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Random effects on reactivity in molten salt reactors

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ABSTRACT

The problem of the effect of fissile lumps spatially appearing in a random fashion inside a fluid fuel reactor is addressed. The effect on static reactivity is evaluated by means of first-order perturbation theory. The analysis is carried out in diffusion theory with the presence of delayed neutron emissions, taking into account the fuel motion that introduces a distortion of the space distribution of the delayed neutron precursors. The method is applied to a one-dimensional configuration to investigate the general features of the random process. Afterwards, a more realistic two-dimensional cylindrical geometry is considered. The estimation of the mean value and standard deviation of the reactivity inserted is performed by Monte Carlo simulations and a deterministic quadrature approach, to compare the methods in terms of computational effort and accuracy of the results. The reconstruction of the probability density function of the reactivity is also performed by polynomial chaos expansion. The results presented show that random reactivity effects constitute an important issue in the assessment of these innovative molten salt systems.

1. Introduction

The molten salt nuclear reactor is one of the concepts of new systems proposed for investigation in the Generation IV international forum. The fluid salt containing fissile material constitutes the fuel and it is recirculated through the primary circuit to remove the power generated by the fissions in the core region. The system design is thus highly simplified. The re-fueling process can be carried out without shutting down the reactor and fission products can be removed on-line, constantly keeping a low inventory of radioactive materials in the primary circuit (Alekseev et al., 1997; Mathieu et al., 2006, 2009; Merle-Lucotte et al., 2008). In a thermal neutron spectrum design, the salt flows in tubes through a moderator material, while in fast systems the moderator is absent. The fast design is particularly attractive for the heavy radioactive nuclide transmutation and fertilization properties.

The motion of the fissile material introduces some physical features that lead to the need for more rigorous modeling to correctly account for the displacement of the delayed neutron precursors from locations where fission events take place; hence, delayed neutrons are emitted at positions different from the positions where they have been generated and some cannot contribute to the chain reaction if emitted outside the core, while flowing in the external circuit. This leads to a reduction of the role of the delayed emissions and, consequently, to a more prompt response in time-dependent situations, due to the reduction of the effective delayed neutron fraction (Mattioda et al., 2000). Furthermore, the motion of delayed neutron precursors modifies the mathematical structure of the steady-state problem and thus the multiplication k_{eff} eigenvalue depends also on the delayed emission parameters (Dulla, 2005; Pázsit and Jonsson, 2011).

An important issue in the assessment of the performance of a molten salt reactor concerns the presence of stochastic phenomena connected to changes of the densities of the materials constituting the molten salt mixture. This may be the case when in the refueling process, to keep the critical state of the reactor, the fissile component reaches the solubility limit and precipitates: lumps of solid material are generated in the system at random positions and with random size. These lumps move then through the primary circuit, inducing reactivity effects that need to be properly quantified. Another phenomenon that must be studied is the generation of gas bubbles, that may also induce a stochastic reactivity effect. The gas bubbles may be generated by gaseous fission products or they may be introduced on purpose during the operation of the plant in order to drag out the fission products themselves. The stochastic characteristics (mean values, variances and probability distribution functions) of the reactivity introduction, consequence of the appearances of the random disturbances, should be investigated.

In the present work it is assumed that the perturbations can be considered small with respect to the reference critical configuration. Therefore, first-order perturbation theory is adopted throughout the paper, properly extending the classical theory developed for a solid-fuel system to the fluid-fuel case with recirculation of the fissile material in an external circuit. It is important to point

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out that the results here presented are focused on the estimation of the effects of the random presence of a fissile lump on the static reactivity. Therefore, the paper is not concerned with the evaluation of the kinetic effects following the introduction of the perturbation, that may include also the motion of the lump within the system. These aspects may be object of a future work.

The present work is mainly methodological and addresses some basic problems concerning the quantification of the stochasticity of the reactivity associated with random perturbations in a molten salt system. The scope of the paper is to obtain physical insight into the problem and to evaluate the characteristics of the effects. The study is restricted to the case where only one perturbation is present in the system. The extension to the case involving the simultaneous presence of multiple perturbations is deferred to future work. A general theoretical presentation for geometries allowing a fully analytical modeling is given and only results obtained with a one-group diffusion model are illustrated. Nevertheless, numerical results point to some significant stochastic effects that may play an important role in the assessment of this type of reactor.

2. Application of perturbation theory to fluid-fuel systems with recirculation

The system considered for the following analyses is characterized by a fuel motion along the axial dimension or the reactor (plug-flow), here denoted with the variable z. Therefore, a convective term in the balance equations for the delayed neutron precursors is introduced, with a fixed velocity u. The reference critical steady-state structure can then be described by the following system of balance equations for neutrons and precursors:

$$\begin{cases} \widehat{\mathfrak{L}}\varphi + \dfrac{1}{k_{eff}}\widehat{\mathfrak{F}}_p\varphi + \displaystyle\sum_i^R \lambda_i \mathscr{E}_i = 0 \\ \lambda_i \mathscr{E}_i + u\frac{\partial \mathscr{E}_i}{\partial z} = \dfrac{1}{k_{eff}}\widehat{\mathfrak{F}}_{d,i}\varphi, \quad i = 1,\dots,R, \end{cases} \tag{1}$$

where the delayed neutron emissivity $\mathscr{E}_i$ for the ith family is defined in general as $\chi_{d,i}C_i/4\pi$, $\chi_{d,i}$ being the delayed neutron emission energy spectrum. The leakage ($\widehat{\mathfrak{L}}$), prompt fission ($\widehat{\mathfrak{F}}_p$) and delayed fission ($\widehat{\mathfrak{F}}_{d,i}$) operators are introduced and defined to support a multigroup model for the neutron balance. The direct state of the system is given by a space-dependent column vector $\mathbf{\Xi}$ including group fluxes and delayed neutron precursor emissivities. Proper boundary conditions for the neutron flux must be introduced. Furthermore, boundary conditions must also be introduced for the delayed neutron precursors, stating that exiting delayed neutron precursors are re-introduced into the system after a transit time τ in the external circuit, and thus reduced by the radioactive decay in the circuit. Therefore, we can write a generic form of the boundary condition, relating the concentration of precursors at the exiting surface of the system, $\mathscr{A}_{out}$, to the re-entering precursors through the surface $\mathscr{A}_{in}$, in the form:

$$\int_{\mathscr{A}_{in}} \mathscr{E}_i(\mathbf{r})d\mathscr{A} = \int_{\mathscr{A}_{out}} \mathscr{E}_i(\mathbf{r})d\mathscr{A}e^{-\lambda_i\tau}. \tag{2}$$

If the reasonable hypothesis of remixing in the external circuit is introduced, the concentration at the incoming surface is supposed uniform, and condition (2) becomes:

$$\mathscr{E}_i(r,z=0) = \frac{1}{\mathscr{A}}\int_{\mathscr{A}_{out}} \mathscr{E}_i(r,z=H)d\mathscr{A}e^{-\lambda_i\tau}, \tag{3}$$

where we have assumed that the system considered is in general a prism or a cylinder of height H with both bases of area $\mathscr{A}$. Further simplifications of the geometry can be introduced reducing the dimensionality of the problem to a 1D slab geometry, as will be done in the following.

A comment on the role of delayed neutron precursors is worth making at this point. The direct observation of the model above shows that the delayed emissions play an important role also to determine the steady-state configuration, quite differently from the solid-fuel case. In fact, the delayed neutron concentrations cannot be eliminated from system (1), since the presence of a streaming term does not allow to extract the delayed emissivity from the second equation and substitute it back into the balance equation for neutrons.

The importance model can be easily written down by taking the mathematical adjoint of system (1), once the inner product is defined as usual through a two-dimensional vector product followed by space integration:

$$\begin{cases} \widehat{\mathfrak{L}}^\dagger\varphi^\dagger + \dfrac{1}{k_{eff}}\widehat{\mathfrak{F}}_p^\dagger\varphi^\dagger + \dfrac{1}{k_{eff}}\displaystyle\sum_i^R \widehat{\mathfrak{F}}_{d,i}^\dagger \mathscr{E}_i^\dagger = 0 \\ \lambda_i\mathscr{E}_i^\dagger - u\dfrac{\partial \mathscr{E}_i^\dagger}{\partial z} = \lambda_i\varphi^\dagger, \quad i = 1,\dots,R. \end{cases} \tag{4}$$

The adjoint state is thus a row vector $\mathbf{\Theta}^\dagger$, whose first component is the neutron importance and the second one is the importance associated to the delayed neutron precursors. The boundary condition for the delayed neutron precursor adjoint function is specified on the basis of the theory of the importance function, as:

$$\mathscr{E}_i^\dagger(r,z=H) = \frac{1}{\mathscr{A}}\int_{\mathscr{A}_{in}} d\mathscr{A}\mathscr{E}_i^\dagger(r,z=0)e^{-\lambda_i\tau}. \tag{5}$$

The effect of the introduction of a small perturbation of the leakage and fission operators may be estimated by resorting to standard first-order perturbation theory (Gandini, 1967). The resulting perturbation of the effective multiplication constant can thus be evaluated and the reactivity can be expressed by the following quite simple formula:

$$\rho \equiv \frac{\delta k_{eff}}{k_{eff}} = \frac{(\mathbf{\Theta}^\dagger, \delta\widehat{\mathfrak{F}}\mathbf{\Xi}) - (\mathbf{\Theta}^\dagger, \delta\widehat{\mathfrak{L}}\mathbf{\Xi})}{(\mathbf{\Theta}^\dagger, \widehat{\mathfrak{F}}\mathbf{\Xi})}, \tag{6}$$

where, as usual, parentheses denote the inner product, involving also an integration over the phase-space.

The analysis is now restricted to a one group diffusion model with one family of delayed neutron precursors; the generalization to more families is rather straightforward. In this particular case the delayed emissivity is simply the precursor concentration and the state vector for the direct and adjoint problems are defined as:

$$\begin{aligned} \mathbf{\Xi}(z) &= [\Phi(z);\ C(z)]^t \\ \mathbf{\Theta}^\dagger(z) &= [\Phi^\dagger(z);\ C^\dagger(z)], \end{aligned} \tag{7}$$

and one can write explicitly for the leakage and fission operators the following matrix operators:

$$\widehat{\mathfrak{L}} = \begin{pmatrix} \nabla\cdot D\nabla - \Sigma_a & \lambda \\ 0 & -u\dfrac{\partial}{\partial z} - \lambda \end{pmatrix}; \quad \widehat{\mathfrak{F}} = \begin{pmatrix} (1-\beta)\nu\Sigma_f & 0 \\ \beta\nu\Sigma_f & 0 \end{pmatrix}. \tag{8}$$

The appearance of a lump of fissile material of volume V_L inside the system introduces a perturbation amounting to an increase of both the fission and the absorption cross sections in such volume. In order to preserve the total mass of the fissile material, simultaneously the concentration of the fissile material must be decreased in the background volume V_B. The relationship between the atomic concentration of the fissile nuclide in the lump, $N_F^{(L)}$, and the concentration in the background $N_F^{(B)}$ can be established by the following formula:

$$N_F^{(B)} = \frac{N_F V_T - N_F^{(L)} V_L}{V_B}, \tag{9}$$

where V_T is the total dimension of the system considered and N_F is the unperturbed initial concentration. Therefore, two perturbations