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In-core fuel management optimization of pebble-bed reactors

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ABSTRACT

A reduction of the power peak in the core of High Temperature pebble-bed reactors is attractive to decrease the maximum fuel temperature and to increase fuel performance. A calculation procedure was developed, which combines fuel depletion, neutronics and thermal–hydraulics to investigate the impact of a certain (re)loading scheme for the pebble-bed type HTR. The procedure has been applied to a model of the Pebble Bed Modular Reactor (400 MW) design.

This paper shows that an important reduction in axial power peaking can be achieved by adopting a multi-pass recycling scheme for the pebbles. By dividing the core into several radial fuel zones in combination with multi-pass recycling the power profile can be flattened in the radial direction. For a core with two fuel zones the impact on the k_{eff} and maximum power density as a function of the zone size has been investigated. A heuristic method has been used to find the optimal pebble loading pattern for several (re)loading schemes. Using this method a reduction of the maximum power density from 10.0 to 8.2 MW/m^3 has been achieved for a core with three radial fuel zones.

The effects of the improved power profiles on the fuel temperature during normal operation and a Depressurized Loss Of Coolant (DLOFC) accident have been analyzed. It was found that the optimized power profile results in a reduction of the maximum fuel temperature of 80 °C and 300 °C for normal operation and DLOFC conditions, respectively.

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1. Introduction

In a High Temperature pebble-bed Reactor, fuel (and moderator) pebbles are used to form a porous bed through which helium coolant flows. The pebbles are loaded at the top of the core and move downward by gravity. At the bottom of the core the pebbles are removed from the reactor and depending on the fuel (re)loading strategy and the burnup level they can be re-introduced at the top. In the case of a once-through-then-out (OTTO) scheme (Hansen et al., 1972) the pebbles are discharged after one cycle.

Reactor operation starts from an initial core composition in which pebbles with various fuel content or burnable poison are used. If a certain loading strategy is applied consistently during operation the core reaches an equilibrium composition, which is different from the initial composition.

Some of the current pebble-bed reactor designs with increased thermal power (>300 MW), such as the designs considered in the HTR-PM and the Pebble Bed Modular Reactor (PBMR) 400 MW, include an inner and outer graphite reflector. The power profile in the annular pebble bed can exhibit peaks near these reflectors caused by the local abundance of thermal neutrons. Furthermore, the tall core geometry, adopted for thermal–hydraulic reasons, causes a large difference in the burnup level between top and bottom of the core, resulting in an axial power peak at the top. These power peaks can result in high fuel temperatures during normal operating and accident conditions.

By using several pebble inlet positions at the top of the core the pebble distribution and therefore the nuclide distribution over the core can be influenced. The power profile can be influenced in the radial direction by systematically placing pebbles with different enrichment or fertile content at a different radial starting position. In the extreme case, a central reflector can be formed using pebbles without fuel for the inner core zone (Koster et al., 2003). Experiments were conducted in the AVR reactor (Bäumer et al., 1990), in which 'breeder' pebbles were loaded at the center position and 'driver' pebbles at the outer position (four loading tubes). This flattened the radial power profile.

The axial power profile can be modified by recycling the pebbles several times through the core. This multiple recycling scheme has a secondary advantage, since it provides the reactor operator with pebbles containing different amounts of fissile nuclides. By recycling these pebbles at different radial reloading positions, for example by placing fresh pebbles in the outer region of the core, it is possible to modify the radial power profile while omitting the use of pebbles with different enrichments or burnable poison (Kloosterman, 2003).

Optimizing the pebble loading pattern, thereby improving the power profile, can lead to a reduction of the fuel temperature for a fixed helium outlet temperature. In this paper a calculation tool

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is used to evaluate several pebble loading schemes. The effect of the improved power profile on the fuel temperature is quantified. The methodology for the calculation of the equilibrium nuclide concentration in the core is presented in Section 2. The 400 MW_{th} Pebble Bed Modular Reactor (PBMR-400) (Koster et al., 2003) is used in the analysis as the reference design and its operating characteristics are presented in Section 3.1. The effect of pebble recycling on the axial power profile of this reactor is described in Section 3.2, followed by an investigation of the effect of radial fuel zoning on the radial power profile (Section 3.3). Furthermore, an optimization routine is used to find the optimal pebble loading pattern for cores with multiple fuel zones. In Section 4 the conclusions are drawn.

2. Determination of the equilibrium core composition and power profile

In this section a calculation procedure is presented which determines the equilibrium nuclide concentration in the core, from which the power and temperature profile can be derived. This calculation tool is used to analyze the design modifications to the reference design.

The general equation for fuel depletion, including fuel movement, is as follows (Massimo, 1976):

$$\frac{DN_i}{Dt} = \sum_{j \neq i} \left(\phi\gamma_{ji}\sigma_{aj} + \alpha_{ji}\lambda_j\right)N_j - (\phi\sigma_{ai} + \lambda_i)N_i \quad (1)$$

where $\frac{DN_i}{Dt}$ is the material derivative of nuclide i, N_i the atomic concentration of nuclide i, ϕ the neutron flux, γ_{ji} the probability that a neutron interaction with nuclide j will yield nuclide i, σ_{aj} the absorption cross section of nuclide j, α_{ji} the probability that the decay of nuclide j will yield nuclide i, λ_j the decay constant of nuclide j, σ_{ai} the absorption cross section of nuclide i, and λ_i is the decay constant of nuclide i.

Eq. (1) is evaluated assuming that the pebble is irradiated with a fixed flux level during a certain time interval, when it moves from one point in the core to the next.

Similar to what is done in (Terry et al., 2002) we try to find the asymptotic nuclide distribution directly, without calculating any intermediate distribution. Assuming we have reached this equilibrium core, the neutron flux profile ϕ does not change in time. Instead of adopting the analytical approach (Terry et al., 2002), a numerical calculation scheme, similar to (Fratoni and Greenspan, 2007), was adopted using existing codes.

The outline of the calculation method is presented in Fig. 1 and consists of several codes. The codes are used iteratively until convergence is reached on both the inner and the outer iteration. The criterion for the inner loop is the change in the neutron flux, convergence on the outer loop is determined by the deviation from a preset k_{des} value. The final burnup level of the pebbles, Bu_{fin}, is modified to meet this criterion. The total residence time T that the pebbles remain in the core is modified in turn to reach this burnup level.

The inner loop of the program consists of the following steps:

2.1. Fuel depletion calculation

Provided the flux profile in the core is known, resulting from a certain pebble recycling scheme, the depletion of the fuel in the pebble during its lifetime can be calculated. To this end the core is divided into several discrete radial and axial zones in which one or more pebble burnup classes can be present. The actual depletion calculation is performed using the ORIGEN module from the (SCALE-5, 2005) code system, Between burnup steps the cross sections are updated using successive 1D transport calculations for

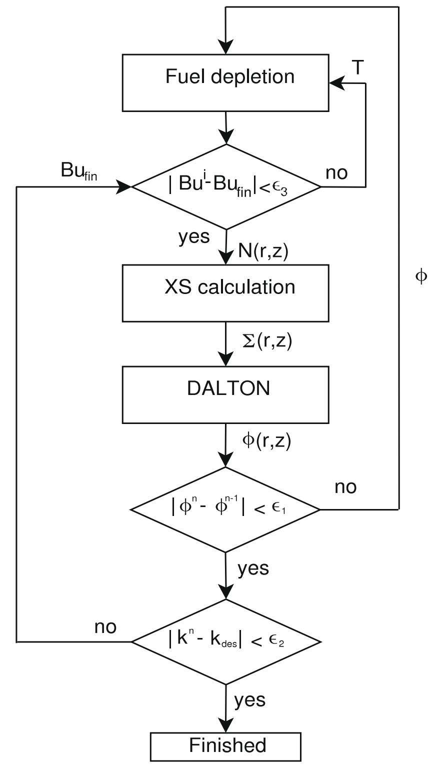

Fig. 1. Flow scheme of calculation procedure for the calculation of the power profile in the core.

the TRISO coated particle and pebble geometry. To this end a 172 energy group XMAS library is used based on the JEFF3.1 library. The nuclide distribution over the core is known after the calculation of each burnup interval.

It is noted that the pebbles are allowed to pass through the core several times for some (re)loading strategies. Therefore, it is possible that pebbles having different nuclide densities are located at the same position.

2.2. Calculation of the neutron cross sections

Zone averaged nuclide concentrations $N(r,z)$ are now used for generating neutron cross sections for the entire reactor following the procedure described in (Boer et al., 2008).

The double heterogeneity of the fuel is taken into account by performing a cell weighting of a fuel particle in moderator material using a Dancoff factor calculated according to the method of (Bende et al., 1999). Furthermore, in this calculation step the resonance treatment is performed by the Bondarenko method and the Nordheim Integral Method for the unresolved and resolved resonances, respectively. This step is followed by a 1D transport calculation of a pebble geometry including the surrounding helium. Radial and axial (1D) transport calculations are used to calculate zone weighted cross sections for the entire reactor. Finally, a two dimensional cross section library ($\Sigma(r,z)$) is created.

2.3. Dalton

The neutron cross sections are used to calculate the two dimensional multi-group flux profile $\phi(r,z)$ with the neutron diffusion code DALTON (Boer et al., 2008). Average fluxes are generated for each fuel depletion zone and scaled to the desired reactor power. The k_{eff} of the reactor is calculated.

Once the nuclide distribution over the core is known and the cross section generation step is applied for several temperatures

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