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Characters of neutron noise in full-size molten salt reactor

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ABSTRACT

In the present paper, the frequency-dependent and space-dependent behavior of the neutron noise in a full-size Molten Salt Reactor (MSR) is investigated. The theoretical models considering the fuel circulation are established based on one-group neutron diffusion theory. Green's function of the neutron noise induced by a propagating perturbation is introduced with linear noise theory, due to the small perturbation. The equations are numerically calculated by developing a code, in which the eigenfunction expansion method is adopted. The static results show that the effective delayed neutron fraction changes non-monotonically with the increasing fuel velocity. In the dynamic case, the results are compared to those obtained in 1D MSR and a traditional reactor, in order to figure out the effects of both the fuel circulation and the system size. It is found that there is no difference in 1D and 3D MSR systems from the view of fuel circulation, i.e., the fuel circulation enhances the spatial neutronic coupling and leads to the stronger point kinetic effect. The more prominent space-dependent effect founded in 3D traditional reactors is also observed in the MSR, due to the looser neutronic coupling and the unique singularity of Green's function in the location of the perturbation. Another interesting finding is that Green's function for low frequencies changes non-monotonically with increasing velocity. The largest magnitude of Green's function is observed at the velocity where the effective delayed neutron fraction reaches its minimum. Finally, the neutron noise induced by a specific propagating perturbation is calculated and analyzed.

1. Introduction

The advantages of the Molten Salt Reactor (MSR) such as inherent safety, excellent neutronic economy and non-proliferation make MSR attract increasing attentions in recent decades, especially after it was selected as one of the six candidates for the Generation IV rectors in Generation-IV International Forum (GIF, 2002). Unlike the traditional reactors (e.g. LWRs), the fuel used in MSR is dissolved into the coolant and can thus circulate throughout the primary loop. The main effect of the fuel circulation is the loss of the delayed neutrons due to some precursors decaying outside the core. Therefore, the effective delayed neutron fraction decreases and the effect of the prompt neutrons becomes more important. If the fuel with a smaller fraction of delayed neutrons per fission is used in MSR, this difference becomes more prominent (Pázsit and Jonsson, 2011). Moreover, the thermal feedback effect in MSR is much stronger than that in traditional reactors, because of the tighter combination between the fuel and the coolant. Above all, MSR entirely differs from the traditional reactors and becomes quite a different design. These differences induced by the fluid fuel circulation not only bring challenges and problems in the design and operation, but they also cause difficulties in the basic understanding of the static and particularly dynamic properties of MSR.

The dynamic property of MSR has been intermittently studied for decades since the early works made by Oak Ridge National Laboratory (ORNL) in 1960–1970s (Rosenthal et al., 1970). In recent years, the renewed attentions have been mostly focused on the dynamic responses following various transients, such as rod drop, pump coast down and inlet temperature drop. Several representative articles are summarized and compared in the literature (Cammi et al., 2011). In these works, the dynamic calculations for the whole MSR are needed, because the system is strongly affected and deviates far from the static condition. As a result, the calculation process is complicated, and a large amount of computing resources is required.

To provide the basic understanding of the dynamic property of MSR, an alternative method is to investigate the neutron fluctuation around the static condition. This fluctuation, also known as the neutron noise, can be induced in traditional reactors by two different kinds of perturbations such as the movement of reactor component and the fluctuation of coolant temperature.

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Whereas in a simplified blanket-type MSR (Zhang et al., 2009), the internal component of the core is removed. The only type of perturbation is the fluctuation of coolant temperature, which propagates with the fuel flow and is thus called the propagating perturbation. The time-dependent perturbation results in the time-dependent neutron noise. Therefore, by analyzing the behavior of the neutron noise, several dynamic properties of MSR can be obtained. In addition, the calculation can be greatly simplified because the neutron noise is merely dependent on the static distributions and the concrete type of perturbation. Therefore, when one needs to determine the system response to a perturbation generated in a reactor near critical, if the perturbation is small enough, it is not necessary to perform a complete, new calculation of the perturbed system. Instead, by means of noise theory, the response to the small perturbation can be obtained (Bell and Glasstone, 1970). Moreover, another interest on the neutron noise stems from the practical reactor diagnostics because the neutron noise contains helpful information which can be used for the identification and localization of the perturbation (Demazière and Andhill, 2005).

Previous works on the neutron noise were mainly done by the Department of Nuclear Engineering, Chalmers University of Technology, and most efforts were devoted to the study of the neutron noise in traditional reactors. Demazière (2004) developed a noise simulator for the 2D 2-group neutron noise, which can be used to model any realistic core and has been proven working satisfactorily. Later, a new 3D core simulator was developed by Demazière (2011) to study the neutron noise induced by propagating density/temperature perturbations for 3D heterogeneous rectangular core. For the case of PWR, even the thermal hydraulic module was included, i.e. coupled calculations were performed (Larsson and Demazière, 2012). In addition, the developed noise simulator complemented with thermo-hydraulic module has also been extended recently to BWR-type reactors (Demazière et al., 2015). More details on the neutron noise induced by propagating perturbations can also be found in literature (Vinai et al., 2014), in which the self-sustained density wave oscillation and its neutronic response in a 3D heterogeneous system are investigated.

Studies on the neutron noise in MSR just started in recent years and were mainly performed in simplified 1D systems (Pázsit and Jonsson, 2011; Jonsson and Pázsit, 2011). The benefits of such simplification are doubled. On the one hand, several interesting basic problems and new properties induced by the fuel circulation can be found. The results are expected to be valid in a full-size MSR to a particular extent. On the other hand, the calculation process is greatly simplified and the closed-form analytical solutions in the extreme case of infinite velocity can be obtained, which leads to a more intuitive interpretation of the dynamic property of MSR. However, as was indicated in the case of traditional reactors, the results from the study on the 1D system underestimate the space-dependent effect, which is more prominent in the 2D or 3D system (Demazière, 2004). Therefore, to obtain a more realistic picture of the dynamic property of MSR, the system should be extended to three dimensions.

The purpose of the present paper is thus to study the behavior of the neutron noise in a full-size (3D) MSR. The structure of this paper is as follows. In the beginning, the MSR system is described. Next, the theoretical models considering the fuel circulation are established based on one-group neutron diffusion theory. Green's function of the neutron noise induced by a propagating perturbation is introduced with linear noise theory, due to the smallness of the perturbation. Then, the equations are numerically calculated by developing a code, in which the eigenfunction expansion method is adopted. In the static case, the effects of the fuel velocity on both the spatial distributions and the effective delayed neutron fraction are studied. In the dynamic case, the solutions are compared to those obtained in 1D MSR and a corresponding traditional reactor, in order to figure out the effects of the system size and the fuel velocity. Finally, the neutron noise induced by a specific propagating perturbation is calculated and analyzed.

Table 1
System parameters.

Parameters	Values used
H (cm)	300
L (cm)	500
R (cm)	150
D (cm)	0.33
Σ_a (cm^{-1})	0.01
β	0.0065
Λ (s^{-1})	0.1
v (cm/s)	220000
P (MW)	60
e_f (J)	3.2e-11

2. MSR system description

A conceptual MSR comprises three circuits, of which the primary one, including the core and an external channel, is adopted in this paper. The core is assumed to be a 3D cylindrical blanket of radius R and height H. The one-phase fuel flow is assumed to be taking place axially from the core inlet $z = 0$ to the core outlet $z = H$ and then returns to the core inlet through the external channel of length L. Assuming the fuel velocity to be u, the time for the recirculation will be $\tau = (H + L)/u$, and the time for passing through the external channel will be $\tau_L = L/u$. For brevity, the thermal feedback effect is neglected and the core is assumed as homogeneous. The basic parameters of the MSR system are listed in Table 1.

3. Theoretical models

3.1. Governing equations and boundary conditions

For most practical noise problems, neutron diffusion theory has been proven fully sufficient (Pázsit and Demazière, 2010). Hence, in the present work, the neutron kinetics model is established based on diffusion theory. Moreover, in the assumption of one-phase fuel flow, the boiling is absent, which indicates that the local component of the neutron noise is much weaker than the global component of the neutron noise. Thus, one-group theory is applicable and the diffusion equations can be written as

$$\frac{1}{v}\frac{\partial}{\partial t}\phi(\mathbf{r},t) = D\nabla^2\phi(\mathbf{r},t) + (1-\beta)\nu\Sigma_f\phi(\mathbf{r},t) - \Sigma_a\phi(\mathbf{r},t) + \lambda C(\mathbf{r},t) \tag{1}$$

$$\frac{\partial C(\mathbf{r},t)}{\partial t} + u\frac{\partial C(\mathbf{r},t)}{\partial z} = \beta\nu\Sigma_f\phi(\mathbf{r},t) - \lambda C(\mathbf{r},t) \tag{2}$$

Symbols in Eqs. (1) and (2) have their usual meanings. The vector $\mathbf{r} = (r, z, \theta)$ represents an arbitrary position in the core, where the radial, axial, and circumferential locations are r, z, and θ, respectively.

The boundary conditions for the neutron flux are set as vacuum at the core inlet, outlet and on the radial boundary; the symmetric boundary condition is applied for the core axial. For the delayed neutron precursors, the boundary condition on the radial boundary is also set as vacuum. Due to the fuel recirculation, the precursor density at the inlet is the same as that at the outlet with a time τ_L earlier, but decreased by the amount of the precursors decaying in the external channel during this time, namely,

$$C((r,0,\theta),t) = C((r,H,\theta),t-\tau_L)e^{-\lambda\tau_L} \tag{3}$$