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Applicability of adiabatic approximation on neutron noise analysis in molten salt reactor

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ABSTRACT

In this paper, the applicability of the adiabatic approximation on the neutron noise analysis in the molten salt reactor (MSR) is investigated. The neutronic model considering the fuel recirculation is established based on one-group neutron diffusion theory. In linear perturbation theory, the fluctuation equations are derived due to the smallness of the perturbation. Following the standard procedure, the kinetic equations for the fluctuations of amplitude factors, which are dependent on the unknown fluctuations of shape functions, are obtained. If the fluctuations of shape functions are neglected, the solutions of both the total neutron noise and its point kinetic term are inaccurate. In order to estimate the effects of the fluctuations of shape functions and the interference between the point kinetic and space-dependent terms, the adiabatic approximation is applied. The solutions are compared to the exact ones and those obtained in the point kinetic approximation to figure out the applicability of the adiabatic approximation. The results show that the adiabatic approximation is accurate enough for low velocities. With higher velocities, the solutions obtained in both the point kinetic and adiabatic approximations gradually deviate from the exact ones, whereas the adiabatic approximation can still provide good estimation of the frequency- and space-dependent behavior of neutron noise in the plateau region. In particular, the spatial oscillation of the amplitude of neutron noise can be well reconstructed. Moreover, the characteristic peak, which is related to the inverse of fuel recirculation, is absent in the point kinetic approximation but can be observed in the adiabatic approximation. Therefore, the adiabatic approximation can be regarded as an effective tool for reconstructing and interpreting the neutron noise in MSR.

1. Introduction

The neutron noise, i.e. the difference between the time-dependent neutron flux and its time-averaged value assuming all the processes are stationary and ergodic in time, has been investigated for decades since the early works made in 1970s (Kosály and Williams, 1971). The main interest on the neutron noise stems from the fact that its spatial distribution contains useful information which can be used for the reactor diagnostic purpose. Namely, by analyzing the space dependence of the noise amplitude or/and phase, the type of the noise source (or the perturbation) can be identified and its position can be localized (Demazière and Andhill, 2005). Previous studies on the neutron noise were mainly carried out by Department of Nuclear Engineering, Chalmers University of Technology and focused on the cases of traditional reactors using solid fuels (e.g. Pressurized Water Reactors (PWRs)). Both the forward and backward approaches, i.e. calculating the neutron noise induced by a known noise source and unfolding the noise source from a few detector readings, have been studied in details with the help of the reactor transfer function technique (Demazière, 2004; Pázsit and Demazière, 2010; Demazière et al., 2015). Unlike the traditional reactor, the fuel used in the molten salt reactor (MSR) is dissolved in the coolant and can thus circulate throughout the primary loop. The fuel recirculation partly leads to the loss of delayed neutrons because a certain amount of precursors leaved out the core decay outside, and partly results in the stronger neutronic coupling by transporting the precursors from the place of their generation to the place where they decay (Pázsit and Jonsson, 2011). As a result, the neutron noise in MSR is expected to be much stronger and behave in a more complicated way than that in the corresponding traditional reactor following the same perturbation. Moreover, the time-dependent perturbation can lead to the time-dependent neutron noise, thus several dynamic behavior of MSR can be obtained by analyzing the neutron noise. The calculation can also be simplified because the

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neutron noise is merely dependent on the static distributions and a specific perturbation. Thus there is no need to perform a complete, new calculation of the perturbed system (Wang et al., 2013, 2014; Zhang et al., 2015; Liu et al., 2016).

Researches on the neutron noise in MSR were started in recent years especially after MSR was selected as one of the six candidates for the Generation IV reactors (GIF, 2002). Similar to the traditional reactor cases, most of previous works on the neutron noise in MSR were performed by Department of Nuclear Engineering, Chalmers University of Technology. The main efforts were devoted to the new features induced by the fuel recirculation in a simplified one-dimensional (1D) bare homogeneous system. At the beginning, the neutron noise induced by a stationary propagating perturbation was investigated in one-group diffusion theory (Pázsit and Jonsson, 2011). Considering the fact that one-group theory is not proper for the noise problems induced by perturbations such as the localized boiling, Jonsson and Pázsit (2011) extended the investigation in two-group diffusion theory, the effects of different neutron spectral properties were also analyzed. In these two works, the perturbation was assumed as the fluctuation of only the absorption cross section. The effects of fluctuations of other cross sections and fuel salt velocity, and their interactions were also studied (Dykin and Pázsit, 2014). However, as indicated in the traditional reactor case, the results obtained in the 1D system will underestimate the space-dependent effect, which is more prominent in the 2D and 3D systems (Demazière, 2004). Therefore, in order to get more realistic picture of the neutron noise, calculations should be carried out in the full-size MSR system. Such work has been carried out recently in a 3D bare homogeneous MSR based on one-group diffusion theory (Wang and Cao, 2015).

In one-group diffusion theory, the neutron noise can be splitted into the point kinetic and space-dependent terms (Pázsit and Dykin, 2010; Pázsit and Demazière, 2010), accounting for the reactivity effect and the non-uniform spatial distribution of the perturbation, separately. In small tightly-coupled reactors, the point kinetic term is dominated whereas the effect of space-dependent term is negligible. However, due to the larger deviation from point kinetics in power reactor, the contribution of the space-dependent term on the total noise becomes more significant. Although both the point kinetic and space-dependent terms are smooth functions of space, their interference leads to the spatial oscillation of the amplitude of the total neutron noise, making the possibility of using the space dependence of neutron noise for the reactor diagnostic purpose. For traditional reactors, the interference between these two terms has been studied in details (Kosály et al., 1977; Pázsit and Dykin, 2010). It is found that these two terms are independent of each other and can be determined by using only the static distributions and the specific perturbation, the distribution of the total neutron noise is not needed. This brings great convenience to interpret the interference between these two terms and make better understanding of the behavior of the total neutron noise. For MSR, the attempt of deriving the point kinetic equations has also been performed recently (Pázsit et al., 2014; Dykin and Pázsit, 2014). The results show that because of the fuel recirculation, the point kinetic term of neutron noise in MSR still contains some unknown shape functions (i.e. the space-dependent terms of noise). Therefore, to obtain the exact solutions of these two terms, the distribution of the total noise must be first determined and the calculation will be more complicated. To overcome this disadvantage, some approximation methods should be taken into account.

In practical noise problem, only the lowest order approximations, i.e. the point kinetic and adiabatic approximations, are used. In the point kinetic approximation, only the contributions of the point kinetic terms are considered, the space-dependent effect is regarded as unimportant and correspondingly the space-dependent terms are neglected. This approximation has been proven to be appropriate in the cases of low frequencies or small tightly-coupled cores. However, as the frequency increases or in power reactors, the effect of the space-dependent term becomes more significant and even dominant. Moreover, differing from the traditional reactor case, if the space-dependent terms are neglected, even the exact point kinetic terms in MSR cannot be obtained (Pázsit et al., 2014). Therefore, the space-dependent terms play more important roles of the total noise in MSR than in the corresponding traditional reactor. In order to estimate the space-dependent terms, the adiabatic approximation can be applied, in which the equations for the space-dependent terms are artificially decoupled from those for the point kinetic terms. Thus both of these two terms and their interference can be obtained, which makes us a better understanding of the behavior of the total noise. Another benefit of the adiabatic approximation is that the neutron noise can be easily estimated by slightly modifying the static codes (Kosály et al., 1977). This is very convenient especially for the reactor cores with complex geometric structure. Although the neutron noise obtained in better approximations, such as the quasistatic approximation, is more accurate, the equations for the point kinetic and space-dependent terms remain coupled, and the solution of the latter is rather complicated. Thus the solutions cannot be interpreted intuitively as those of the adiabatic approximation (Pázsit and Demazière, 2010).

Therefore, the purpose of this paper is to study the applicability of the adiabatic approximation on the neutron noise analysis in MSR. The structure of this paper is as following. At the beginning, the neutronic model considering the fuel recirculation is established relying on one-group neutron diffusion theory. Next, the equations for fluctuations are derived based on linear perturbation theory, in the assumption that the perturbation is much smaller than the static value. Then, following the standard procedure stated in the previous work (Pázsit et al., 2014), the kinetic equations for the fluctuations of amplitude factors are derived. The unknown fluctuations of shape functions, i.e. the space-dependent terms of noise, are estimated by means of the adiabatic approximation. All the space-dependent equations are solved by developing a code, in which the eigenfunction expansion method is used. Finally, the applicability of the adiabatic approximation is analyzed in details by comparing the neutron noise and its two terms to the exact solutions and those obtained in the point kinetic approximation.

2. Theoretical models

It is known that the primary difference between MSR and traditional reactor is caused by the fuel recirculation. When neglecting the perturbance effect, it has been noticed that there is no difference between the 1D and 3D systems from the view of fuel recirculation (Wang and Cao, 2015). Thus the MSR in the present work is simplified as a 1D bare homogeneous system, i.e. the thermal feedback is also neglected. The one-phase molten salt, acting as both the fuel and coolant, flows along the axial z direction from the core inlet $z = 0$ to the outlet $z = H$, and then returns to the core inlet through the external pipe of length L. Assuming the velocity to u, the time for recirculation will be $\tau = (H + L)/u$, and the time for passing through the external pipe will be $\tau_L = L/u$. The basic design parameters of the MSR model are listed in Table 1.

2.1. General theory

Neutron diffusion theory has been proven fully sufficient for most practical noise problems (Pázsit and Demazière, 2010). Thus in this paper, the neutron kinetic model is established based on