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Comparison of different neutronics analysis technique for Accelerator-Driven System

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ABSTRACT

For the much detailed study of the beam transients on an Accelerator-Driven System (ADS), the 3-dimensional deterministic transport calculation mode for ADS dynamics calculation code is developed. The transport calculation mode is validated by the comparison with the benchmark problem published by OECD/NEA. The transport calculation and the diffusion calculation are compared by analyzing the ADS core with the use of the 3-dimensional deterministic transport calculation modes and the diffusion calculation mode equipped with ADS dynamic calculation code to reveal the effect of the transport calculation. As a result, the transport calculations show the larger fluxes than those by the diffusion calculation. The strong anisotropic fluxes are found to yield the significant effect on the flux calculations, and the influence of the anisotropy is increased by the abnormal beam condition. Therefore, the application of the transport calculation is very important for the precise evaluation of an ADS.

1. Introduction

An Accelerator-Driven System (ADS) has been studied with the aim of the reduction of the high-level radioactive wastes such as a minor actinide (MA) and a long-lived fission product (LLFP). An ADS is the innovative reactor system and is composed of a high-intensity proton accelerator, a spallation target and a sub-critical core. The use of a sub-critical core enables ADS to have high safety margin for the reactivity accident and the high transmutation efficiency of Mas and LLFPs compared to the conventional critical reactors. Since the power of an ADS is controlled by the operation of an accelerator, the instantaneous shutdown of a system is also possible. There are many R&D topics for the development of an ADS. In the field of the reactor physics, almost the experimental facilities using the spallation neutron source are under contemplation or construction, and the analyses by conventional codes have been mainly performed for the system using the spallation source. Some studies reported the analysis results of the accident events like unprotected loss-of-flow (ULOF) and the beam over power (BOP). The beam transients, which are defined as the variation of a beam shape and beam incident position with the stable beam power in this paper, are peculiar event in ADS because an ADS is controlled by an accelerator operation. However, there has been no reports of the beam transients because the conventional codes cannot treat the dynamic calculation of the variation of beam parameters.

ADS dynamic calculation code ADSE had been developed (Sugawara et al., 2006; Suzuki et al., 2009) to analyze the dynamic change of the beam profiles such as the variations of the beam shape and the position, a beam power increase and so on. ADSE consisted of the neutronics calculation module and the thermohydraulics calculation module, and the neutronics calculation module had three calculation modes: the diffusion calculation (DSE-C), the transport calculation by Monte Carlo code (DSE-M) and the transport calculation by 2-dimensional deterministic code (DSE-T). However, their modes had each problem; DSE-C cannot precisely treat the anisotropy of flux due to the diffusion theory and its computational grid was coarse, DSE-M took very long time in its execution, and DSE-T was unable to calculate an asymmetric beam distribution such as the case of the beam incident position change. For the detailed study of the beam transients, such calculation capabilities as the 3-dimentional transport calculation in a short execution time were desired.

In this study, the transport calculation mode by 3-dimensional deterministic transport code (DSE-3T) was developed for the much detailed analyses of the beam transients. In Section 2, the outlines of the development and the validation of DSE-3T were described. Then, Section 3 was aimed at revealing the difference of the calculation results in the diffusion and transport calculations and the effect of the transport calculation by the application of the newly-developed DSE-3T and the other calculation modes DSE-C and DSE-T. This study was summarized in Section 4.

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2. Development of 3-dimentional deterministic transport calculation mode

2.1. Review of neutronics calculation of ADS dynamic calculation code

Fig. 1 showed the calculation flow of the neutronics calculation module of ADSE. The neutron flux was calculated on the basis of the databases of the spallation neutron source and the temperature dependent macro cross section. The high energy particle transport problem was calculated by using PHITS (Iwase et al., 2002) and then, the database of the spallation neutron source was constructed. The database of the cross section was made on the basis of the SRAC (Okumura et al., 2007) calculations. Their calculations were based on the JENDL library. ADSE calculated the time–space dependent neutron flux by the use of these databases and the application of the quasi-static scheme. The flux was represented as the product of the shape function and the amplitude function as $\Phi(r, t) = \varphi(t)\cdot\psi(r, t)$. By the application of the quasi-static scheme to the neutron transport equation and the equation of the equilibrium of the precursor, the equations were transformed and the neutron flux was derived. The procedures of the transformation of the equations and the deviation of respective functions were well-described in the past study (Sugawara et al., 2006). ADSE calculated the shape function first, and then the adjoint function. The amplitude function was calculated on the basis of the parameters such as the effective neutron lifetime, the effective delayed neutron fraction rates and so on which derived from the previous calculation results. The parameters employed in the calculation of the amplitude function were calculated at each time step on the basis of the results of the shape function. The neutron flux was normalized by the thermal power of an ADS on the normal condition of the beam profiles. DSE-C, DSE-T and DSE-M were available in the calculation of the shape function and the adjoint function. DSE-C and DSE-M employed hexagonal computational grid and the grid was corresponding to the fuel assemblies. DSE-T employed the cylindrical computational grid and the size of the grid was variable. In this study, the transport calculation mode by 3-dimensional deterministic transport code, DSE-3T, was newly developed in the calculation of the shape function and the adjoint function.

2.2. Development of DSE-3T

The deterministic S_N transport code THREEDANT (Los Alamos National Laboratory, 1995) was introduced for 3-dimensional deterministic transport calculation mode. THREEDANT can solve the 3-dimensional transport equation in x–y–z and r–z–θ computational grid in arbitrary size. In addition, THREEDANT can treat the calculation of the adjoint function. In the neutronics calculation module, THREEDANT was employed in the calculations of the shape function and the adjoint calculation as the same as other calculation modes. R–z–θ computational grid was adopted in this calculation mode since ADS core was mostly composed by hexagonal assemblies and it was difficult to describe the core by using x–y–z computational grid. The arbitrary size of the grid was available in ADSE, and the maximum S_N order was set to 8 due to the capability of ADSE.

2.3. Validation of DSE-3T

The 3-dimensional deterministic transport mode DSE-3T was validated by the comparison with the benchmark problem (OECD/NEA, 2001). This benchmark problem was intended to the lead–bismuth-cooled subcritical system driven by 1 GeV proton beam which loads MA and plutonium mixed nitride fuel. The calculation model of the core was shown in Fig. 2. The detailed core specifications referred to the benchmark problem. Seven organizations contributed to this benchmark exercise, and analyzed with employing the respective deterministic transport and Monte Carlo calculation codes. The results of CIEMAT and JAERI, based on the nuclear data library JENDL-3.2, were compared with DSE-3T. Many subjects were calculated in the benchmark, and in this validation, the k_{eff} and the neutron flux distributions at the beginning of life of the start-up core and the equilibrium core were compared.

The k_{eff} of DSE-3T at the start-up core was almost the same as JAERI's result, and at the equilibrium core, that was between the results of JAERI and CIEMAT as shown in Table 1. The differences seen in the k_{eff} were assumed to result from the calculation method of the cross section. The neutron flux distributions at the start-up core were shown in Figs. 3–5 as one example of the flux distributions. The radial distribution at the mid-plane (Z = 100 cm) and the axial distributions at the center of the target region (R = 0 cm) and the fuel region (R = 56 cm) were compared at each core. On the whole, the shapes of the distributions were similar, and the fluxes of DSE-3T almost ranged between the results of two benchmarks. The relatively large disagreements were seen in the reflector regions of each distribution and the axial distributions at the target. Some differences were over 10%, but the difference in the reflector region were caused by the erratic readings since the

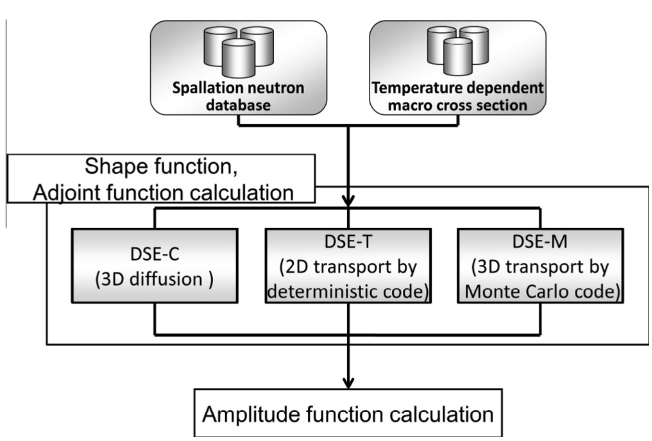

Fig. 1. Calculation flow of neutronics calculation module of ADSE.

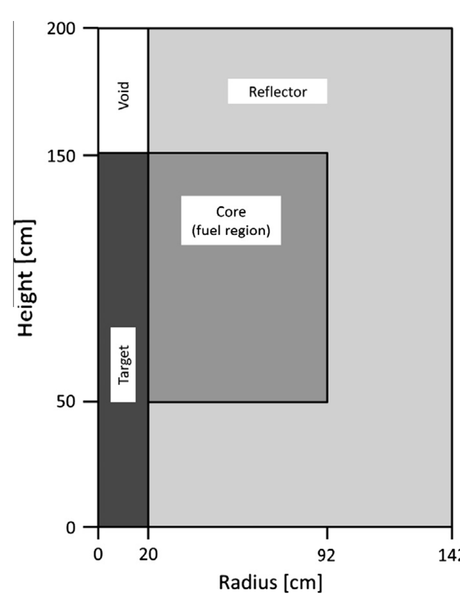

Fig. 2. Calculation model of benchmark problem.