Simulation on fluctuations in molten salt reactor with 1D coupled neutronics/thermal-hydraulics model

WANG Jiangmeng, and CAO Xinrong*

College of Nuclear Science and Technology, Harbin Engineering University, Harbin, 150001, P.R. China (wangjdmeng@163.com, caoxinrong@hrbeu.edu.cn)

Abstract: In this study, the more realistic behaviors of the fluctuations in neutron fluxes, fuel temperature and velocity induced by a propagating perturbation in the molten salt reactor (MSR) are simulated by coupling the neutronic and thermal-hydraulic models. The neutron kinetic model is established based on neutron diffusion theory, in which the neutron is classified into two groups and the delayed neutron precursors into an averaged family. The thermal feedback is considered by introducing a heat transfer model, in which the temperature-dependent group constants are produced with the HELIOS code. The equations for the fluctuations are deduced based on linear perturbation theory, assuming the perturbation is small enough. All the equations are discretized and numerically solved by developing a code. In the static case, the increasing fuel velocity is found to have significant influence on the precursors, whereas the fast and thermal neutron fluxes nearly stay the same due to the small delayed neutron fraction of the fuel. In the dynamic case, the main efforts are devoted to the effects of several factors on the fluctuations. The applicability of linear perturbation theory is also quantitatively evaluated. The results show that linear perturbation theory works well in the scope of 5K temperature change. In addition, the difference between the amplitudes of the temperature noises in the coupled and pure neutronic models increases oscillatorily along the flow direction, thereby indicating the much stronger spatial oscillation of the neutron noises in the realistic system. Moreover, the fluctuations in various kinds of group constants have significant effects on the neutron noises and their contributions should be accounted for.

Keyword: MSR; neutron noise; temperature noise; coupled neutronics/thermal-hydraulics; propagating perturbation.

1 Introduction

The molten salt reactor (MSR), counted as one of the six candidates for Generation IV reactors [1], attracts increasing attention in recent years because of its numerous potentials such as inherent safety, excellent neutron economy and high thermal efficiency. Unlike the case of traditional solid-fuelled reactors, the fuel used in MSR is dissolved into the coolant and can circulate throughout the primary loop. As a result, the delayed neutron precursors can leave out the core and decay outside, leading to a smaller effective delayed neutron fraction [2]. The fuel circulation also results in the tighter neutronic coupling by transporting the precursors from the place of their generation to their decay. Therefore, the dynamic response of MSR is much stronger than that of corresponding traditional reactors following the same transient [2]. Furthermore, when considering the neutronics/thermal-hydraulics coupling caused by the combination between fuel and coolant, the realistic static and particularly dynamic properties of MSR become more complicated [3].

The dynamic property of MSR has been investigated intermittently since the early works made by Oak Ridge National Laboratory (ORNL) in 1960-1970s [4]. Several representative articles are summarized and compared in the literature [3]. To provide the basic understanding of the dynamic property of MSR, in recent years, an alternative method of studying the fluctuations around the static condition has been applied. This fluctuation, also known as the reactor noise, can be induced in traditional reactors by two different types of perturbations such as the coolant temperature fluctuation and the reactor component oscillation. However, in the blanket-type MSR, the internal components are removed and the core is simplified as a blanket, for instance the Molten Salt Actinide Recycler & Transmuter (MOSART) [5]. The only kind of perturbation is the fluctuation in coolant temperature, which propagates with the fuel flow and is thus called the propagating perturbation [2]. The

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time-dependent perturbation results in the time-dependent reactor noises. Therefore, by analyzing their features, several dynamic properties of MSR can be obtained [6]. Another important interest on the reactor noise stems from the fact that the reactor noise, primarily the neutron noise, contains helpful information which can be used for the identification and localization of the perturbation [7].

Studies on the reactor noises in MSR were just started in recent years and were focused on the neutronic aspect, i.e. the neutron noise. Most works were performed in the 1D bare homogeneous systems. In this simplified model, several basic problems and new properties induced by the fuel circulation can be obtained and the results are expected to be valid in a 3D MSR [2][8][9]. The behavior of the neutron noise in a full-size MSR has also been investigated recently, which confirmed that there is no difference between the 1D and 3D cases from the view of fuel circulation [10]. Thus, the 1D model can be regarded as an appropriate model to study the dynamic property of MSR considering the fuel circulation.

In traditional reactors, the fuel is separated from the coolant. If a perturbation is generated in the coolant, the induced fluctuations in the group constants of the solid fuel have a certain time delay and their magnitudes are relatively smaller, due to the thermal resistance caused by the claddings and gas gaps. The neutronic and thermal-hydraulic field can thus be regarded as independent to a particular extent. However, the case of MSR becomes very different because of the tight combination between fuel and coolant. Both the neutron spectrum and fuel density change sharply as soon as the perturbation is generated. Therefore, the dynamic response of MSR is more prominent and complicated than that in the corresponding traditional reactor following the same perturbation. To obtain more realistic dynamic property of MSR, the effect of the thermal feedback should be taken into account.

The purpose of the present work is thus to study the realistic behavior of fluctuations in a 1D MSR system with the coupled neutronics/thermal-hydraulics model. The organization of this paper is as follows. First, the neutronic and thermal-hydraulic models are established based on neutron diffusion theory and the conservation law of mass and energy, respectively. Next, equations for fluctuations are derived in linear perturbation theory, with the assumption of the small perturbation. The group constants dependent on the temperature are produced by means of HELIOS code to build the thermal feedback. HELIOS is a neutron and gamma transport code for lattice burnup, in general 2D geometry [11]. Then, equations for both the static case and fluctuations are discretized and numerically calculated by developing a coupled code. Finally, the effects of several factors on the reactor noises are discussed. The applicability of linear perturbation theory is also evaluated.

2 Theoretical models

A conceptual MSR comprises three loops, of which the primary one, including the core and an external pipe, is adopted in this paper. For brevity, the core is assumed as one-dimensional, in which the fuel circulation is set to be taking place along the axial z direction from the core inlet $z=0$ to the outlet $z=H$ and then return to the inlet through the external pipe of length L. The fuel salt is heated in the core by the fission reaction and cooled down by transporting the heat to the second loop. The molten salt which acts as both the fuel and coolant is selected as $^{7}LiF\text{-}BeF_2\text{-}ThF_4\text{-}^{233}UF_4$ with the mole percentage of 71.7%-16%-12%-0.3% [3]. The basic parameters of the system are listed in Table 1.

Table 1. MSR design parameters

Parameter	Value used
Core height H (cm)	300
External length L (cm)	400
Inlet temperature T_i (K)	839
Outlet temperature T_o (K)	977
Heat capacity c_p (J g^{-1} K^{-1})	1.08832
Fuel salt density ρ (g cm^{-3})	3.9361-0.00019857*T
Heat conductive ratio k (Wcm^{-1})	0.005323
Heat released per fission E_f (J)	3.2**e**-11

2.1 Neutron kinetics

Previous works have proven that neutron diffusion theory is sufficient for most practical noise problems [6]. Thus in this paper, the governing equations for the neutron kinetics are established based on neutron diffusion theory, in which the neutron is classified into two groups and precursors into an averaged family as

$$\frac{1}{v_1}\frac{\partial\phi_1}{\partial t}=\nabla\bullet D_1\nabla\phi_1-\left(\Sigma_{a,1}+\Sigma_{1\to2}\right)\phi_1 + \frac{1-\beta}{k_{eff}}\left(\nu\Sigma_{f,1}\phi_1+\nu\Sigma_{f,2}\phi_2\right)+\Sigma_{2\to1}\phi_2+\lambda C \quad (1)$$

$$\frac{1}{v_2}\frac{\partial\phi_2}{\partial t}=\nabla\bullet D_2\nabla\phi_2-\left(\Sigma_{a,2}+\Sigma_{2\to1}\right)\phi_2+\Sigma_{1\to2}\phi_1 \quad (2)$$

$$\frac{\partial C}{\partial t}+\nabla\bullet\left(uC\right)=\frac{\beta}{k_{eff}}\left[\nu\Sigma_{f,1}\phi_1+\nu\Sigma_{f,2}\phi_2\right]-\lambda C \quad (3)$$

where ϕ is the neutron flux; C is the precursor density; D is the diffusion coefficient; Σ is the macroscopic cross section; λ is the decay constant; β is the delayed neutron fraction per fission; v is the neutron velocity; ν is the number of neutron released per fission; k_{eff} is the effective multiplication factor; u is the fuel velocity. The subscripts *1* and *2* represent the fast and thermal group of neutron; *a*, *f* and *g'*-*g* $\left(g',g=1,2\right)$ denote the absorption, fission and transfer cross sections.

The boundary conditions for the fast and thermal neutron fluxes are set as vacuum at both the core inlet and outlet. Because the precursors can leave out the core and decay outside, their densities at the inlet and outlet should satisfy the following condition as

$$u\left(0,t\right)C\left(0,t\right)=u\left(H,t-\tau_L\right)C\left(H,t-\tau_L\right)\mathbf{e}^{-\lambda\tau_L} \quad (4)$$

where τ_L is the time for passing through the external pipe.

The equations for the static condition can be obtained by eliminating the time-dependent terms in Eqs. (1) -(3) as

$$0=\nabla\bullet D_1\nabla\phi_1^0-\left(\Sigma_{a,1}+\Sigma_{1\to2}\right)\phi_1^0 + \frac{1-\beta}{k_{eff}}\left(\nu\Sigma_{f,1}\phi_1^0+\nu\Sigma_{f,2}\phi_2^0\right)+\Sigma_{2\to1}\phi_2^0+\lambda C^0 \quad (5)$$

$$0=\nabla\bullet D_2\nabla\phi_2^0-\left(\Sigma_{a,2}+\Sigma_{2\to1}\right)\phi_2^0+\Sigma_{1\to2}\phi_1^0 \quad (6)$$

$$\nabla\bullet\left(uC^0\right)=\frac{\beta}{k_{eff}}\left[\nu\Sigma_{f,1}\phi_1^0+\nu\Sigma_{f,2}\phi_2^0\right]-\lambda C^0 \quad (7)$$

The boundary condition for the precursor density in Eq. (4) becomes

$$u\left(0\right)C^0\left(0\right)=u\left(H\right)C^0\left(H\right)\mathbf{e}^{-\lambda\tau_L^0} \quad (8)$$

where the superscript *0* represents the static values.

When a perturbation is generated in MSR, the system deviates from the static condition and all the parameters fluctuate around their static values. The time-dependent parameter $X\left(z,t\right)$ can thus be splited into the static value $X^0\left(z\right)$ and a fluctuation $\delta X\left(z,t\right)$ as

$$X\left(z,t\right)=X^0\left(z\right)+\delta X\left(z,t\right) \quad (9)$$

Replacing Eq. (9) in Eqs. (1)-(3) and removing Eqs. (5)-(7) for the static condition, the equations for the fluctuations can be obtained. With the assumption of small perturbations, linear theory can be applied, i.e. the high-order terms of fluctuations can be ignored. Performing a temporal Fourier transform on the remaining terms, the frequency-dependent equations for fluctuations can be achieved as

$$-\delta S_1=-\nabla\bullet D_1^0\nabla\delta\phi_1 - \left(\frac{1-\beta}{k_{eff}}\nu\Sigma_{f,1}-\Sigma_{a,1}-\Sigma_{1\to2}-\frac{i\omega}{v_1}\right)\delta\phi_1 \quad (10)$$

$$-\delta S_2=-\nabla\bullet D_2\nabla\delta\phi_2+\left(\Sigma_{a,2}+\Sigma_{2\to1}+\frac{i\omega}{v_2}\right)\delta\phi_2 \quad (11)$$

$$-\delta S_C=\left(i\omega+\lambda\right)\delta C+\nabla\bullet\left(u\delta C\right) \quad (12)$$

where the perturbations, or the noise sources, can be expressed as follows:

$$\delta S_1=-\nabla\bullet\delta D_1\nabla\phi_1^0+\left(\delta\Sigma_{a,1}+\delta\Sigma_{1\to2}\right)\phi_1^0 - \frac{1-\beta}{k_{eff}}\left(\delta\nu\Sigma_{f,1}\phi_1^0+\nu\Sigma_{f,2}\delta\phi_2+\delta\nu\Sigma_{f,2}\phi_2^0\right) - \left(\delta\Sigma_{2\to1}\phi_2^0+\Sigma_{2\to1}\delta\phi_2\right)-\lambda\delta C \quad (13)$$

$$\delta S_2=-\nabla\bullet\delta D_2\nabla\phi_2^0+\left(\delta\Sigma_{a,2}+\delta\Sigma_{2\to1}\right)\phi_2^0 - \left(\Sigma_{1\to2}\delta\phi_1+\delta\Sigma_{1\to2}\phi_1^0\right) \quad (14)$$

$$\delta S_C=-\frac{\beta}{k_{eff}}\sum_{g=1}^{2}\left(\nu\Sigma_g\delta\phi_g+\delta\nu\Sigma_{f,g}\phi_g^0\right)+\nabla\bullet\left(\delta uC^0\right) \quad (15)$$

where δS_1, δS_2 and δS_C represent the noise source for the fast neutron flux, thermal neutron flux and delayed neutron precursors, respectively.

The boundary condition for the precursor noise turns to

$$u\left(0\right)\delta C\left(0,\omega\right)=u\left(H\right)\delta C\left(H,\omega\right)\mathbf{e}^{-\left(\lambda+i\omega\right)\tau_L^0} \quad (16)$$

2.2 Thermal-hydraulics

In MSR, the fuel velocity field depends on the fission source term, which determines the density variation and the temperature distribution of the fuel salt [3]. Therefore, in order to obtain an accurate description of the dynamic behavior, the coupling mechanisms should be accounted for.

In this paper, the thermal-hydraulic field is described with the conservation equations for both continuity and energy. The equation for momentum is neglected with the assumption of constant pressure [12].

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho u) = 0 \quad (17)$$

$$\frac{\partial \rho T}{\partial t} + \nabla \bullet (\rho u T) = \frac{1}{c_p}\left(\kappa \nabla^2 T + Q\right) \quad (18)$$

where Q is the heat source, which can be evaluated by the neutron fission reaction as

$$Q = E_f \sum_{g=1}^{2}\left(\Sigma_{f,g}\phi_g\right) \Big/ k_{eff} \quad (19)$$

The Dirichet condition is adopted for the inlet. At the outlet, the free outflow is assumed.

Similar to Sec. 2.1, the equations for the fluctuations in fuel temperature, density, and velocity can be obtained by using linear perturbation theory as

$$-\delta S_u = \nabla \bullet \rho \delta u \quad (20)$$

$$-\delta S_T = i\omega\rho\delta T + \nabla \bullet (\rho u \delta T) - \frac{\kappa}{c_p}\nabla^2 \delta T \quad (21)$$

where the noise source for velocity and temperature are defined as

$$\delta S_u = i\omega\delta\rho + \nabla \bullet u\delta\rho \quad (22)$$

$$\delta S_T = i\omega T\delta\rho + \nabla \bullet (\rho T\delta u + uT\delta\rho) - \frac{\delta Q}{c_p} \quad (23)$$

and the fluctuation in heat source δQ can be written as

$$\delta Q = E_f \sum_{g=1}^{2}\left(\delta\Sigma_{f,g}\phi_g^0 + \Sigma_{f,g}\delta\phi_g\right) \Big/ k_{eff} \quad (24)$$

2.3 Thermal feedback manner

The fuel temperature determines both the fuel density and the neutron spectrum, which in turn affects the group constants. Therefore, it is expected to express the group constants as the functions of temperature to establish the thermal feedback. In this paper, the temperature-dependent two-group group constants are produced by means of the HELIOS code [11], in the assumption of beginning of life fuel composition, i.e. the burn-up dependence of the group constants is neglected. Such approximation can be regarded as appropriate in the case of MSR because its neutronic characteristics are relatively independent of the core life time [13]. In the calculation, the master library with 190 neutron groups is adopted to generate the microscopic cross section database, which is then merged into two-group macroscopic group constants. Finally, with the least square method, all the group constants are fitted as the functions of temperature and can be written in the unified form as

$$\Sigma_x(T) = a + bT + cT^2 \quad (25)$$

where a, b and c are the coefficients determined by the fitting process.

The fluctuations in group constants can be estimated with

$$\delta\Sigma_x(\delta T) = b\delta T + 2cT\delta T \quad (26)$$

3 Numerical methods

The equations for fluctuations (10)-(12), (20) and (21) can be written in the following unified form as

$$\frac{\partial}{\partial z}\left(\Gamma_X \frac{\partial \delta X}{\partial z}\right) + \frac{\partial \rho_X u \delta X}{\partial z} + S_{PX}\delta X = -\delta S_{CX} \quad (27)$$

where δX represents the fluctuations in neutron fluxes, delayed neutron precursors, fuel temperature and velocity. δX and the coefficients are listed in Table 2.

The static equations have the similar form as that of the fluctuation equation in Eq. (27), only the last term at the right-hand side is eliminated.

Table 2. Parameters of the variables in the unified form

δX	ρ_X	Γ_X	S_{PX}	δS_{CX}
δu	ρ	0	0	δS_u
δT	ρ	$-\kappa/c_p$	$i\omega\rho$	δS_T
$\delta\phi_1$	0	D_1	$(1-\beta)/k_{eff}\,\nu\Sigma_{f,1} - \Sigma_1 - i\omega/v_1$	δS_1
$\delta\phi_2$	0	D_2	$-\Sigma_2 - i\omega/v_2$	δS_2
δC	1	0	$\lambda + i\omega$	δS_C

To solve the space-dependent terms in the static and fluctuation equations, a spatial discretization scheme has to be chosen. The finite difference method (FDM) is adopted for its efficiency and simplicity.

From Eq.(27), the coefficient matrix of the discretized equation system is a tridiagonal matrix. Hence, all the equation systems are solved with the Tri-Diagonal Matrix Algorithm (TDMA) [14].

4 Results and discussion

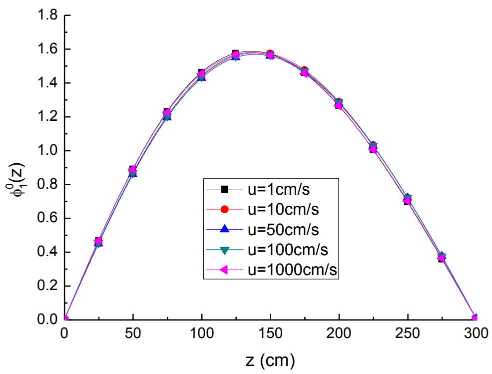
4.1 Static condition

Because the primary difference between MSR and traditional reactors are caused by the redistribution of the delayed neutron precursors and their decaying outside the core due to the fuel circulation, the main effort is devoted to the effect of fuel velocity on the spatial distributions of the static neutron fluxes and precursor density. Calculations are carried out for different inlet velocities. The results are displayed in

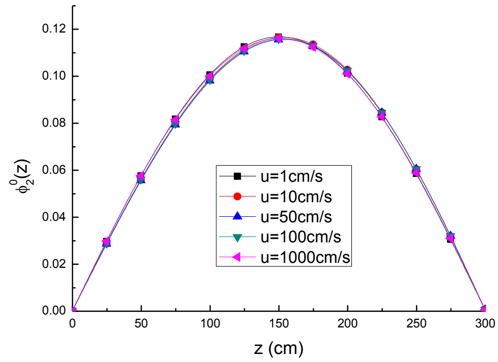
Fig. 1, in which all the parameters are normalized with the fast neutron flux.

As was noticed in the previous work [10], the increasing velocity has two opposite effects on the delayed neutron precursors. On the one hand, the peak of the precursor distribution moves to the outlet and thus the amount of precursors leaved out the core increases, which may result in a larger loss fraction of the delayed neutrons. On the other hand, the time for passing through the external pipe decreases, thereby indicating that the larger fraction of precursors leaved out the core can return to the inlet. At low velocity, the former effect is dominant, the spatial distribution of precursors deviates the symmetry. At high velocity, the latter one presents more prominent, the precursor distribution in the core becomes symmetric again, as seen in Fig. 1(c).

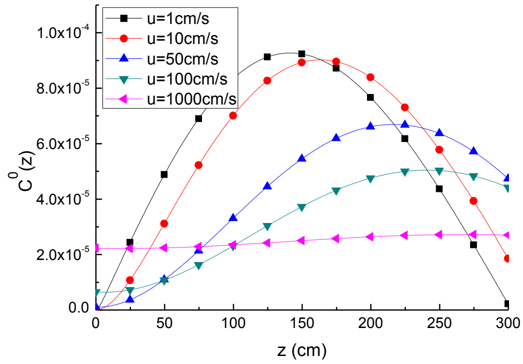
However, as seen in Figs. 1(a) and 1(b), the spatial distributions of the fast and thermal neutron fluxes for various inlet velocities nearly overlap, which is very different as compared to those in literatures [2][10]. This can be mainly attributed to the fact that the fuel adopted in the present work has smaller fraction of delayed neutrons per fission ($\beta = 0.00322$). The contribution from the prompt neutrons becomes more important and thus the variation of precursors has small effect on the neutron flux distributions. Correspondingly, the spatial distributions of the temperature determined by the fission source also overlap, as seen in Fig. 2.



(a) Fast neutron flux



(b) Thermal neutron flux



(c) Precursor density

Fig. 1 Static spatial distributions of neutron fluxes and precursors for various inlet velocities.

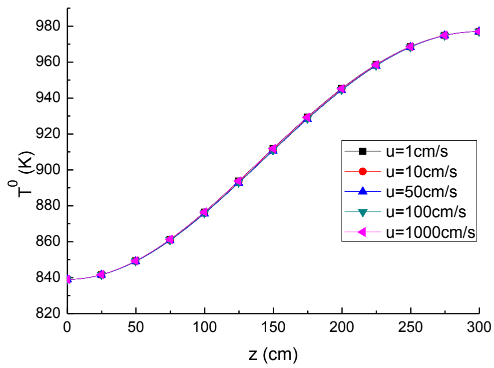


Fig. 2 Static spatial distributions of temperatures for various inlet velocities.

In MSR, because of the precursors decaying outside the core, only a certain amount of delayed neutrons participate in the fission reaction. When investigating the static and especially the dynamic properties of MSR, the effect of the loss of delayed neutrons should be considered. Similar to the previous work [10], this purpose can be achieved by introducing the concept of the effective delayed neutron fraction β_{eff} as

$$\beta_{eff}(u) = \alpha(u)\beta \tag{28}$$

where

$$\alpha(u)=\frac{\int_0^H C_0(z)dz-\int_0^H C_0(z)e^{-\lambda(H-z)/u}dz\left(1-e^{-\lambda L/u}\right)}{\int_0^{H+L}C_0(z)dz}+\frac{C_0(H)Le^{-\lambda L/u}\left(1-e^{-\lambda H/u}\right)}{\int_0^{H+L}C_0(z)dz} \quad (29)$$

The velocity dependence of the factor $\alpha(u)$ is shown in Fig. 3, from which it is seen that the increasing velocity has a non-monotonic effect on the effective delayed neutron fraction. The minimum is observed at the inlet velocity about $u=100\,cm/s$, which is much higher than that in the previous work [10]. This can be attributed to the larger decay constant of precursors ($\lambda=0.481s^{-1}$). For the same velocity, the fraction of precursors leaved out the core returning to the inlet becomes bigger.

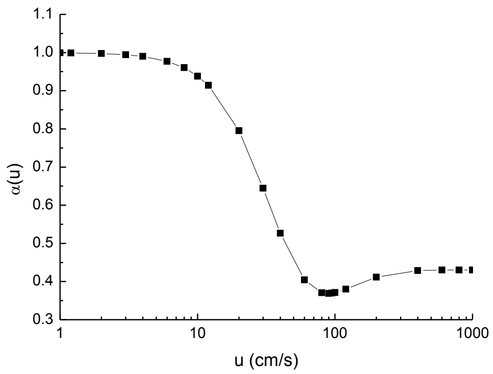


Fig. 3 Changing tendency of α with velocity.

4.2 Reactor noises

At low frequencies, the neutron noise has been found to be changing non-monotonically as the velocity increases, the largest magnitude is observed at the velocity where the effective delayed neutron fraction reaches its minimum [8][10]. From this point, it can be concluded that the largest deviation between MSR and traditional reactors appears at such a medium velocity rather the infinite one. Thus in the following parts, the inlet fuel velocity is set as $u=100\,cm/s$. In this assumption, the perturbation is expected to make the largest influence on the system.

As was stated above, the fluctuations in traditional reactors can be induced by two typical kinds of perturbations, i.e. the oscillation of reactor structure and the fluctuation in coolant temperature. However, in the blanket-type MSR, the internal component of the core is removed and only the coolant temperature fluctuation can be generated. In addition, because of the tight combination between fuel and coolant in MSR, this perturbation can be generated more often and its effect is more prominent. Therefore, the study on the reactor noise induced by the temperature fluctuation in MSR becomes more important.

4.2.1 Convergence and validation of calculation

The perturbation is assumed as the inlet temperature drop of $\Delta T=-1K$. Calculations are performed for the frequency $\omega=4\pi\,rad/s$ and various grid distances. The space dependences of the amplitudes of the precursor noises are displayed in Fig. 4. It is seen that the curves for the grid distances of *0.5cm* and *0.2cm* overlap with each other, which indicates that the solution is independent of the grid distance. Hence, the distance of $\Delta z=0.5cm$ is adopted as the final grid system.

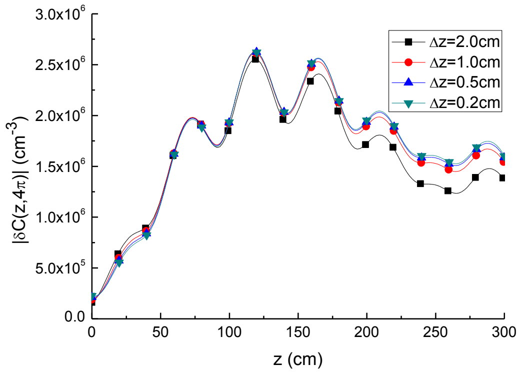


Fig. 4 Space dependences of amplitudes of precursor noises for various grid distances.

It is known that the neutron noise induced by a specific perturbation can be calculated analytically by integrating the product of the Green's function G and the perturbation δQ over the whole system as

$$\delta\phi(z,\omega)=\int_0^H G(z,z',\omega)\delta Q(z',\omega)dz' \quad (30)$$

In this paper, the solution from Eq. (30) is selected as the benchmark to validate the calculation. The neutron is divided into one group and all the parameters are taken from the literature [2]. The results are compared in Fig. 5, in which the velocity is assumed as infinite and the perturbation as a white noise process, *i.e.*,

$$\delta Q(z',\omega)=0.01\Sigma_a\mathbf{e}^{-i\omega z/u}\phi^0(z') \quad (31)$$

From Fig. 5, the two curves overlap with each other, thereby indicating the validation of the calculation.

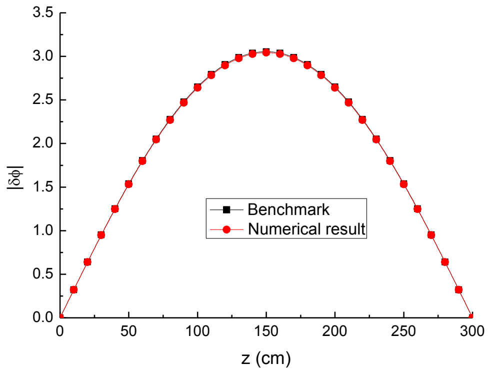


Fig. 5 Validation of the calculation.

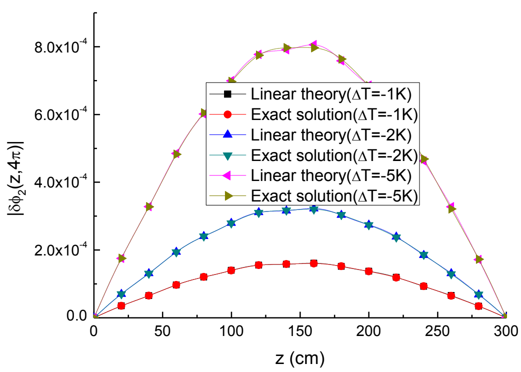


Fig. 6 Space dependences of amplitudes of normalized thermal neutron noises induced by various inlet temperature drops.

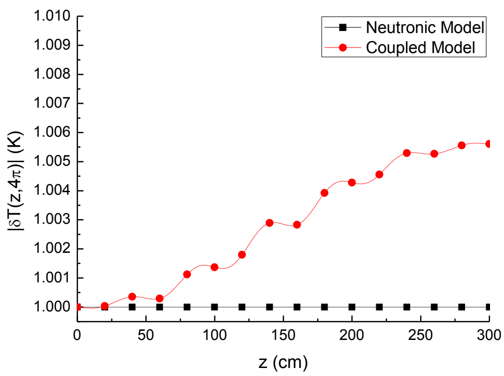
4.2.2 Applicable scope of linear perturbation theory

The equations for fluctuations are derived based on linear perturbation theory, which can be regarded as appropriate only when the perturbation is small enough [6]. Whereas the quantitative analysis on the applicability of linear perturbation theory in the case of MSR is absent. This is because the previous works were focused on the study of the basic properties of neutron noise with the Green's function technique, which is independent of the perturbation but only determined by the unperturbed system [6].

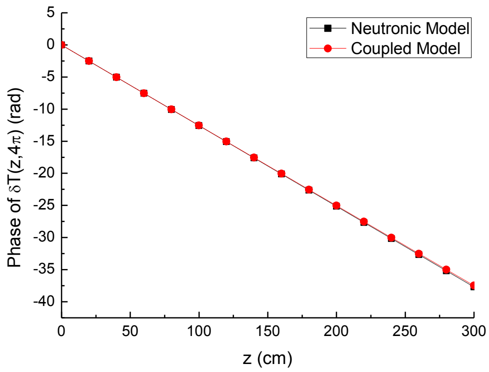
However, when investigating the realistic case of the fluctuations induced by a particular perturbation, the applicable scope of linear perturbation theory should be firstly determined. Calculations are performed for various inlet temperature drops and for the frequency $\omega = 4\boldsymbol{\pi} rad/s$. The amplitudes of the induced thermal neutron noises are compared in Fig. 6. In the case of $\Delta T = -1K$, the two curves overlap, indicating the accuracy of linear perturbation theory. As the absolute value of ΔT increases, the difference between the two curves increases, because the system gradually deviates far from the static condition and the effects of the higher-order terms of fluctuations become more prominent. In the case of the even higher temperature drop $\Delta T = -5K$, the solution with linear perturbation theory can still provide a good estimation of the realistic behavior of the neutron noise. Therefore, it can be concluded that linear perturbation theory works well in the scope of 5K temperature change.

4.2.3 Effect of thermal feedback

Previous studies on the reactor noises in MSR were focused on the neutronic aspect, *i.e.* the neutron noises [2][8][10]. The perturbation is usually considered as a white noise process and thus has constant amplitude over the whole core. However, the case becomes different when taking the thermal feedback effect into account. Fig. 7(a) displays the space dependences of the amplitudes of the temperature noises calculated in the pure neutronic and coupled neutronics/thermal-hydraulics model, assuming the inlet temperature drop of $\Delta T = -1K$. It is seen that the amplitude of the temperature noise considering the thermal feedback increases oscillatorily along the flow direction. The maximal difference is observed at the outlet but the magnitude is very small. As a result, the fuel velocity is slightly affected and the phases of the temperature noises in these two models overlap and decrease linearly in space, as shown in Fig. 7(b).



(a) Amplitudes of temperature noises



(b) Phases of temperature noises

Fig. 7 Space dependences of temperature noises in neutronic and coupled models.

The fast and thermal neutron noises in these two models are also calculated and their amplitudes are shown in Fig. 8. Because of the larger magnitude and the spatial oscillation of the temperature noise, the amplitudes of the neutron noises in the coupled model are more significant and also oscillate in space. Moreover, when comparing Fig. 8 with Figs. 1(a) and 1(b) for the static neutron fluxes, it can be found that the perturbation has more prominent effect on the thermal neutron flux, because the fuel material used in this paper is in a thermal spectrum.

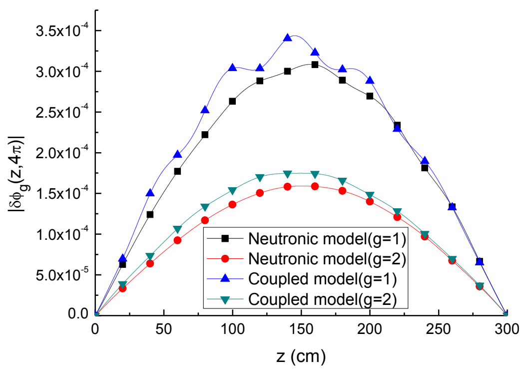


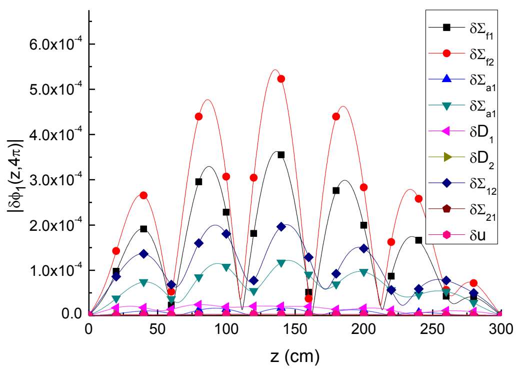
Fig. 8 Space dependences of amplitudes of normalized fast and thermal neutron noises.

4.2.3 Effect of fluctuation in various group constants and velocity

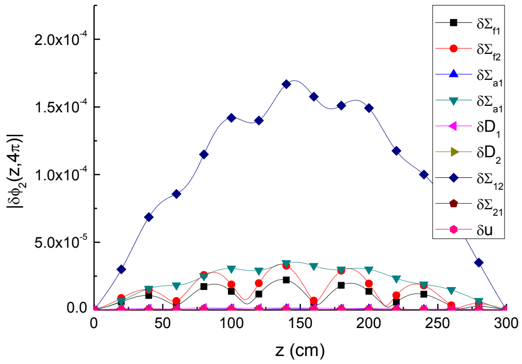
In traditional reactors, due to the thermal resistance caused by claddings and gas gaps, the temperature fluctuation generated in the coolant has significant effect on only the absorption cross section. When studying the neutron noises induced by such temperature fluctuation, only the effect of the fluctuation in the absorption cross section should be considered [15].

However, in MSR, the same temperature fluctuation generated in the molten salt will simultaneously lead to the strong variation of both the fuel density and the neutron spectrum because of the tight combination of fuel and coolant. As a result, all the group constants and fuel velocity are affected. Therefore, to obtain more realistic picture of the neutron noises, the effects of the fluctuation in each group constant and the velocity should be considered. Calculations are performed in the assumption of the single variable, *i.e.* the fluctuation is generated in one group constant (or velocity) and others are set as zero. The results are shown in Fig. 9, in which the inlet temperature fluctuation is set as $\Delta T = -1K$. It is seen that the fast neutron noise is more sensitive to the fluctuations in the fission, transfer and absorption cross sections. The thermal neutron noise is more sensitive to the fluctuation in the transfer cross section. The effects of the fluctuations in both the diffusion coefficient and fuel velocity are much smaller and can be neglected.

Another interesting finding is that the neutron noises induced by fluctuation in different group constant or velocity are very different from the realistic ones in Fig. 8, because of the complicate and nonlinear interferences among the effects of the fluctuations in these factors [15]. Therefore, to obtain more realistic behavior of the reactor noise in MSR, the contributions from the fluctuations in these group constants should be taken into account.



(a) Fast neutron noises



(b) Thermal neutron noises

Fig. 9 Space dependences of amplitudes of normalized neutron noises induced by fluctuations in different group constants and velocity.

5. Conclusion

In the present paper, the reactor noises induced by a propagating perturbation in MSR are simulated in the coupled neutronics/thermal-hydraulics model. The group constants for various temperatures are produced by means of the HELIOS code to build the thermal feedback manner. The equations for both the static case and fluctuations are discretized and numerically calculated by developing a code.

In the static case, the results show that the increasing fuel velocity has significant influence on the delayed neutron precursors, whereas the distributions of the fast and thermal neutron fluxes nearly stay the same as the velocity increases. This can be attributed to the fact that the contribution from the delayed neutrons decreases due to the smaller fraction of the delayed neutrons per fission.

In the dynamic case, the perturbation is assumed as the inlet temperature drop. The main efforts are devoted to the study of the effects of several factors on the reactor noises by investigating their amplitude and phase distributions. In addition, the reactor noises obtained in linear perturbation theory are compared with the exact solutions to determine the applicable scope of this linear theory. The conclusions are summarized as follows. First, linear perturbation theory works well in the scope of 5K temperature change. In addition, the difference between the amplitudes of the temperature noises in the coupled and pure neutronic models increases oscillatorily along the flow direction, thereby indicating a much stronger spatial oscillation of the neutron noises in the realistic system. Moreover, the fluctuations in various kinds of group constants have significant effects on the reactor noise and their contributions should be accounted for.

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