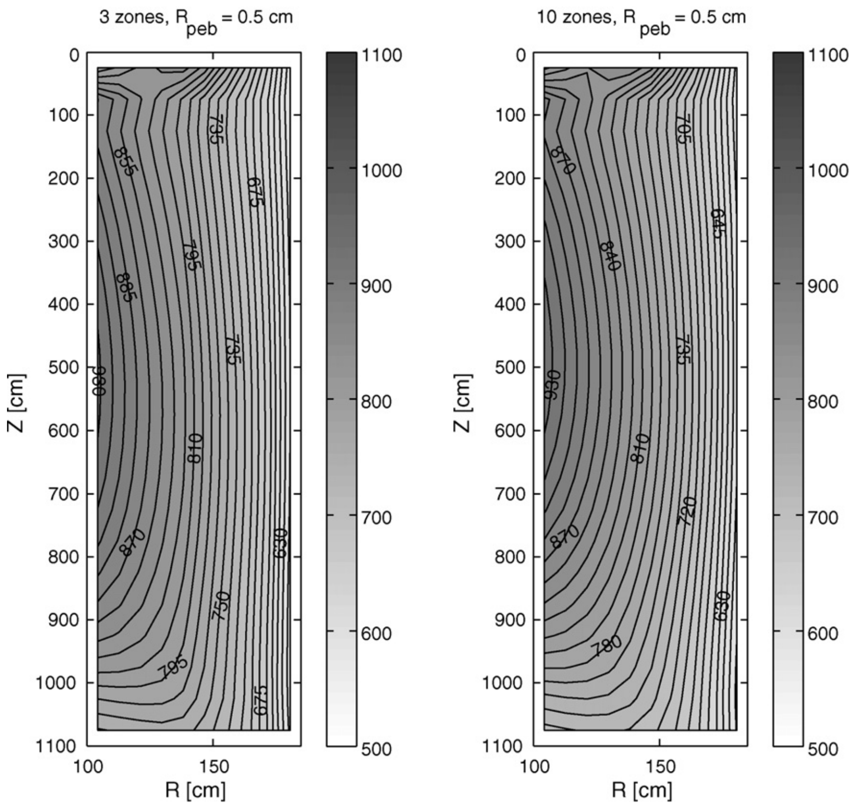

Fig. 9. Fuel temperature profiles [°C] in a core with 3 (left) and 10 (right) radial fuel zones for a pebble radius of 0.5 cm.

cessed with NJOY. To account for the fuel-shadowing effect of the fuel kernels in the graphite matrix of the pebbles a Dancoff factor is used, which is analytically determined Bende et al. (1999) and is a function of the number of fuel particles and the radii of the kernel, the fuel zone and the pebble.

2. The homogenized neutron cross-sections for the TRISO material are used in a one-dimensional transport calculation in which a sphere of TRISO material, with radius R_1, is surrounded by a layer of graphite and helium with radius R_2 (see Fig. 6). In this calculation R_1 is equal to the fuel zone in the pebble and $R_2 = \sqrt[3]{R_{peb}^3/\varepsilon}$.

   This transport calculation results in homogenized cross-sections for “pebble bed material”.
3. As a last calculation step several one-dimensional transport calculations, representing a certain axial or radial cross-section of the core, are performed. In general the geometry consists of a pebble bed region surrounded by graphite reflector regions. These regions are split up into several zones to generate zone weighted few group cross-sections. In order to model the transverse neutron leakage in these 1D calculations the reactor height (or width) is supplied from which a buckling factor is derived. The zone weighted cross-sections of these 1D calculations are allocated to the positions of the corresponding material in the 2D cross-section map.

The above described procedure is repeated for several fuel and moderator temperatures resulting in a 2D temperature dependent cross-section library. Temperature feedback is taken into account by performing several iterations between DALTON and THERMIX.

A procedure to directly determine the equilibrium core composition is used (Boer et al., 2009), which consists of several iterations between DALTON, SCALE and ORIGEN (SCALE-5, 2005).

3.4. Results of the modified in-core pebble recycling schemes

The resulting power profiles for 3 and 10 radial zones are presented in Fig. 7. In the case that 10 radial zones are used, each zone represents 1 pebble pass, while for 3 radial zones, the pebbles pass through the inner and outer zone 3 times and 4 times in the middle zone (Fig. 5). The profile for the 10 zone case shows a smooth surface, while the 3 zone case exhibits two jumps at positions of the fuel region interfaces. In Fig. 3 the radially averaged power profiles of the two numerical solutions are compared with the optimal radial profile. The corresponding 1D temperature profiles, calculated with Eq. (1), are presented in Fig. 4. It can be seen that the discontinuities vanish in the power profile when 10 zones, instead of 3, are adopted. However, the profile does not significantly improve with respect to the difference with the optimal profile.

The effect of the power profile, calculated with THERMIX (Struth, 1995), on the 2D pebble center temperature profile can be seen in Figs. 8 and 9. In the case of 3 radial fuel zones and a pebble radius of 3 cm, three peaks in the temperature profile can be identified that correspond with the peaks in the power profile. If the number of fuel zones is increased to 10 and the pebble radius reduced to 0.5 cm only one peak in the temperature profile remains, which is located next to the inner reflector. The difference in the temperature between the outside and inside of the core is larger for the smaller pebble size. This results from a reduction in the overall thermal resistance (see Eq. (15)). It is noted that the average (and maximum) temperatures in the cores with the small pebbles are lower as compared to the reference.

4. Results of modified in-core pebble recycling in combination with small pebbles

The combined effect of pebble size reduction and the fuel management scheme on the pressure loss and maximum fuel tem-

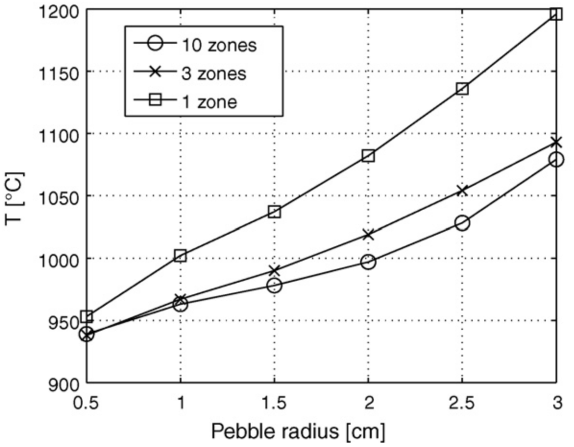

Fig. 10. Effect of pebble size on the maximum fuel temperature for a radially cooled reactor calculated with THERMIX for a core with 1, 3 or 10 radial fuel zones.

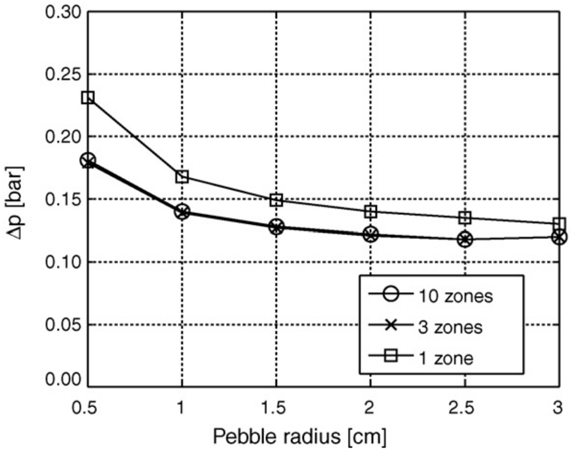

Fig. 11. Effect of pebble size on the pressure drop in the core (pebble bed and reflector flow paths) calculated with THERMIX for a core with 1, 3 or 10 radial fuel zones.

perature has been investigated with a two-dimensional reactor model in the thermal-hydraulics code THERMIX (Struth, 1995) for normal and LOFC conditions.

4.1. Normal operating conditions

For the normal operating conditions, three different power profiles are used in the analysis. The first case represents a core configuration without radial fuel zoning (1 zone), while in the two other cases, the power profiles calculated in Section 3.2 for 3 and 10 radial zones are used. In all cases a total of 10 pebble passes is used and the pebble radius is varied between 0.5 and 3.0 cm.

The maximum fuel temperature for the normal operating conditions as a function of the pebble radius for several pebble radii is presented in Fig. 10. Both the use of more fuel zones and a reduction of the pebble size result in considerably lower fuel temperatures. It is noted that the adoption of the radial fuel zones is advantageous during DLOFC conditions, since a larger part of the decay heat is generated closer to the heat sink at the outer surface of the reactor pressure vessel.

The average pressure drop over the pebble bed calculated with THERMIX for a 3.0 cm pebble radius was found to be 2.1×10^{-3} bar, which compares well with the 2.0×10^{-3} bar that resulted from the analytical calculation. The THERMIX calculation shows that less than 2 % of the total pressure drop occurs in the pebble bed for this case, while the main part is caused by the pressure drop at the slits and flow paths in the inner reflector. The total pressure drop in the core as a function of the pebble radius is shown in Fig. 11. Although the pressure drop increases with a reduction of the pebble size it remains more than an order of magnitude smaller compared to the axially cooled pebble bed for all cases.

4.2. LOFC conditions

The maximum and average fuel temperatures are calculated for both a Pressurized and Depressurized Loss of Forced Cooling (DLOFC and PLOFC) accident for a core with 10 fuel zones and R_{peb} = 0.5 cm.

It is assumed that a reactor SCRAM is performed at the beginning of the transients and that the outer surface of the pressure vessel is cooled effectively by the decay heat removal system, which is simulated by a fixed temperature and heat transfer coefficient. Adiabatic boundary conditions are assumed for the top and bottom of the model. During the first 13 s of the transients the system pressure is reduced from 90 to 1 bar in the depressurized case and to 60 bar in the pressurized case. In both cases the mass flow is reduced to zero in the same time period.

In Fig. 12 the results for maximum and average temperature during the DLOFC and PLOFC transients are shown.

The initial temperature profile for the transients can be seen in Fig. 9 and the initial maximum and average temperatures in Fig. 12 are 939 and 753 °C, respectively. In the first few hundred seconds of the transients the maximum fuel temperature reduces quickly since the fission power reduces quickly and the total reactor power consists only of the decay heat. In the following hours, the maximum and average temperature of the pebble bed rise for both the DLOFC and PLOFC cases. The natural circulation in the PLOFC case distributes the heat over the entire core and to the inner reflector. This heat transfer mechanism is absent in the DLOFC case and since the heat is mostly generated in the outer region of the core (see Fig. 3), the highest temperature is located in this region, while for the PLOFC case the highest temperature occurs at the inner region of the core. The heat of the reactor is removed through conduction in the outer reflector and finally through convection and radiation on the outside of the reactor pressure vessel. Therefore, the heat is more effectively removed in the DLOFC case. The temperature profiles for both cases at the time point of the maximum fuel tem-

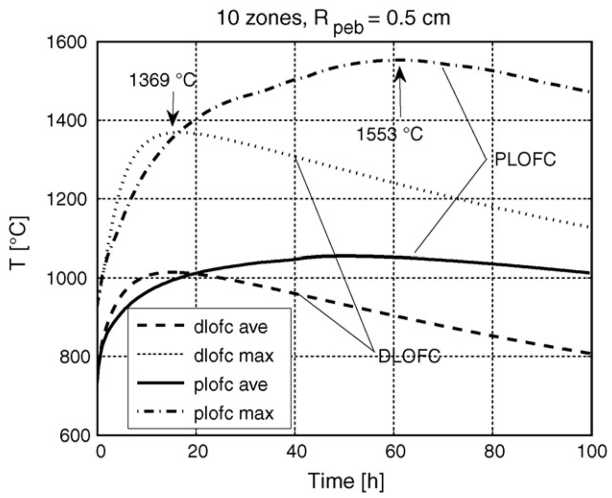

Fig. 12. Maximum (max) and average (ave) fuel temperatures during a pressurized (plofc) and depressurized loss of cooling (dlofc) situation for a 10 zone core with R_{peb} = 0.5 cm.

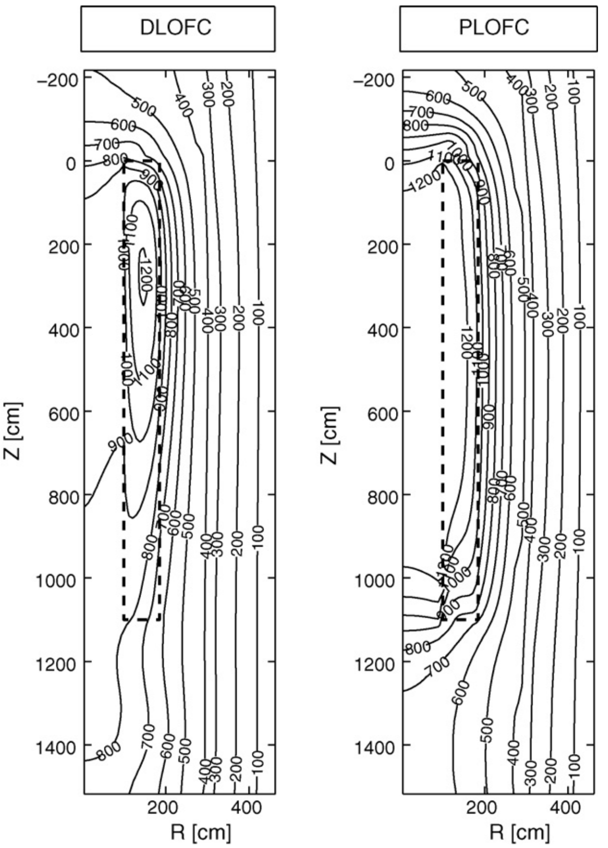

Fig. 13. Temperature profiles [°C] during DLOFC (left) and PLOFC (right) transients at the time of the maximum fuel temperature.

perature is presented in Fig. 13 to illustrate the above described effects.

The maximum fuel temperature for the PBMR-400 design using 6 pebble passes and an axial coolant flow was calculated to be 1594 ° C and no radial fuel zoning. It can be seen that the temperatures for the DLOFC and PLOFC cases for the radially cooled design are significantly lower.

The transient temperature history for pebbles larger than a 0.5 cm radius is similar to that of Fig. 12, since the reactor power during the transients is determined by the decay heat, which is small compared to the fission power during normal operation. Therefore, the difference in temperature between surface and center of the pebble is in the order of several Kelvin. It is noted that reduced DLOFC peak temperatures can be achieved (Boer et al., 2009) in an axial cooled PBMR design with radial fuel zoning (2 or 3 zones). However, this design does not benefit from the low core pressure drop of the radially cooled design.

5. Conclusion

By altering the coolant flow from axial to radial direction, the pressure drop in the pebble bed can be reduced from 2.8 to 0.002 bar for a standard pebble size (R_{peb} = 3.0 cm). The core average pebble center temperature increases with 100 °C. By reducing the pebble size and altering the (re)fueling scheme of the reactor this temperature can be reduced to 50 ° C below the reference temperature, while maintaining the low pressure drop. This would result in a reduction of the pumping power with several percent of the generator power.

By recycling the pebbles from the outside of the core to the inside the analytically derived optimal temperature profile can be approximated by adopting 3 or more radial fuel zones. For a standard pebble the improved power profile results in a decrease of the maximum fuel temperature with 125 °C.

The optimized power profile is also advantageous during LOFC accidents since the peak is located at the outer zone of the pebble bed and the decay heat is removed more easily to the environment. In both PLOFC and DLOFC transient cases, the maximum fuel temperature remains below that of the axial cooled design (1594 °C). This allows for an increase in reactor power (helium outlet temperature).

In the PLOFC transient the natural circulation of the helium between pebble bed and flow paths in the inner reflector causes higher temperatures in the pebble bed after several hours compared to the DLOFC transient. Further investigation on the influence of the geometry of the flow paths and slits in the inner reflector on these natural circulation flows is recommended.

In contrast with the large pressure drop over the pebble bed in an axially cooled design, the total pressure drop in a radially cooled design is determined by losses in the coolant flow paths in the inner and outer reflector. Further research on the effect of the geometry of the flow paths on the pressure drop is recommended.

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