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Very High Temperature Reactor Physics Studies using a 3D Neutronic / Thermal-hydraulics Coupling System for Block Type Gas Cooled Reactors

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Abstract

The very high temperature reactor (VHTR) is one of the six projects selected in the Generation-IV nuclear power plant research program. The VHTR is a graphite-moderated, helium-cooled reactor with a once-through uranium fuel cycle. It is designed to be a high-efficiency power production system, flexible to adopt uranium/plutonium fuel cycle, minimize waste production and retaining the desirable safety characteristics offered by its modularity. The bundling of dispersed fuel made in coated particles and the graphite as moderator leads to special core physics. The strong neutronic and thermal-hydraulics spatial dependency is one of the most important consequences of this bundling.

This paper is a contribution to VHTR core studies. It presents the improvements made on the neutronic and thermal-hydraulics coupling system of the French Atomic Energy Agency (CEA). Especially the use of spatial de-homogenization temperature model and the possibility to insert the operating and start-up control systems into the coupling model. In addition, it exposes some preliminary results of VHTR core depletion calculation. The paper discusses also the reflector thermal effect and the location of both neutronic and thermal hottest area during the fuel cycle and it is consequence on core safety.

KEYWORDS: Very high temperature reactor, neutronic and thermal hydraulics coupling, temperature de-homogenization, core depletion calculation, safety.

1. Introduction

Physics analysis of the very high temperature reactors (VHTR) [**1**], requires different modeling capabilities from those implemented for the current light water reactors in both neutronic and thermal-hydraulics. The models must include the double heterogeneity of coated fuel particles, neutron streaming in coolant channels, the core/reflector coupling, the gas convection in the fine cooling channels and the by-pass gas repartition between the active region and the reflector. Furthermore, several important phenomena such as reactivity temperature coefficients must be evaluated with a good accuracy in the full core. That is real challenge because of the strong in-

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teraction between neutronic and thermal-hydraulics resulting from the use of dispersed coated fuel particles associated with a quite poor moderator material. Therefore, it appears essential to develop adapted deterministic analysis tools and calculation scheme for the design of VHTR.

In order to take part into the international research programs on the High Temperature Reactors (HTR) and in particular, on the VHTR, the French Atomic Energy Agency (CEA) is deploying special efforts to develop new models and qualify its advanced deterministic codes for VHTR design and licensing. In this perspective, the CEA is collaborating with EDF and AREVA-ANP to develop NEPHTIS [**4**] the neutronic calculation scheme for High Temperature Reactors. The CEA is also building its own neutronic and thermal-hydraulics coupling system for VHTR core physics analyzing [**3**].

This paper deals with the neutronic and thermal-hydraulics coupling modeling (N&TH) dedicated to the block type HTR. It is divided into three parts. The first part of the paper describes the last improvements made on the advanced neutronic and thermal-hydraulics coupling system for block type HTR.

The second part presents some preliminary physical results of the VHTR core calculation using the N&TH coupling model. These results concern the core power and temperature distributions during an equilibrium fuel cycle and the dependency of the different temperature coefficients on fuel depletion and core power.

The last part of the paper discusses some physical specificities of the VHTR such as the reflector thermal effect and the location of the hottest region and its impact on the safety of the core.

2. Very High Temperature Reactor core characteristics

The VHTR (**Fig.1**) studied here is a graphite-moderated reactor with a once-through uranium fuel cycle. In this paper, we will focus on prismatic block reactor. The fuel loaded into the core is uranium oxide in a TRISO configuration. The controls rods are inserted in the surrounding graphite reflector. All core characteristics are shown in **Tab.1** and **Tab.2**.

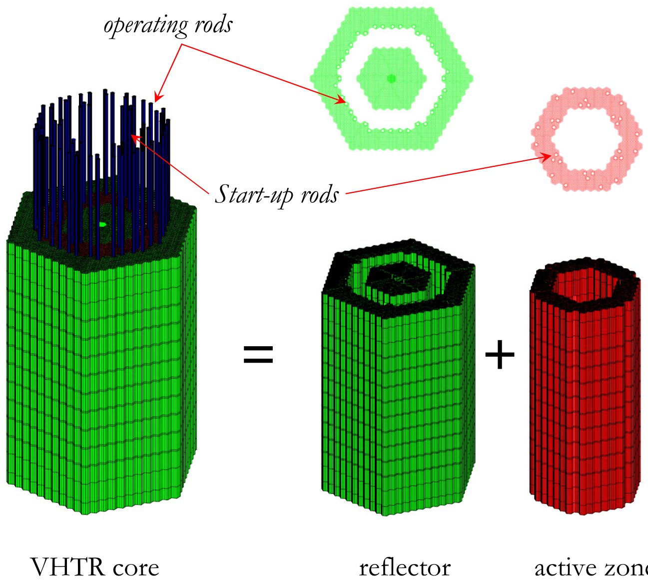
Table 1: VHTR core characteristics

Global core characteristics	Value (unity)
Active height	8 m
Equivalent diameter of the active zone	2.96 / 4.84 m
Axial reflector height	1.3 m
Number of column in the annular core	102
Number of standard element	720 (10 per column)
Number of control element	300 (10 per column)
Type of fuel loaded into the core	UO_2
Mass of fuel loaded in the core	4524 kg
^{235}U enrichment [% by weight]	15 %
Core power	600 MWth
Power density in the active zone	6.6 $MW.m^{-3}$
Inlet and outlet helium temperature	723K / 1123 K
Helium pressure	70 bars
Core helium mass flow	288 $kg.s^{-1}$
Bypass (Fuel, Reflector, rods)	80% – 15% – 5%

Table 2: Fuel assemblies' characteristics

Assemblies characteristics	Value (unity)
Distance between opposite sides [cm]	36
Height of fuel element [cm]	80
Helium gap between elements [mm]	1.0
Number of fuel rods (Std/Ctrl)	216 / 174
Number of cooling holes (Std /Ctrl)	108 / 80
Number of compacts in a rod (Std/Ctrl)	15 / 15
Compacts per element (Std/Ctrl)	3240 / 2610
Radius of fuel compacts [cm]	0.6225
Radius of cooling holes (Std/Ctrl) [cm]	0.794 (102 / 86)
	0.635 (6 / 6)
Height of a compact [cm]	4.928 cm
Std/Ctrl = standard/control element	
Density of the graphite of the element	1.74
Density of the graphite in a compact	1.74
Porous media in fuel element	
Porous media in reflector blocks	

Figure 1: VHTR core geometry: reflector and active zone



3. Neutronic and thermal-hydraulics coupling model

3.1 Coupling model description

The advanced coupling system for block type high temperature reactor [**2**, **3**] is an external coupling system. It is composed of the neutronic calculation scheme NEPHTIS [**4**] and the thermal hydraulics model ARCTURUS [**5**].

3.1.1 Neutronic calculation scheme

NEPHTIS is based on a transport–diffusion calculation scheme using the transport code APOLLO2 [**6**] and the transport-diffusion code CRONOS2 [**7**]. The transport code is used to calculate the fuel element in an infinite medium and to provide condensed and homogenized cross-sections libraries. These cross-sections are homogenized on several regions which have the same physical properties and are functions of some parameters (fuel, moderator and reflector temperatures, poison concentration, burn-up, control rod position …).

3.1.2 Thermal-hydraulics model

The CAST3M/Arcturus model uses a two-level approach. On the first level, singularities of fuel particles, fuel compacts and helium-cooling channels with inter-assembly helium cavity are homogenized to obtain equivalent thermal properties for the porous media [**8**] and the cooling gas. On the second level, thermal-hydraulics equations system is solved on the homogenized geometry using CAST3M [**5**] code.

3.1.3 Coupled model

In our approach, each calculation code has its own input deck and internal convergence loop. A global loop deals with data exchange and convergence. Exhaustive parameter sensitivity studies have been done to optimize the coupling model in term of precisions and time calculation [**3**]. However, the initial coupling model was unable to correctly calculate the thermal coefficient in the fuel because it didn't take into consideration the difference between the moderator and the fissile isotopes temperatures. In fact, only the porous media temperature was reachable through the thermal-hydraulic calculation (1).

$$\begin{cases} P = \mathbf{N}\left[\Sigma\left(T_{porous}\right)\right] \\ \left[T_{porous}, T_{fluid}\right] = \mathbf{TH}\left[P\right] \end{cases} \tag{1}$$

One of the major improvements of the coupling model is the de-homogenization calculation which guarantees a better description of the local thermal calculation in the fuel.

3.2 Spatial temperature de-homogenization

The aim of the de-homogenization model is to transform the initial coupling model (1) into a model written as (2).

$$\begin{cases} P = \mathbf{N}\left[\Sigma\left(T_{fuel}, T_{moderator}\right)\right] \\ \left[T_{porous}, T_{fluid}\right] = \mathbf{TH}\left[P\right] \\ \left[T_{fuel}, T_{moderator}\right] = \mathbf{DZ}\left(T_{porous}\right) \end{cases} \tag{2}$$

3.2.1 Mathematical approach

The first step of the de-homogenization consists in cylindrization transformation for both homogeneous and heterogeneous representation (**Fig.2**). The second step, we are solving conduction/convection problems in both heterogeneous and homogeneous cylindrical geometries (3) (*see Nomenclature paragraph for terms definitions*).

$$\underbrace{\begin{cases} \lambda^* \Delta T^*(r) = P_k & r \in \Omega^* \\ -\lambda^* \vec{\nabla} T^*(r) = h\left(T^* - T_f\right) & r \in \partial\Omega^* \end{cases}}_{Homogeneous\ cylindrical\ problem} \quad \underbrace{\begin{cases} \lambda_k \Delta T_2^*(r) = P_k & r \in \Omega_k^* \;\; k = 1,2 \\ -\lambda_2 \vec{\nabla} T_2^*(r) = -\lambda_1 \vec{\nabla} T_1^*(r) & r \in \Omega_2^* \cap \Omega_1^* \\ T_2^*(r) = T_1^*(r) & r \in \Omega_2^* \cap \Omega_1^* \\ -\lambda_2 \vec{\nabla} T_2^*(r) = h\left(T_2^* - T_f\right) & r \in \partial\Omega_2^* \end{cases}}_{Heterogeneous\ cylindrical\ problem} \tag{3}$$

The final step is dedicated to the calculation of the mean temperature values differences Δ_k between heterogeneous regions Ω_1^* and Ω_2^* and in homogeneous one Ω_p^* (4).

$$\begin{aligned} \Delta_k &= \langle T^* \rangle - \langle T_k^* \rangle = f(P_k)\left[\Delta_k^s(r_k) + \Delta_k^p(\lambda_k, h)\right] \quad k = 1,2 \\ \langle T \rangle &= \left(\int_\Omega \rho c_p T(r)\, d\Omega\right)\left(\int_\Omega \rho c_p\, d\Omega\right)^{-1} \end{aligned} \tag{4}$$

Then, the mean temperature values of the heterogeneous regions Ω_1 and Ω_2 are calculated as following (5).

$$\langle T_k \rangle = \langle T \rangle - \Delta_k \quad k = 1,2 \tag{5}$$

To summarize, the de-homogenization approach consists in calculating analytically the differences between the mean temperature values of homogeneous and heterogeneous cylindrical problems. After that, we suppose that they are equal to those between original homogeneous and heterogeneous geometries. This assumption was validated against a large variety of configurations referring to HTR fuel assemblies (**Fig.3**).

The spatial temperature de-homogenization was also evaluated by comparison with another homogenization/de-homogenization model [**9**]. The results demonstrated the coherence of our model as long as the fraction of radiation energy transfer is less then 30% of the convective energy transfer.

Figure 2: Cylindrisation in the spatial de-homogenization model

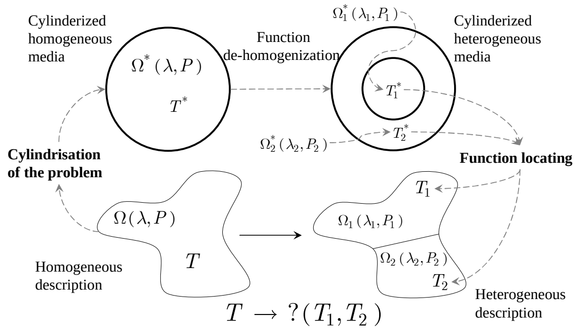
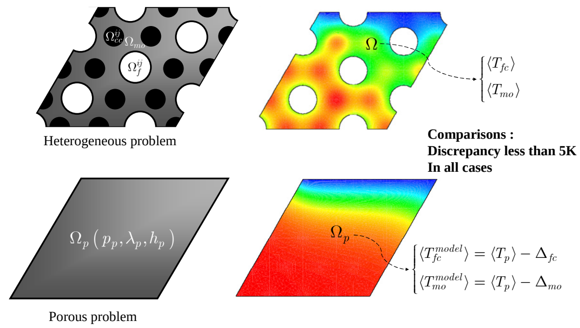


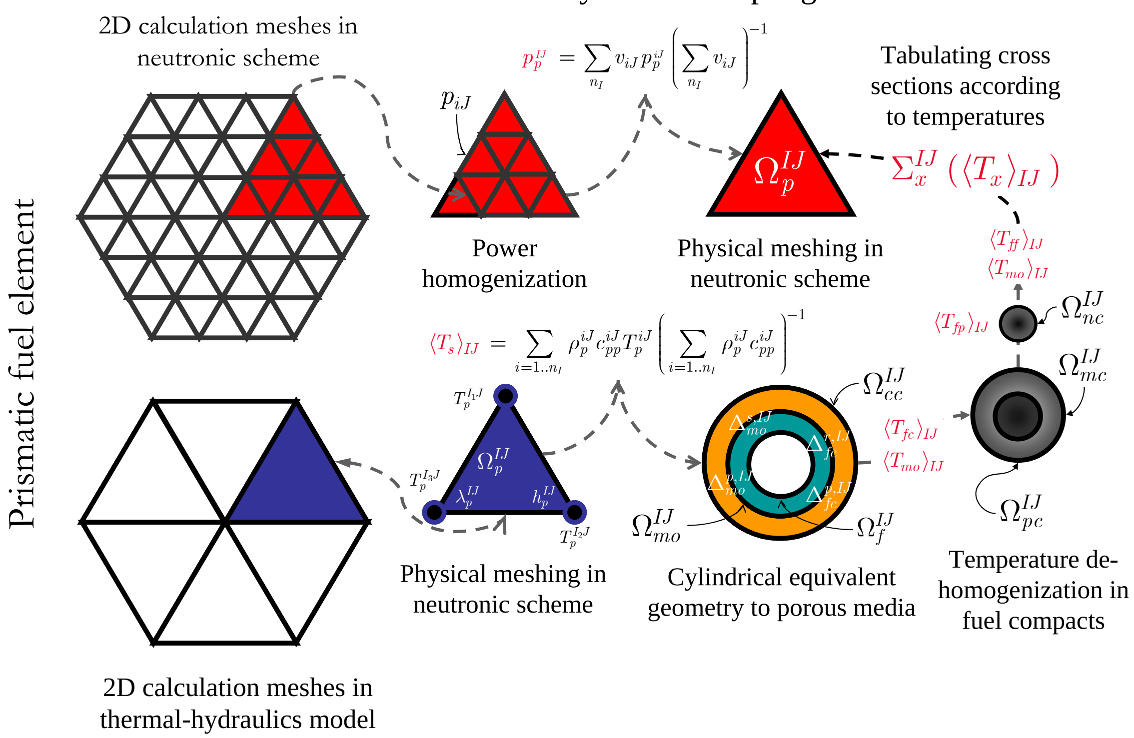
Figure 3: Validation of the de-homogenization model



3.2.2 From porous media temperature to compact and moderator temperature

The de-homogeneous model applied to the VHTR core calculation is a double-level model. In the first level, it calculates the mean temperatures of fuel compact $\langle T_{fc} \rangle^{IJ}$ and moderator $\langle T_{mo} \rangle^{IJ}$ in each physical mesh Ω^{IJ}. In the second level, it calculates the mean temperatures of the fuel coated particles $\langle T_{fp} \rangle^{IJ}$ and the kernel fuel particles $\langle T_{ff} \rangle^{IJ}$. Finally the temperature $\langle T_{ff} \rangle^{IJ}$ and $\langle T_{mo} \rangle^{IJ}$ are used with nucleus compositions to interpolate the values of cross-sections (**Fig.4**).

Figure 4: overview of the integration of the de-homogenization model in the neutronic and thermal-hydraulics coupling model



The use of the de-homogenization model in a coupled neutronic-thermal-hydraulics simulation permits the description of the temperature effect of each media in the fuel assembly. The comparison between a coupling calculation using a single porous temperature T_{porous} and the calculation considering the de-homogenization model shows local power discrepancies of about 7 % between the tow calculations. The corresponding variation of the core effective multiplication factor reaches 500 pcm.

4. VHTR core physics

4.3 Core depletion analysis

The core depletion calculation is performed with the N&TH coupling system with the temperature de-homogenization. The neutronic calculation is carried out considering microscopic cross-sections. The cross-sections library contains microscopic cross-sections for each isotope. The cross-sections library is made-up of 20 heavy nuclides and 8 fission products (allowing Xenon and Samarium calculation).

The analysis consists in a core equilibrium fuel cycle search. At the beginning of the first core depletion calculation the core is charged with two fuel batches (fresh fuel and irradiated fuel with Burn-up of 60 000 $MW.d.t^{-1}$) witch is a shuffling strategy as in [**10**]. The core power is supposed to be constant and equal to 600 MW_{th}.

Only one group operating control rods is considered. The reactor is kept critical by adjusting the insertion of the operating group along the fuel cycle. The position of the operating group is a quasi-static equilibrium state depending on local temperatures and local Xenon concentrations. Both fuel and reflector elements contain 6 radial depletion zones. The number of the axial depletion zones varies according to the position of the control rods. For each depletion zone: fuel and moderator temperature for the fuel assemblies and graphite temperature for reflector blocks are issued from the thermal-hydraulics calculation (**Fig.4**).

All the calculations were performed with a precision of 10^{-4} on the flux, 10^{-5} on the eigenvalue, +/-100 pcm for critical state, 5.10^{-3} m on the operating group position and 1 K on temperature distribution. It must be noticed that an heterogeneous description of the control rods is used in the core depletion calculation. This provides results with a good accuracy but involves a large number of axial depletion zones.

In the depletion calculation we have fixed the B_4C poison concentration at an optimized value. This guarantees a small insertion for the operating group.

4.4 Preliminary results

The optimized poison concentration combined with the *Xenon* effect gives an initial K_{eff} value of 1,03094. During the core depletion the K_{eff} decrease because of the decreasing of the U^{235} isotopes and at the same time increase because of the B_4C consumption. This leads to the K_{eff} evolution curve plotted in **Fig.4**. In the first part of the fuel cycle, the effect of the consumption of the poison is more important that the diminution of the fissile atoms. As a consequence the Keff will increase in the first part of the depletion (**Fig.5**). The K_{eff} maximal value (1,04017) is reached in the middle of the fuel cycle (70224 $MW.d.t^{-1}$). It corresponds to a moment when the effect of the diminution of the U^{235} becomes more important that the diminution of the B_4C. The critical operating group positions are plotted in **Fig.6**. The core is maintained critical with a K_{eff} equal to 1±100 pcm (**Fig.4**). One can notice that the maximal insertion corresponds to the maximum of core K_{eff}.

Figure 5: Core K_{eff} evolution with and without the operating group insertion

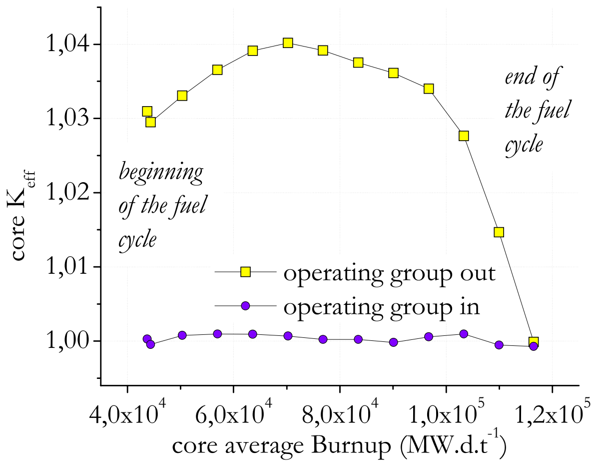
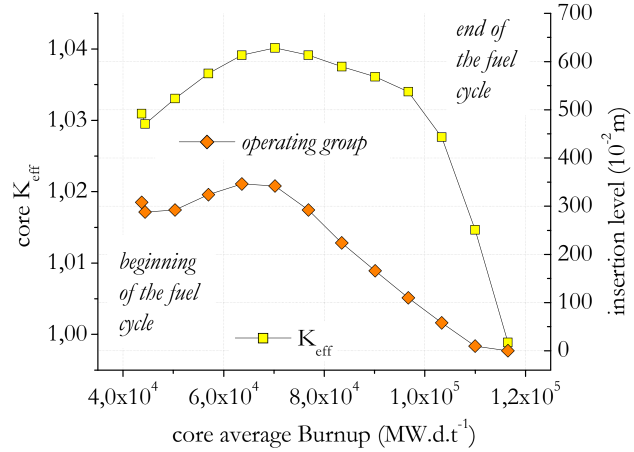


Figure 6: Operating group insertion level evolution toward the core K_{eff} values



More than a real optimization study of the fuel management in that kind of core, the primary objective of this VHTR physcial study is clearly dedicated to understand the behavior of the core in normal working conditions. The core behavior is analyzed by considering the evolution of the temperatures, the power density and the Xenon concentration during the depletion. The major phenomenon is the total power shifting between the beginning and the end of the depletion. In fact, if we compare **Fig.7** and **Fig.8**, corresponding respectively to the beginning and the end of the depletion, we can notice that the major power is released in the lower part of the core in the first case and the higher part in the second case. Another result is the important role played by the Xenon. It is necessary to compute this fission product individually to evaluate an accurate power level in equilibrium with Xenon concentration.

Figure 7: Axial power and Xenon concentration at 43907 MW.d.t^{-1}

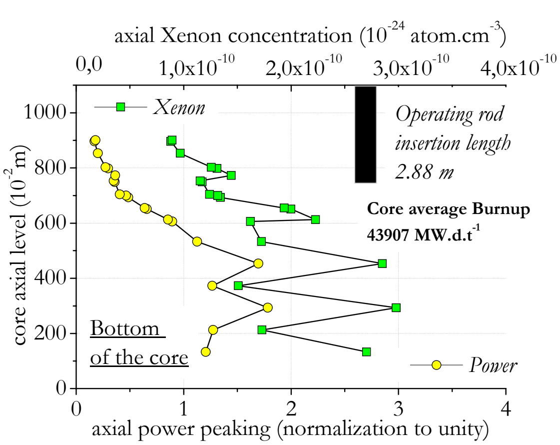
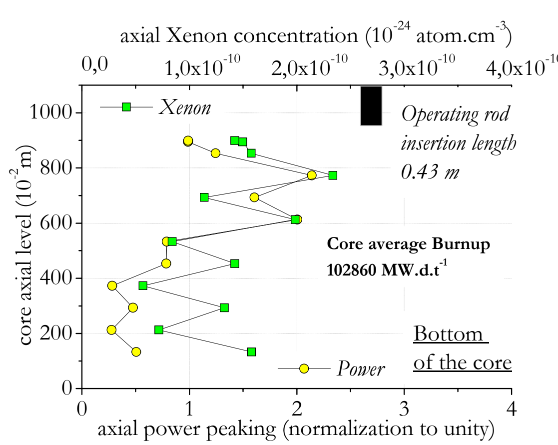


Figure 8: Axial power and Xenon concentration at 102860 MW.d.t^{-1}



Another phenomenon concerns the axial temperatures evolutions. At the beginning of the fuel cycle, we can point out that the fuel and the moderator temperatures values are increasing from the top to the bottom of the core. The hottest temperatures are located exclusively in the lower part of the core (see **Fig.9**). At the end of the depletion we don't observe the shifting phenomenon that characterizes the power density. As long as the operating group is withdrawn from the core, temperatures get higher in those locations. As a consequence, the global core temperature is increasing (**Fig.9**).

During the core depletion, the maximum of the power discrepancies between fuel assemblies are significant near the control rods and especially near the fuel/reflector interface; these regions correspond to the highest Burnup values.

Figure 9: Axial power and temperature evolution at 43907 MW.d.t^{-1}

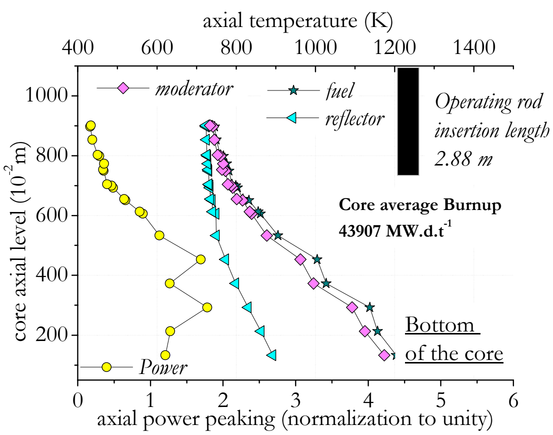
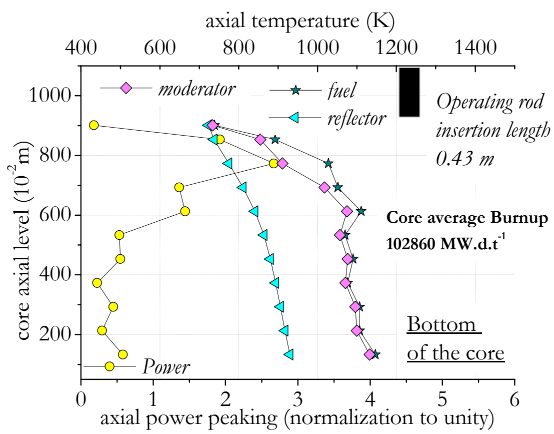


Figure 10: Axial power and temperature evolution at 102860 MW.d.t^{-1}



5. Discussions about VHTR core physics

5.1 Thermal effect

Fuel, moderator and reflector thermal coefficients were evaluated at different steps of the depletion calculation. It appears that the VHTR core has a strong negative fuel temperature coefficient. This coefficient remains nearly constant during the fuel cycle (-4.8 pcm.K^{-1}). The moderator thermal coefficient is also negative but its decreases during the fuel irradiation (-2.8 pcm.K^{-1} at the beginning of the fuel cycle and -2.1 pcm.K^{-1} at the end). This is due to the effect of fission product build-up and the changes in neutron spectrum. The analysis established that the reflector effect is positive and increases during the depletion. The great migration length during the slowing down process in the reflector and the strong impact of the temperature on this process modifies the Maxwell spectrum and the albedo at the core-reflector interface. They are the principal mechanisms generating the positive effect.

5.2 Location of hottest assemblies

As shown in **Fig.9** and **Fig.10**, the maximal power and temperature values are not located at the same axial level. This fact is valid during all the depletion. The consequence is the assurance of a better behavior of the TRISO particles and the possibility to reach higher Burnup rates without damaging the fuel particles.

5.3 Core safety and design

It must be noticed that the reflector thermal coefficient is highly correlated with the by-pass helium values. In fact, the increase of the helium flow rate by 5% in the reflector generates a strong power discrepancy (the peak power increases of 4%) in the fuel assemblies located at the interface with the reflector. Simultaneously the positive coefficient of the reflector decreases. By contrast, decreasing reflector by-pass value will reduce the power peaking in the fuel but enhance the reflector positive effect and may overheat the core vessel. Studies are underway to determine an optimal helium flow rate in the reflector. These studies belong to the efforts undertaken to optimize the VHTR core.

Other core optimizations might be performed with this coupled neutronic-thermal-hydraulics model. Especially the impact on neutronic and thermal-hydraulics parameters by increasing the core outlet helium temperature should be addressed in a near future. In addition, such a coupled model is ready to be adapted to simulate the core behavior during an *Accident Transient without Scram* in which the prediction of the evolution of the 3D temperature profile will strongly affect the analyzed results.

6. Conclusions

This paper presents the spatial thermal de-homogenization model in the neutronic and thermal-hydraulics coupling system dedicated to the VHTR core. The thermal-hydraulics model uses an equivalent porous media approach. Thanks to the de-homogenization model it is possible to take into account separately the thermal coefficients of the moderator and the fissile media. This gives a better representation of the local thermal effect in the active zone.

Furthermore, another objective of this paper was to provide first results obtained with the coupling tool. Therefore, 3D core cycle simulations have been carried out on a typical prismatic bloc type VHTR. Several important results could be retained for the VHTR core physics point of view. The major ones are the particular axial power and temperature profiles, the importance of the reflector thermal feed-back and the spatial separation of the maximal power and temperature values.

The core depletion study shows the importance of fuel cycle management strategy in VHTR core physics. In fact, due to the strong temperature gradient and in order to reduce the power peak, an important effort is to be devoted to an optimized fuel strategy searches, for each given cycle lengths which could be envisaged, by adjusting parameters like the enrichment, the burnable poison, the fuel shuffling, … .

Well dedicated to such kind of study, the coupling system will be used in a near future for performing transient-type calculations such as anticipated transient without scram (ATWS) for the VHTR.

Nomenclature

P : *core power value*
$\mathbf{N}$: *neutronic system*
T_{porous} : *porous temperature*
T_{fluid} : *helium temperature*
Σ : *cross section*
$\mathbf{TH}$: *thermal - hydraulics system*
T_{fuel} : *fuel temperature*
$T_{moderator}$: *moderator temperature*
$\mathbf{DZ}$: *de - homogenization system*
λ : *thermal conductivity*
h : *convection coefficient*
$\langle T \rangle$: *temperature mean value*
Δ_k^s : *spactial de - homogenization cefficient for region k*
Δ_k^s : *physical de - homogenization cefficient for region k*
ρ : *density* c_p : *heat capacity*
T_{mo} : *moderator temperature*
T_{fc} : *fuel compact temperature*
T_{mc} : *moderator compact temperature*
T_{fp} : *fuel particules temperature*
T_{ff} : *fissile fuel temperature*
Ω_k^{ij} : *physical region k located in position (ij)*

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