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ON THE APPLICATION OF SIRER-ADS IN THE SIMULATION OF TRANSIENTS IN ACCELERATOR DRIVEN SYSTEM (ADS)

Rubens Souza dos Santos[1], José Rubens Maiorino[2]

[1] Instituto de Engenharia Nuclear (IEN / CNEN - RJ)
Rua Hélio de Almeida, 75 - Cidade Universitária
21941-906 Rio de Janeiro, RJ
rsantos@ien.gov.br

[2] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
maiorino@ipen.br

ABSTRACT

An innovative reactor proposed to be used as an incinerator of Minor Actinides (MAs) like Np, Am and Cm is in progress. This technology, named Accelerator Driven System (ADS), consists in a subcritical core, having a central region where there is a target, as Lead-Bismuth Eutectic (LBE), which suffers collisions with a proton beam from an accelerator. The collisions produce neutrons depending of the proton energies. These fast neutrons produce fissions in the fuel and some of them are captured at the blanket, which surrounds the fuel region, for transmuting the transuranic elements (TRUs). Apparently this reactor is intrinsically safe, as compared with thermal ones, but the control of the reactor is based on the proton beam, which does not depend on intrinsic or internal control rod. Even so, in the scope of the development of ADS, benchmark problems have been proposed by Nuclear Energy Agency (NEA) to analyze some transients that may occur due to variation in the current of the accelerator as well as perturbation in the subcritical core. In this paper it is shown the application of SIRER-ADS code on one of the benchmarks. In our application we identified an error on the wetted perimeter for the channel, as specified in the benchmark. Of course that leads different results. Because of that, some extra calculations are made to validate SIRER-ADS showing good agreement with the analytical solution. Calculations with the correct perimeter and the benchmark one are shown. In both cases SIRER-ADS exhibits consistent results.

1. INTRODUCTION

Accelerator Driven System (ADS), which basic concepts were initially proposed by Rubia et al [1] as Energy Amplifier (EA), is an innovative Reactor in development as a dedicated burner in a Double Strata Fuel Cycle to incinerate nuclear waste, aiming to reduce the requirements in the geological repository [2]. This system consists of a fast sub-critical assembly driven by an external source of neutrons, basically composed by: Accelerator (Cyclotron or Linac) [3], which accelerates the proton beam (1GeV, a few mA); the target (window or windowless), where neutrons are produced by Spallation reactions; the Coolant (loop or pool), using Sodium, Lead, or Lead-Bismuth Eutectic (LBE) melted, or gas (Helium); the sub-critical core (k_{eff} ~0.95-0.97), consisting of an array of fuel in metallic, oxide or nitride form with nuclear fissile material [U, Th, Pu, minor actinides (MA), such as Np, Am, Cm, etc.] where energy is generated with a positive energy gain (G= energy generated/energy to drive the accelerator), and incineration of the transuranics TRUs (Pu and MA), or Long Lived Fission Products (LLFP), is possible, and with breeding (U/Pu or Th/U) [2].

Although ADS are intrinsically safety reactors, transients may occur due to variations in the current of the accelerator as well as perturbations in the sub-critical core. Numerical Benchmarks on Beam Interruptions in a Lead-Bismuth-Cooled and MOX fueled XADS was realized by Nuclear Energy Agency (NEA) [4], and in short it consists in a comparative assessment of different computational methods used to evaluate power and temperature transients induced by beam interruptions of different duration. Most of the participants in the NEA benchmark used point kinetics to describe the neutronic behavior, and the temperature feedback was calculated using spatial dependent thermal hydraulics.

The goal of this work is the application of SIRER-ADS code on the benchmark problem to qualify it as tool of transient analysis of beam interruption in an average channel of a subcritical core of a typical ADS.

2. MODEL OF SIRER-ADS

The SIRER-ADS code consists of the point kinetic model, considering the external source of neutron and the thermal hydraulic of an average channel.

2.1 Thermal Hydraulic Model

As the rod is much longer than the diameter, heat flux is assumed only in radial direction. Along the coolant channel it is assumed one-dimensional. Conductivity and pressure are disregarded along the channel. The coolant flow is in a convective regime. The channel is segmented in various sections. At fuel region the heat equation is discretized assuming that temperatures are interface centered. That permits representing the hole in the centerline. The gap between fuel surface and internal surface of cladding is dealt with a resistance to the heat flux. In the fuel region the properties and temperatures are discretized as given by Fig. 1, which follows:

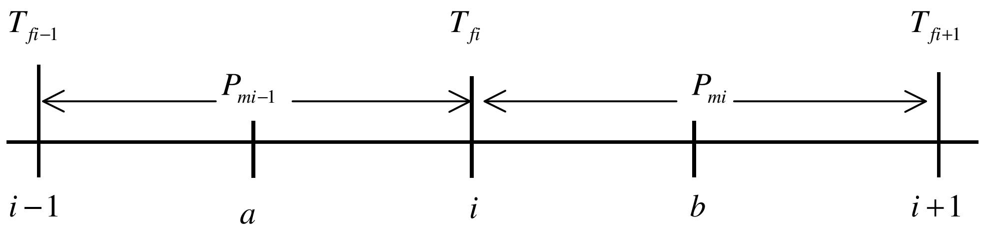

Figure 1. Temperature discretization centered at interface.

With that, a generic integration along the radius is given by:

$$\int_a^b r\,dr \left[\rho_m c_m \frac{\partial T_m}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r K_m \frac{\partial T_m}{\partial r} + q_m''' \right] \quad , \qquad (1)$$

having in mind that m means f (fuel) or c (cladding). $P_m = P_m(r,z,t)$ can represent: ρ_m (density); c_m (specific heat); K_m (conductivity) or q_m''' (heat density). In the cladding T_c represents an average value in the volume and $q_m''' = 0$.

For the coolant, the integration is given by:

$$\iiint dv\left(\rho_\ell c_\ell \frac{\partial T_\ell}{\partial t} = -\rho_\ell c_\ell \vec{U}.\nabla T_\ell - \nabla.\vec{q}^{\,''}\right) \quad . \tag{2}$$

Using Gauss' theorem,

$$\iiint dv \nabla.\vec{q}^{\,''} = \oiint d\vec{s}.\vec{q}^{\,''} , \tag{3}$$

defining the volume element $dv = A_c dz$ we have,

$$\int_z^{z+\Delta z} A_c dz \rho_\ell c_\ell \frac{\partial T_\ell}{\partial t} = -\int_z^{z+\Delta z} A_c dz \rho_\ell c_\ell U \frac{\partial T_\ell}{\partial z} - \oiint d\vec{s}.\vec{q}^{\,''} . \tag{4}$$

From the viewpoint of the coolant volume and using $q^{''} = h_\ell (T_{sc} - \overline{T}_\ell)$, we have:

$$\oiint d\vec{s}.\vec{q}^{\,''} = -\oiint ds q^{'''} = P_h \Delta z h_\ell \left(T_{sc} - \overline{T}_\ell\right) , \tag{5}$$

where, for triangular channels, the heated and the wetted perimeters are given by:

$$P_h = P_w = \pi R_c . \tag{6}$$

The discretized Eq. (1) and Eq. (2), in an axial section j, can be written in a matrix formulation given by:

$$\frac{1}{2}\underline{\underline{A}}\frac{d\underline{X}}{dt} = \underline{\underline{M}}\underline{X} + \underline{B} , \tag{7}$$

where:

$$\underline{\underline{A}} = diag(\rho_{f1}c_{f1}, \rho_{f2}c_{f2}, \rho_{f3}c_{f3}, ..., \rho_{fN-1}c_{fN-1}, \rho_{fN}c_{fN}, \rho_c c_c, \rho_\ell c_\ell) , \tag{8}$$

$$\underline{X} = (T_{f1}, T_{f2}, T_{f3}, ..., T_{fN-1}, T_{fN}, T_c, \overline{T}_\ell) \quad , \tag{9}$$

$$\underline{B} = (q_{f1}^{'''}, q_{f2}^{'''}, q_{f3}^{'''}, ..., q_{fN-1}^{'''}, q_{fN}^{'''}, 0, \dot{m} c_\ell T_{\ell z} / A_c \Delta z) \quad . \tag{10}$$

Redefining the matrices:

$$\underline{\underline{E}} = \underline{\underline{A}}^{-1}\underline{\underline{M}} \quad , \tag{11}$$

$$\underline{\Gamma} = \underline{\underline{A}}^{-1}\underline{B} \quad , \tag{12}$$

we have:

$$\frac{1}{2}\frac{d\underline{X}}{dt} = \underline{\underline{E}}\underline{X} + \underline{\Gamma} \quad . \tag{13}$$

For time discretization, SIRER-ADS uses Crank-Nicholson approximation for Eq. (13), i.e.:

$$\underline{X}^{n+1} = \underline{X}^{n} + \frac{\Delta t}{2}\left(\frac{d\underline{X}^{n+1}}{dt} + \frac{d\underline{X}^{n}}{dt} \right) . \tag{14}$$

Assuming linearization on the properties during transient between time-steps like this:

$$P_m^{n+1} \cong P_m^n \ , \tag{15}$$

gives:

$$\left[\underline{I} - \Delta t \underline{\underline{E}}^n\right]\underline{X}^{n+1} = \left[\underline{I} + \Delta t \underline{\underline{E}}^n\right]\underline{X}^{n} + \Delta t\left(\Gamma^{n+1} + \Gamma^{n}\right) . \tag{16}$$

Redefining,

$$\underline{Y} = \left[\underline{I} + \Delta t \underline{\underline{E}}^n\right]\underline{X}^{n} + \Delta t\left(\Gamma^{n+1} + \Gamma^{n}\right) , \tag{17}$$

the temperatures are given by:

$$\underline{X}^{n+1} = \left[\underline{I} - \Delta t \underline{\underline{E}}^n\right]^{-1}\underline{Y} \ . \tag{18}$$

This inverse is easily done using the classical LU decomposition since it is a tridiagonal matrix.

2.2 Neutron Kinetic Model

According to reference [5], the point kinetic model is given by;

$$\frac{dp}{dt} = \frac{(\rho - \beta)}{\Lambda} p + \sum_{i=1}^{I} \lambda_i C_i + \frac{S}{\Lambda}, \tag{19}$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} p - \lambda_i C_i ,\ i = 1,2,3,...I , \tag{20}$$

$$\beta = \sum_{i=1}^{I} \beta_i , \tag{20}$$

$$\rho = \rho(t) = \rho(0) + \alpha_f\left[\overline{T}_f(t) - \overline{T}_f(0)\right] + \alpha_\ell\left[\overline{T}_\ell(t) - \overline{T}_\ell(0)\right] \ , \tag{22}$$

where $p = p(t)$ is the normalized power, $C_i = C_i(t)$ is the concentration of the ith group of delayed neutron precursor emitter, $S = S(t)$ is the external source intensity of neutron, α_f and α_ℓ are reactivity coefficients. Since the reactivity is related with k_{eff}, we have:

$$\rho(0) = \frac{k_{eff} - 1}{k_{eff}} \ . \tag{23}$$

In SIRER-ADS code is used Cohen's Methods for the numerical solution of point kinetic equations.

The neutronic and thermal hydraulic are coupled through:

$$q_f'''(r,z,t) = q_f'''(r,z,0)\,p(t)\,. \tag{24}$$

2.3 Steady-State Solution

Since Eqs. (13), (19) and (20) represent initial value problems, it is necessary to obtain the steady-state solution, which is, doing those derivatives null. In this way we have:

$$\underline{X}^0 = -\underline{\underline{E}}^{-1}\underline{\Gamma}^0\ , \tag{25}$$

which can be done using LU decomposition.

$$C_i^0 = \frac{\beta_i}{\Lambda\lambda_i}\ ,\quad i = 1,2,3,\ldots I\ . \tag{26}$$

$$S^0 = -\rho(0) = -\rho^0\ , \tag{27}$$

considering $p^0 = p(0) = 1$.

3. RESULTS

In order to qualify SIRER-ADS to be used as a tool for transient analysis in ADS based on average coolant channel approach, the solution of the benchmark problem proposed by NEA [4] was solved. The data and description of the transient can be obtained from that reference. As one can see there, the boundary conditions are set up in such way that temperatures are fixed in 573K at the entrance and in 673K at exit channel. Thus, we need to fit the mass flow to maintain this condition.

Since the convective heat transfer coefficient depends on the thermal conductivity of the coolant, the hydraulic diameter of the channel, and the Nusselt number (Nu), embedded in the benchmark specifications there is an error in the wetted perimeter, referred as $2\pi r_p$. The correct one is half of it. It is also interesting to note that the coolant flow area value is consistent for a hexagonal pin rod array, as specified. As heat transfer coefficient is directly proportional to the wetted perimeter, to consider or not the correct definition can substantially diverge the results. Besides, as the benchmark specifications considers the hole existence at fuel center, it is important how to define the heat density in the fuel. If we consider the fuel as a solid this gives a smaller value than with a hole. Another detail is what material property to use to represent the hole. To simplify the comparison , we used the follow classification:

Case1 - hole of radius R_H located at central mesh, considering artificially $K_{f1} = \rho_{f1} \cong 0$, fuel volume given by $\pi\left(R_f^2 - R_H^2\right)\Delta z$ and correct wetted perimeter.

Case2 - hole as former but K_{f1}, ρ_{f1} and wetted perimeter as specified in the benchmark, fuel volume given by $\pi R_f^2 \Delta z$.

Fig. 2 and Fig. 3 show the steady-state Case1 and Case2 calculated by SIRER-ADS, respectively, and Fig. 4 shows the benchmark results for a qualitative comparison with SIRER-ADS. Note that the higher value of centerline temperature in Case1 reflects, mainly, the correct wetted perimeter used in SIRER-ADS, and the modeling of properties.

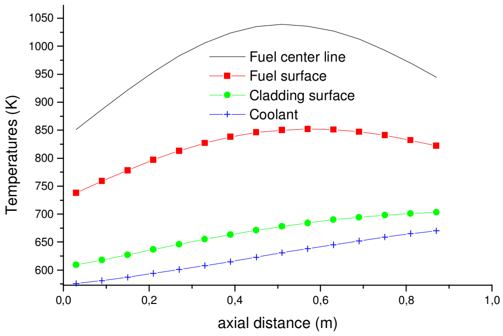

Figure 2. Steady-state Case1.

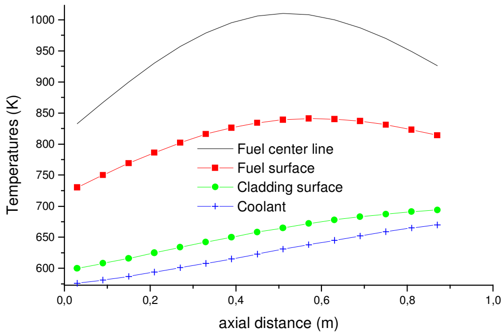

Figure 3. Steady-state Case2.

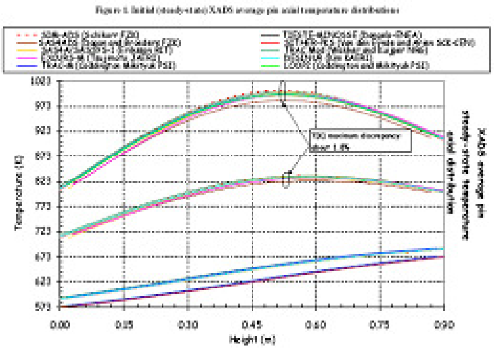

Figure 4. Benchmark steady-state

Fig. 5 shows the excellent agreement between SIRER-ADS and the analytical solution, for a steady-state Case1 with $R_H \cong 0$.

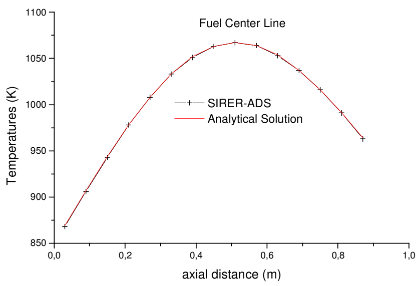

Figure 5. SIRER-ADS versus analytical solution.

Fig. 6 shows beam interruption transients for Case2 and Fig. 7 the benchmark results. In both results we observe good agreement in the time where occur the maximum variations on temperatures in each beam interruption duration. It is interesting to note the response of SIRER-ADS for Case2, where temperatures in the fuel are initially higher. Despite ADS be source dominate, in this case the feedback effect in the fuel gives smaller power variations and, consequently, smaller temperature variations, as foreseen by point kinetics.

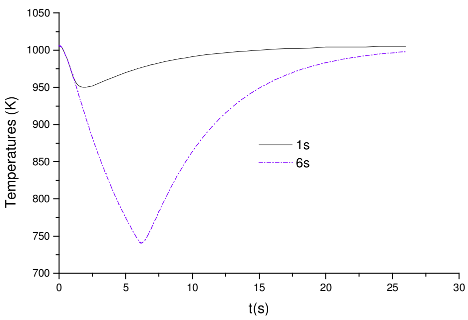

Figure 6. SIRER-ADS solution.

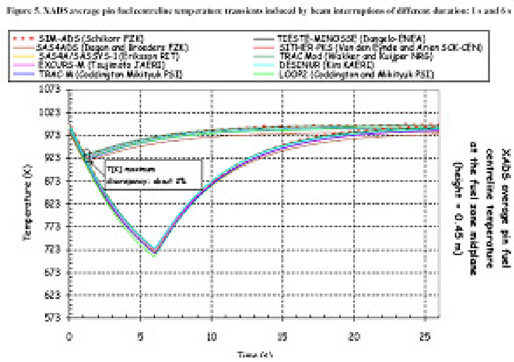

Figure 7. Benchmark solutions.

3. CONCLUSIONS

For all result proposed by NEA benchmark, SIRER-ADS exhibits good agreement and robustness. This former meaning that, even for the case of the wrong wetted perimeter, the Code was able to provide consistent results with that specification. In addition, SIRER-ADS showed sensitivity to capture feedback effects in the reactivity, demonstrating that the Code can be used for monitoring the modeling of neutron kinetic of ADS, issue still in development.

REFERENCES

1. C. Rubbia et al, "Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier", *CERN/AT/95-44 (ET*), 29th September 1995.
2. K. Tucěk, “Neutronic and Burnup Studies of Accelerator-driven System Dedicated to Nuclear Waste Transmutation,” Doctoral Thesis, Royal Institute of Technology, Stockholm, 2004.
3. H. A. Abderrahim et al , “ MYRRHA: A multipurpose accelerator driven system for research & development,” Nuclear Instruments and Methods in Physics Research A 463, 487-994, 2001.
4. “Benchmark on Beam Interruptions in an Accelerator-driven System: Final Report on Phase II Calculations,” http://www.nea.fr/html/science/docs/2004/nsc-doc2004-7.pdf (2004).
5. W. M. Stacey, *Nuclear Reactor Physics,* John Wiley & Sons, New York, 2001.