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MODELING OF CONTINUOUS RELOAD HTR SYSTEMS BY THE PANTHERMIX CODE SYSTEM

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ABSTRACT

The code PANTHERMIX can handle the combined neutronics and thermal hydraulics calculations for a Pebble-Bed HTR. This together with a pebble flow-pattern for a cone-shaped bottom geometry fully models a Pebble-Bed HTR with continuous reload. At any time the pebble distribution is known per fuel type and per burnup class. This work concentrates on the flow pattern modeling and on a consistent distribution of fuel pebbles over burnup classes. Further some calculation results are shown to illustrate the PANTHERMIX capabilities.

1. INTRODUCTION

The High Temperature Reactors to be considered here are cooled with helium and have a core filled with pebbles (balls) instead of fuel rods or blocks. These pebbles, all of the same size (6 cm diameter), are moderator pebbles and fuel pebbles. Different fuel pebbles can contain different types of fuel in the form of small TRISO coated particles in the 5 cm diameter central part. This central part is enclosed in a non-fuel shell. The usage of pebbles makes it possible to discharge them at the bottom of the core, and to reload selected ones at the top in a continuous refuelling scheme.

The purpose of this paper is to describe how the code system PANTHERMIX (Oppe, 1996, 2001) handles the flow of pebbles through the reactor core, and keeps track of their changing properties (burnup), so that these properties can be used, after discharge, to decide for a reload or not. The new code system PANTHERMIX is a combination of existing codes for neutronics modeling (PANTHER, (Bryce, 1998)) and HTR thermal hydraulics modeling (THERMIX/DIREKT, (Struth, 1997)), extended with the capability to handle the pebble flow pattern in the reactor core.

Section 2 describes the features required in PANTHERMIX for the modeling of a Pebble-Bed HTR without moving fuel pebbles. This introduces the combined modeling of neutronics and thermal hydraulics of quasi steady-state (burnup cycle) as well as transient behaviour of the reactor.

A two-dimensional (R-Z) flow pattern of pebbles in the core can be thought of as a combination of axial (downward) and radial (inward) movement of pebbles between the volume elements in the core model. Section 3 describes the changes of physical quantities within these volume elements as a consequence of an axial (downward) shift, whereas section 4 deals with the peculiarities of combined axial and radial movements, which are required for the modeling of the pebble movements in continuous reload HTRs with a conically shaped bottom and a fuel discharge tube.

After that section 5 illustrates some of the PANTHERMIX capabilities. The pebble charges and discharges are shown as a function of time for a HTR from start-up until equilibrium. Also the power is shown as a function of time there.

2. PEBBLE-BED HTR WITHOUT FUEL DISCHARGE AND RELOAD

2.1 Neutronics modeling

The neutronics modeling for a cylindrical HTR core is done by representing the 2-D R-Z cylinder geometry as a 3-D HEX-Z (or X-Y-Z) geometry in PANTHER with homogenized pebbles. Kuijper (1997) shows that this approach is satisfying for hexagons or rectangles taken small enough. So PANTHER is suited for the neutronics modeling of a cylindrical HTR core.

PANTHER requires a nuclear database containing (presently) 2-group nuclear data for all reactor materials depending on irradiation (burnup), fuel temperature, xenon density, etc. The WIMS lattice code (presently version 8, (WIMS8, 1999)) is used to generate this 2-group database, taking into account the fine group spectrum effects by performing one-dimensional pseudo-reactor calculations in radial and axial structures, yielding different 2-group macroscopic cross sections for materials with identical components at different locations. Also the double heterogeneity of the fuel kernels in the pebbles is taken into account with the WIMS PROCOL module (WIMS8, 1999).

2.2 Thermal hydraulics modeling

The thermal hydraulics models included in PANTHER do cover light water (PWR,BWR) and gas cooled (Magnox,AGR) reactors, but not the Pebble-bed High Temperature Gas-cooled Reactors. Therefore the thermal hydraulics code THERMIX/DIREKT (Struth, 1997) from FZ Jülich has been combined with the PANTHER code. This leads to the combined code system PANTHERMIX suitable for HTR steady state and burnup core physics, as well as reactivity transient calculations (Oppe, 1996, 2001 and Kuijper, 1997).

2.3 Combination of neutronics and thermal hydraulics modeling

The combined code system PANTHERMIX is controlled from the PANTHER code, which calls THERMIX/DIREKT from within a calculation loop. PANTHER calculates (in steady-state and transient mode) the 3-dimensional neutron flux and power distribution for a given temperature distribution, whereas the THERMIX/DIREKT code calculates (in steady-state and transient mode) the temperature and coolant flow

distribution for a given power distribution. Data transfer between PANTHER and THERMIX/DIREKT is done with so-called Store/Retrieve files, which contain selected records and components of the PANTHER internal database. To facilitate the data transfer between THERMIX/DIREKT and PANTHER, the THERMIX/DIREKT code was extended with some extra fortran subroutines to read and write data in the required PANTHER Store/Retrieve format. In the PANTHER code the data transfer is handled by some extra macros, written in the PANTHER macro language.

For steady-state calculations the PANTHERMIX code system was checked successfully against the well known VSOP code (Teuchert, 1994) with the so-called PAP20 benchmark (Kuijper, 1997). This fundamental study concerns a (20 MWth) pebble bed reactor with a so-called peu-à-peu (hence PAP) loading scheme. During its lifetime, the core is kept critical by continuously adding fuel pebbles on top, without discharging fuel pebbles at the bottom. The PANTHERMIX code system is capable of calculating the continuously increasing core height as a function of time. Kuijper (1997) also describes two examples of PAP20 transient calculations done with PANTHERMIX: Loss Of Flow Accident (LOFA) and Loss Of Coolant Accident (LOCA).

3. FUEL DISCHARGE AND RELOAD IN A PEBBLE-BED HTR

In general the reactor core contains a mixture of moderator and fuel pebbles. The fuel pebbles may be of different initial enrichment, and can have attained different levels of burnup. In the homogenized volume element modeling for PANTHER this pebble mixture can be characterized by the fuel initial heavy metal (HM) mass, effective initial enrichment and effective burnup. Therefore the HM mass and the enrichment are introduced as extra dependencies for nuclear database interpolation. More detailed characterization contains HM mass and produced energy per burnup class per fuel type for each volume element.

3.1 Physical quantities per volume element

The physical situation of a volume element is described by physical quantities independent of the position within the volume element. These quantities can be averages of position dependent quantities (like mass density and macroscopic cross sections) as well as total values for the whole volume (like fuel mass and produced energy).

The basic quantities for each volume element are the following conserved quantities:

- HM mass, which determines the number of pebbles per fuel type.
- Product of irradiation (burnup) and HM mass, which is the produced energy.
- Volume, which is related to the total number of pebbles in a volume element.

The first two of these are given for each combination of fuel type and burnup class (to be defined later on) and the last one is constant for core volume elements of fixed size, for a given (constant) packing fraction of the pebbles in the core.

For the calculation of the macroscopic cross sections of the mixture of fuel and moderator pebbles in a volume element the following quantities are required:

- Effective enrichment
- Effective irradiation (burnup)

They are calculated from the basic quantities, weighted with the HM mass per fuel type.

The basic quantities introduced above completely characterize the properties of the mixture of fuel and moderator pebbles present in the volume element. The following quantities can also be calculated in each volume element from the basic quantities:

- Number of fuel pebbles for each combination of fuel type and burnup class.
- Number of moderator pebbles.

No distinction is made between different moderator types. Also no distinction is made between a new moderator pebble and a moderator pebble that already was inside the reactor.

3.2 Axial shift principles

A two-dimensional (R-Z) flow pattern of pebbles in the core can be thought of as a combination of axial (downward) and radial (inward) movement of pebbles between the volume elements in the core model. This section describes the changes of physical quantities within these volume elements as a consequence of only axial (downward) shift. The radial shifts to be combined with these axial shifts for a more detailed modeling will be described in section 4, but the principle of changes of physical quantities remains the same for this combination.

A reactor core is described in a PANTHER model by physical quantities that are homogeneous inside each core volume element (HEX-Z or X-Y-Z).

In our shift model we also need so called box volume elements and rings:

- A 'ring' is a ring of core volume elements that have roughly the same distance to the reactor central axis. Each circulation action is defined per ring. This concerns the top height for the position where new pebbles will be added, the bottom height for the position from where pebbles will be removed, and the vertical shift distance per shift action.
- An 'inbox' is a (variable size) volume element containing a mixture of pebbles needed to fill the gaps that arise at the ring tops as a result of a downward shift. This mixture may contain moderator balls and different types of fuel balls for different burnup classes (including the lowest class, i.e. fresh fuel).
- An 'outbox' is a (variable size) volume element to receive pebbles leaving at the ring bottoms as a result of a downward shift. This may be a mixture of pebbles like that in the inbox, except that the fuel can not be fresh here, so there are no lowest burnup class fuel pebbles.

Just like the volume elements in the core the box volume elements contain homogeneous physical quantities, but their sizes are not fixed!

Shifting means changing the physical quantities for the volume elements. Each axial shift action moves material from inboxes to rings in the core, per ring over a certain distance downward, and out of these rings to outboxes. Only the basic quantities are always calculated for each volume element directly from shift distances and volume

fractions. The other physical quantities are derived from these basic quantities only when needed. For example the fuel reload decisions need to know the number of fuel pebbles per combination of fuel type and burnup class only for the box volume elements, not for the core volume elements.

3.3 Pebble circulation actions

Fig. 1 shows the possibilities for pebble circulation actions. The arrows only serve as indicators: not all possible routes are shown, and not every arrow represents a route that must always be followed.

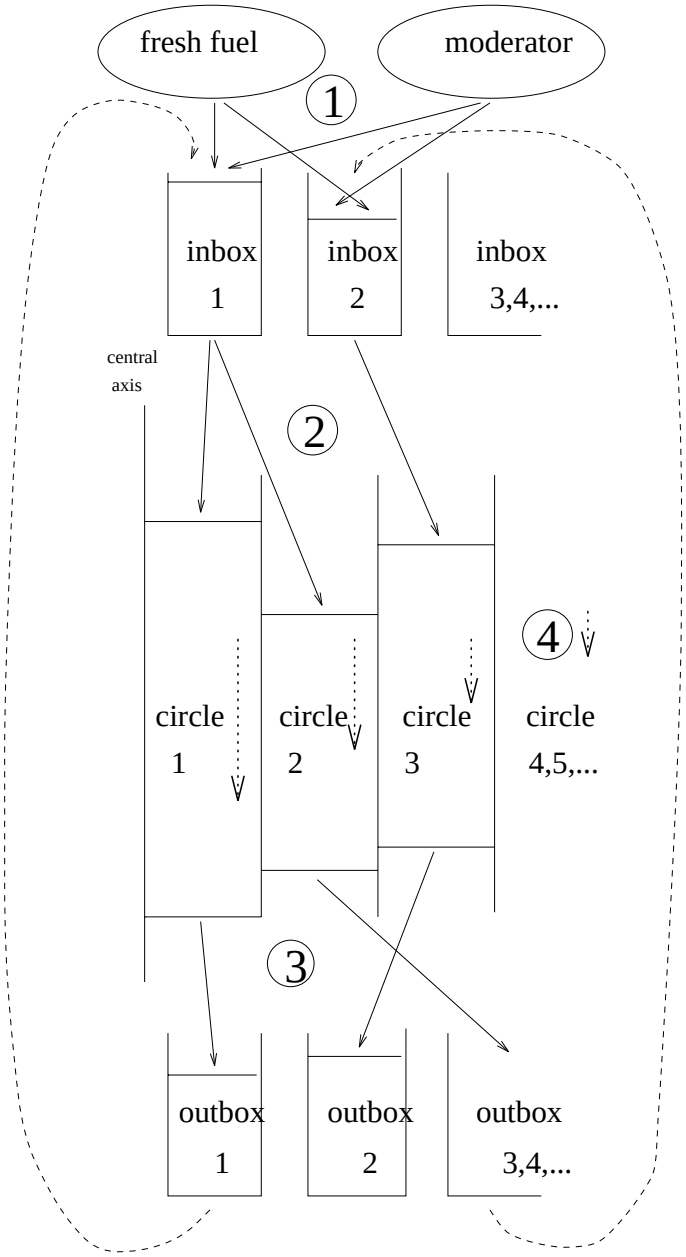

Fig. 1 Pebble circulation scheme.

The pebble circulation actions will now be described according to the encircled numbers in the figure.

1. Fill inboxes (first time empty, later possibly filled to a certain height) with:
   - Different types mixtures of fresh fuel. Extra pebbles are added to the system.
   - Moderator. Extra pebbles are added to the system.
   - Fuel from outboxes. No extra pebbles are added to the system. Each inbox may be filled with any amount of any fuel type and burnup class from any outbox, as long as those pebbles are available in that outbox.
2. Connect for each ring that must shift its top to an inbox. The inbox will be called a parent of the ring here. Each ring may have only one inbox as parent. Each inbox may be parent of zero, one or more rings.
3. Connect for each ring that must shift its bottom to an outbox. Here the ring will be called a parent of the outbox. Each ring may be parent of only one outbox. Each outbox may have zero, one or more rings as parent.
4. Shift downwards the contents of each ring over a specified distance. This distance represents the speed of balls through the reactor. The speed in different rings may be different. The figure only shows the downward directed axial speed components, but there may also be inward directed radial speed components. The top and bottom locations do not change height, only the contents between them will change. Details are listed below.

For each shift the new contents of volume elements are mixtures of old volume element contents. An inbox only loses material and energy. If the shift distance does not exceed the axial mesh layer height then a top axial mesh layer becomes a mixture of its old contents and the old contents of an inbox.The other axial mesh layers become mixtures of their old contents and the old contents of the axial mesh layers directly above them. An outbox only receives material and energy, its new content becomes a mixture of its old content and the old contents of some ring bottom layers. If the shift distance does exceed the axial mesh layer height then the mixture ingredients are a bit more complex. All mixtures are calculated with volume weighted averaging.

3.4 Energy distribution over burnup classes

The administration for fuel reload decisions is covered by burnup classes. Therefore the unbound interval of possible burnup values is divided into a finite number of intervals that cover the total range from 0 to ∞. The lowest class has both upper-bound and lower-bound equal to zero and contains only fresh fuel. The highest class contains all fuel beyond a certain burnup value limit.

Nuclear calculations for a burnup step result in amounts of energy increase per core volume element to be distributed over the different fuel types and burnup classes. This is done according to

$$\Delta E(fuel,class) = \frac{w(fuel,class)M(fuel,class)}{\sum_{f,c} w(f,c)M(f,c)}\Delta E \tag{1}$$

Here ΔE is the energy that must be distributed and ΔE(fuel,class) is that part of the energy that belongs to one burnup class for one fuel type. Further $M()$ stands for HM mass and $w()$ for a weight factor (~k_∞ , which is burnup dependent).

To let the new burnup values $\frac{E(fuel,class)+\Delta E(fuel,class)}{M(fuel,class)}$ be consistent with the burnup-classes the fuel distribution over the classes must be redefined. The following equations show burnup-class relations for every fuel type on every location, therefore only burnup-class indices are used (fuel type and position indices are left out).

For a distribution function $f_i(B)$ of HM mass over the class i burnup interval with boundaries B_{i-1} and B_i the total HM mass in class i is

$$M_i = \int_{B_{i-1}}^{B_i} f_i(B)dB \tag{2}$$

and the total burnup energy in class i is

$$E_i = \int_{B_{i-1}}^{B_i} Bf_i(B)dB \tag{3}$$

The following consistency condition is not automatically satisfied anymore after E_i has been replaced by $E_i + \Delta E_i$

$$B_{i-1} \le \frac{E_i}{M_i} \le B_i \tag{4}$$

Assuming the shape of the distribution function to remain the same, addition of energy ΔE_i means a shift $\Delta B_i = \frac{\Delta E_i}{M_i}$ over the burnup interval for this distribution function.

Now for each combination of a burnup-shifted class i interval and a not burnup-shifted class j interval the interval I_{ij} is defined to be the intersection of these intervals (of course it is a zero-length interval for a lot of i,j combinations). This general description covers the amount of fuel remaining in the same burnup-class as well as the amounts of fuel falling in all possible higher burnup-classes.

So class i with added energy ΔE_i leads to the following contributions for new class j data:

$$M_{ij} = \int_{I_{ij}} f_i(B - \Delta B_i) dB \tag{5}$$

$$E_{ij} = \int_{I_{ij}} B f_i(B - \Delta B_i) dB \tag{6}$$

and the total new consistent contents for class j are:

$$M_j = \sum_i M_{ij} \tag{7}$$

$$E_j = \sum_i E_{ij} \tag{8}$$

A good choice for the distribution function $f_i(B)$ is a step function of two constant function values with one step at the point $B_i^s = \frac{E_i}{M_i}$ with the constant function values determined by equations (2) and (3). Then it is straightforward to prove that $f_i(B)$ always exists, is nonnegative, and consistent for the burnup class.

4. Cone shaped bottom geometry

A pebble flow pattern is an (R,Z) field of axial and radial velocity components. One way to represent pebble flow patterns in a cone shaped bottom core is the VSOP method, shown in fig.2.

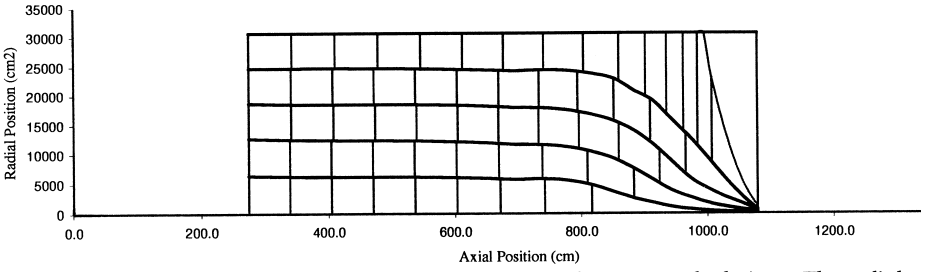

Fig.2 Flow zones in core for VSOP calculations.

Each flow zone is divided into equal volumina components (shown as equal areas in fig.2 because of a quadratic r scaling). Once every shift timestep the full content of each component moves to the neighbouring lower z component in the same flow zone.

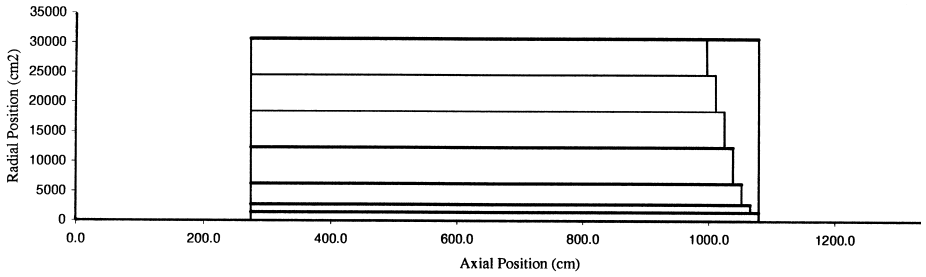

Fig.3 Flow zones in core for PANTHER calculations.

In PANTHER geometry a cone shaped bottom core looks like fig.3. The axial velocity component is represented by an axial shift distance per timestep, and the radial velocity component on an axial mesh border is represented by a fraction of the contents of a ring that moves per timestep to the directly neighbouring ring inside. It is also possible to change the axial speed (shift distance) in a ring on every location where a radial velocity component is specified by means of a ring contents fraction. Verkerk(2001) describes a method to obtain these fractions for a given flow pattern and compares the resulting PANTHER flow with the original flow. A fundamental comparison here concerns fuel residence times in the core, depending on the initial radial position where the fuel entered the core.

4.1 Fuel residence time per flow zone

Special calculations have been done to check the time it takes a fuel pebble to reach the bottom discharge from its top loading at a certain radial distance. Therefore the top layers for the flow zone ring to be checked is totally filled with fuel and all the other volume elements in the core contain only moderator. The fuel discharge profiles (figs.4 and 5) show the spread of the residence times for each flow zone in a core example. This spread is caused by numerical diffusion in the shift calculations, resulting from the free choice of shift distance per timestep. In the VSOP method mentioned above this shift distance is not free to choose, but defined by the equal volumina components in the flow pattern. So this method has no diffusion at all, and all pebbles in a single flow shell have exactly the same residence time. Verkerk(2001) shows that these constant residence times (calculated with VSOP) agree well with the peaks in fig.4 and the half max situations in fig.5. This together with the realisation that a natural flow also contains a certain spread gives confidence that the numerical diffusion is allowed here.

Two different methods were used to do the actual calculations per shift substep.The figs.4 and 5 each contain results from both calculation methods. It shows two slightly different diffusion situations for each flow zone, without changes in the peak and half max timings

The first method is called WARP0 (represented by solid lines in the figures) and allows a great flexibility in the shift scenarios. The second method called WARP1 (represented by dashed lines in the figures) is less flexible but can speed up the calculations for cone shaped bottom geometry by about a factor 10 or more.

The following description of these methods uses the terms shift step and substep. One shift step covers all the actions needed in one timestep to shift pebbles from inboxes via core rings to outboxes according to the flow pattern. A substep here is meant to cover all the actions needed to shift pebbles from selected top loading (can be from an inbox or from a higher axial range with a different axial speed) through axial ranges (higher to lower) of selected rings to selected bottom discharge (can be to an outbox or to a lower axial range with a different axial speed). A shift step is a combination of 1 or more subsequent substeps with inboxes, outboxes at the begin, end of the queue. Such a shift step is applied once every time step.

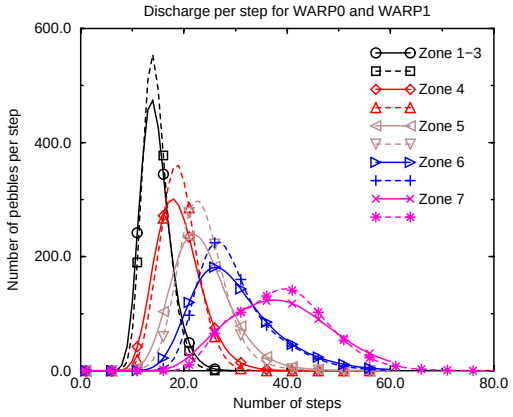

Fig.4 The number of discharged fuel pebbles per time step. Solid lines are WARP0, dashed lines WARP1.

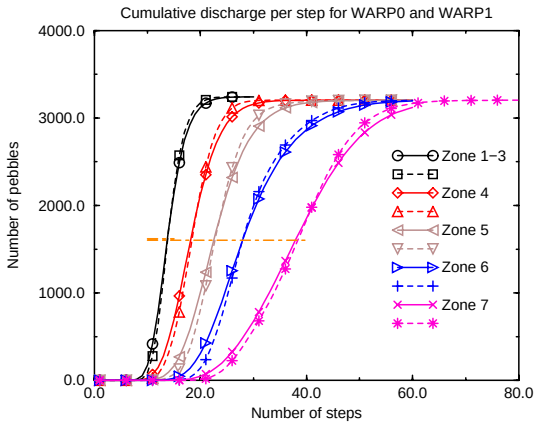

Fig. 5 The number of cumulative discharged fuel pebbles per time step. Solid lines are WARP0, dashed lines WARP1. The horizontal lines are half the final cumulative amounts (for Zone 1-3 slightly higher than for the other Zones).

For a simple model with only axial flows a shift step needs only one shift substep, but for a more detailed cone model each staircase step introduces an extra shift substep. This leads to at least 6 extra shift substeps in fig. 3.

The WARP0 method allows for each shift (sub)step to have radially dependent axial mesh layer ranges and shift distances. For the WARP1 method the shift distances may still be radially dependent, but the axial mesh layer ranges are constant per shift (sub)step and are limited to a maximum size. For the current PANTHERMIX version this maximum size covers 4 axial mesh layers.

The basic WARP0 method only applies transfer of contents between directly neighbouring axial mesh layers for all the core volume elements at once. This means that the basic WARP0 shift distance may not exceed the minimum axial mesh layer height, and the calculations are done for all elements of large arrays.

The basic WARP1 method applies transfer of contents directly between all axial mesh layers in the axial range of the current (sub)step and no transfer of contents between volume elements above or below the axial range. So the basic WARP1 shift distance may not exceed this axial range, and the calculations are done only for small parts of large arrays.

In case of a large shift distance both WARP methods split this large shift distance into smaller shift distances so that the basic WARP methods can be applied sequentially to each of the resulting smaller shift distances. Generally WARP1 needs less splitting, which explains the reduced diffusion compared to WARP0 (as can be seen in figs.4 and 5). This less splitting together with the calculations done only for small parts of large arrays explains the calculation speedup of WARP1 compared to WARP0.

Because a cone shaped bottom geometry leads to high bottom velocities compared to the top velocities, this implies that the largest shift distance per time step is caused by a rather small part of the core. So WARP1 can gain a lot of calculation time here, and its limitations are no problem for cone shaped bottom geometry flow patterns.

5. START-UP PHASE

To illustrate some of the PANTHERMIX capabilities this section shows results calculated for a loading scenario that leads from a core with only moderator and fresh fuel to a full power equilibrium situation in which the burnup distribution over the core is constant in time. During the initial period the core will not be in equilibrium state and the mixture of moderator pebbles with fresh fuel pebbles and partially burnt fuel pebbles changes as function of time.

In the example here a burn-in scheme is followed that employs fuel pebbles as foreseen in the equilibrium state, mixed with moderator pebbles. During this burn-in phase the reactor remains critical by changing the moderator/fuel ratio or by changing the fuelling rate. The results show that (nearly) equilibrium values are reached after more than 1000 operating days.

Figs. 6 to 9 show some interesting data as a fuction of time. The core distribution of these data is also calculated for each timestep, but not shown here.

Fig.6 shows the chosen power buildup from 50% to 100% in 450 days and the constant 100% power after that.

Fig.7 shows the maximum power per pebble during the power buildup and afterward until the equilibrium.

Fig.8 shows the daily fuelling rate at the inlet as function of time distinguished between moderator pebbles, fresh fuel pebbles, and reloaded fuel pebbles. The equilibrium fuelling rate is a total of 3850 pebbles per day, of which 2700 is fuel.

Fig.9 shows the time evolution of the distribution (in terms of pebbles per day) of the fuel pebbles over the different burn-up classes in the discharge tube. Class 1 is fresh fuel (zero burn-up), class 9 is the to-be-discarded class (> 80000 MWD/t). Because the equilibrium average residence time in the core lies around 100 days it is seen here that the pebbles reach the higher burnup classes only after having been reloaded several times.

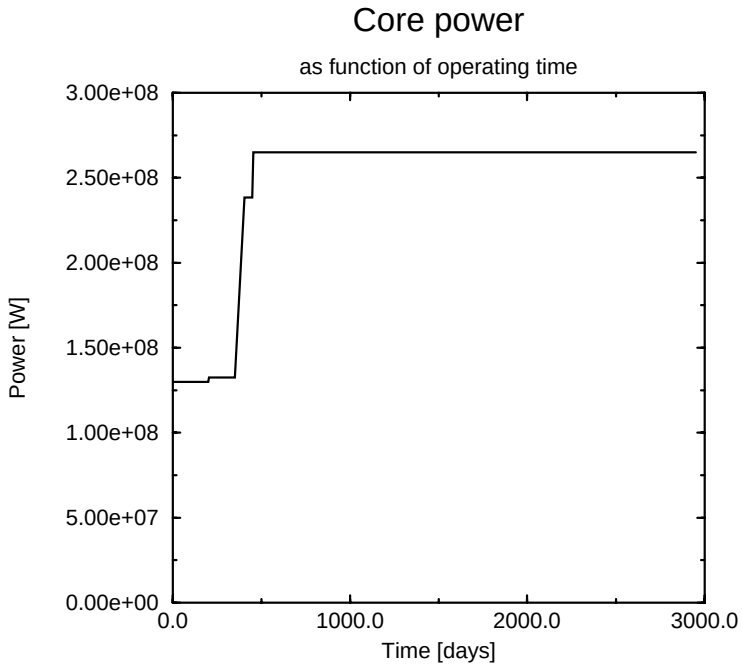

Fig. 6 Total Power.

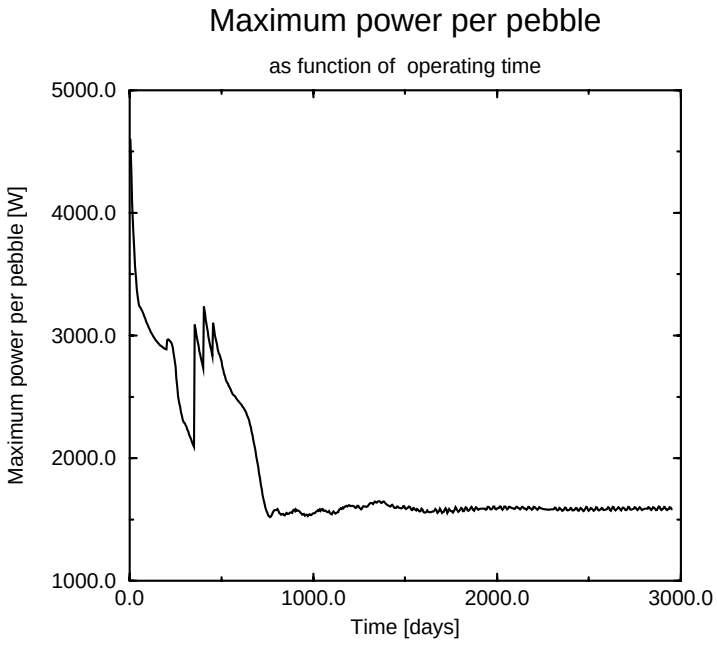

Fig. 7 Power per pebble.

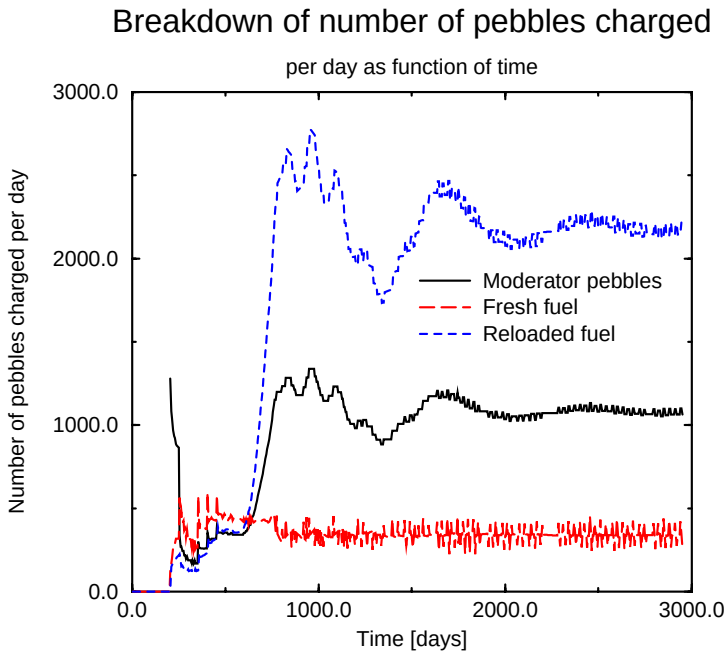

Fig. 8 Daily fuelling rate at the inlet.

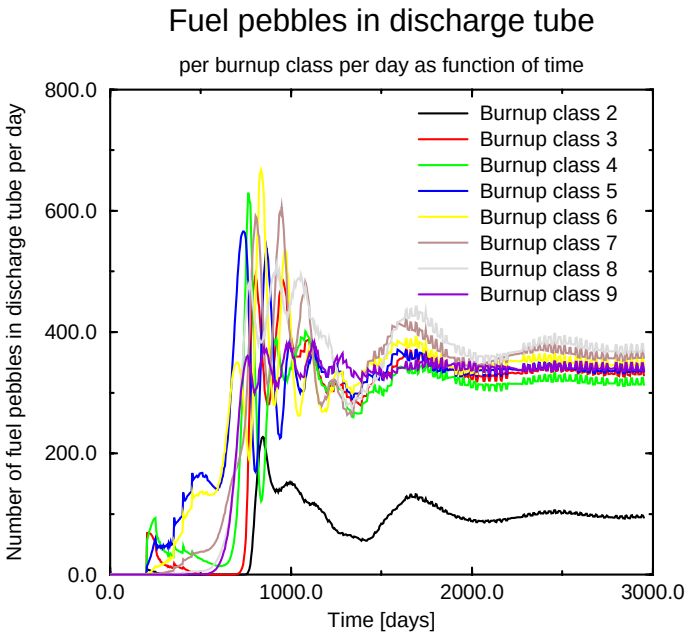

Fig. 9 Fuel pebbles in discharge tube.

6. CONCLUSIONS

The PANTHERMIX code is suited to model the pebble-flow in a HTR core together with the neutronics and thermal hydraulics properties. Therefore a continuous reload equilibrium situation can be calculated in full detail, as well as a start-up phase to reach that equilibrium.

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