Development of Advanced Dynamic Calculation Code for Accelerator Driven System

M. Suzuki [1], T. Iwasaki [1], N. Aizawa [1], T. Sato [1], T. Sugawara [2]

[1] Tohoku University, Japan
[2] Japan Atomic Energy Agency, Japan

Email contact of corresponding author: naoto_aizawa021@neutron.qse.tohoku.ac.jp

Abstract: ADSE (Advanced DSE) was developed by improving DSE (Dynamics calculation code system for Sub-critical system with External neutron source) for studying the dynamics of ADS (Accelerator Driven System). For the neutronics calculation module, the transport codes were introduced instead of the diffusion one to consider the angular distributions of neutron flux. The recalculation function of the adjoint flux was also introduced and the database of external neutron source was improved for three-dimensional system. In addition, the numbers of the geometrical mesh and the energy-group were extended. The thermal-hydraulics calculation module introduced the databases of the temperature correlations for the thermal properties of fuels, claddings and coolant based on latest studies. For the neutronics calculation module, the calculations by ADSE were compared with the experimental results at KUCA (Kyoto University Critical Assembly) and TRACY (TRAnsient experiment Critical facilitY). In the thermal-hydraulics calculation module, the calculations by ADSE and SIMMER-III were compared. As the result, the calculations by ADSE agreed with the every comparison data. ADSE has been developed appropriately and it is useful for the study of the ADS dynamics.

1. Introduction

DSE (Dynamics calculation code system for Sub-critical system with External neutron source) was developed for calculating the dynamics of ADS (Accelerator Driven System) [1]. DSE consists of a neutronics calculation module and a thermal-hydraulics calculation module to calculate the time variations of the thermal power, the neutron flux and the temperatures of fuel, cladding and coolant. The code can calculate those by treating directly the changes of accelerator parameters such as a beam energy, intensity and diameter. In this study, the development of ADSE (Advanced DSE) is conducted to improving DSE for studying the ADS dynamics in detail. In the following, Chapter 2 reviews DSE. Chapter 3 and 4 describes the activities for improving the neutronics and the thermal-hydraulics module respectively. Chapter 5 summarizes this paper.

2. Review of DSE

2.1 Neutronics calculation module

In DSE, the neutronics calculation module solves the time-space dependent neutron diffusion equation by employing the quasi-static scheme. Since DSE is based on the diffusion theory, the neutron flux is treated isotropically. But the neutron flux in ADS has strong anisotropy. The transport theory is required for ADS to calculate the behavior of neutron precisely.

Although DSE adopts the three-dimensional hexagonal mesh, the maximum mesh number is currently limited. It is available to analyze a particular core, but it is not sufficient enough to evaluate a large core. The maximum mesh number should be extended.

There was a problem that DSE does not recalculate the adjoint flux in the dynamic calculation. This method is reasonable for calculating the transient which the neutron flux distribution does not largely change. However, it is not proper to calculate the transient accompanied with the large variation of neutron flux distribution. It is necessary to recalculate the adjoint flux in the transient.

DSE calculate the transport of the high energy particles by using PHITS [2]. A database of the external neutron source is edited and is supplied to the diffusion calculation. In PHITS calculation, the geometrical treatment is limited to the two-dimensional cylindrical system. It is necessary to adopt the three-dimensional treatment for analyzing the variation of the beam incident position.

The diffusion equation is supposed with the three energy-groups cross sections, which is calculated by SRAC [3]. Three energy-groups are enough to calculate the dynamic behavior of the ADS core. However, the number of the energy-group had better be increased for studying the dynamics precisely.

2.2 Thermal-hydraulics calculation module

The thermal-hydraulics calculation module employs a single fuel pin model, which is corresponding to each assembly in the neutronics calculation. This model is similar to that of SAS1A [4]. This module can calculate the temperatures and the coolant flow with single-phase flow treatment and can consider Lead-Bismuth Eutectic (LBE) as coolant.

The temperatures are calculated by solving the heat equation by Gauss elimination method. In the current DSE, the temperature correlations are adopted in some thermo-physical properties of coolant. On the other hand, the properties of fuel and cladding are not correlated in temperature. It is desirable to introduce the temperature correlations for the properties of fuel and the cladding. Since DSE requires the gap conductance by user, it is also desirable to prepare the database of it.

The hydraulics module solves the equations of continuity, momentum and energy. In the current DSE, Nusselt number of LBE coolant for the heat transfer coefficient is obtained based on the correlation related to Reynolds number, Plandtl number, etc. However, the flow state is not considered in this correlation. It is advisable that Nusselt number is determined by the correlation which is based on some experiments about flow.

3. Improvement and Validation of Neutronics calculation module

3.1 Improvement of Neutronics calculation module

The problems mentioned above were improved by the following methods:

- The introductions of the transport code
  - DANTSYS (TWODANT) [5] (DSE-T)
  - GMVP [6] for fine-calculation (DSE-M)
- The extension of the maximum mesh number
- The introduction of the adjoint flux recalculation
- The expansion of external neutron source database to three-dimensional system
- The increase of the energy-group number

3.2 Validation of Neutronics calculation module

For the verification of the module, it is indispensable to validate both the statics and the dynamics calculation. The calculation results were compared with a statics experiments at KUCA (Kyoto University Critical Assembly) [7] and a dynamic experiment at TRACY (TRAnsient experiment Critical facilitY) [8].

3.2.1 Experiment at KUCA

This experiment using KUCA (Fig.3.1) measured the sub-criticalities for several cores with different control insertions and the distributions of the reactivity worth of six control rods [7]. For this experiment, the calculations were conducted by DSE-M.

The results about the k_{eff} are shown in Table3.1. The results of control rod worth are given in Table3.2. The k_{eff} show good agreements at the every case. The control rod worth agrees well although the case C_2 & S_4 had a little difference. It is supposed that this difference of the C_2 & S_4 results from the statistical fluctuation of Monte Carlo method. These results confirm the accuracy of the statics calculation for the neutron flux distribution by ADSE.

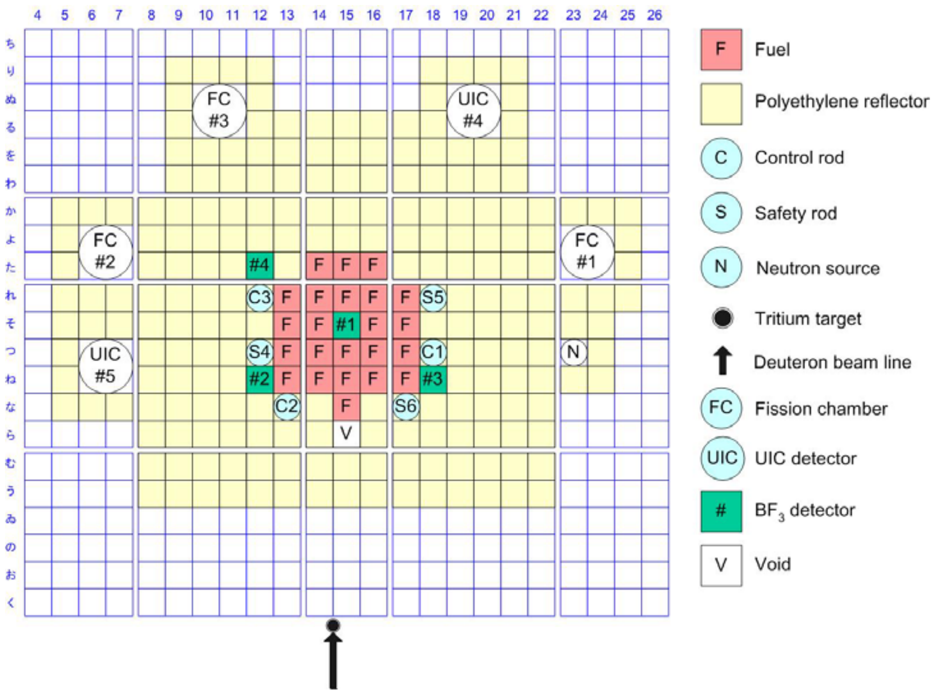


Fig.3.1 Core design of KUCA

Table 3.1 k_{eff} between experiment and calculation

Inserted CR or SR	Experiment	Calculation	C/E
C_1,C_2	0.995	0.995	1.000
C_1~C_3	0.992	0.990	0.998
C_1,C_2,S_4	0.991	0.989	0.998
C_1~C_2,S_5,S_6	0.985	0.983	0.997
C_1~C_3,S_4,~S_6	0.981	0.977	0.996

Table 3.2 rod worth between experiment and calculation

CR or SR	Experiment	Calculation	C/E
C_1,S_4	0.493	0.531	1.077
C_2,S_5	0.344	0.386	1.123
C_3,S_6	0.370	0.387	1.046

3.2.2 Experiment at TRACY

TRACY is the tank type core with fuel solution. For the core, the reactivity can be inserted by the quick driving of a Transient rod. The external neutron source called Pulsatron is available. For the verification of the dynamic calculation, we analyzed a dynamic experiment by TRACY. In the experiment adopted in this study, first the Pulsatron was operated, and then the positive reactivity was inserted by withdrawing the Transient rod. Finally, the Pulsatron was shut down and the experiment was finished. The details are presented in Table3.3 [8]. Three neutron detectors were set around the core and measured the time variation of neutron counts. DSE-T analyzed the power transient of this experiment.

The results are shown in Fig.3.2. The detectors CH-1 and CH-2 show the same relative variation although the detector CH-3 behaves differently since CH-3 was located to the reflector region at the core top. The calculation results show good agreements of the variation of CH-1 and CH-2. From this result, it is confirmed that the dynamics calculation of ADSE is verified.

Table 3.3 Operation flow of experiment

Time [sec]	Tr-rod	Subcriticality	Pulsatron
Initial conditions	DOWN	-3.1$	OFF
0			
10			ON
80	Up (Pulse withdraw)	-1.4$	
100			OFF

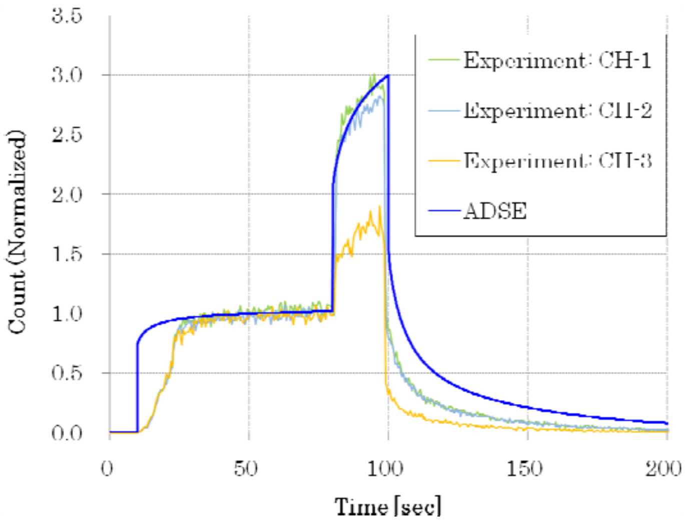


Fig. 3.2Experiment and calculation results

4. Improvement and Validation of Thermal-hydraulics calculation module

4.1 Improvement of thermal-hydraulics calculation module

Latest literatures were investigated to obtain the temperature correlations of the thermo-physical properties for the fuel, cladding and coolant. Based on these literatures, the followings were introduced for the databases of the properties:

- Properties of fuels [9], [10], [11], [12]
    - UN, PuN, NpN, AmN, $(U_{0.8}Pu_{0.2})N$
- Properties of claddings [13], [14], [15], [16]
    - SUS304, SUS316, Mod.9Cr-1Mo, CDS9Cr, ODS12Cr
- Properties of coolant [17]
    - Lead-bismuth Eutectic(LBE) (updated by the latest study)

For Nusselt number, the following correlations were included:

- Subbotin's equation [13]
- equation by Sleicher [18]
- correlation equation by FFTF-CRRP [10]

For the gap conductance, the followings were incorporated:

- the equation by [19]
- default value of SIMMER [20]

4.2 Validation of thermal-hydraulics calculation module

Thermal-hydraulics calculation module also requires the validations for the statics and the dynamics calculation. The statics calculation of ADSE was examined by comparing with the theoretical solution. For the dynamics calculation, the comparison of the calculation results between ADSE and SIMMER-III was conducted.

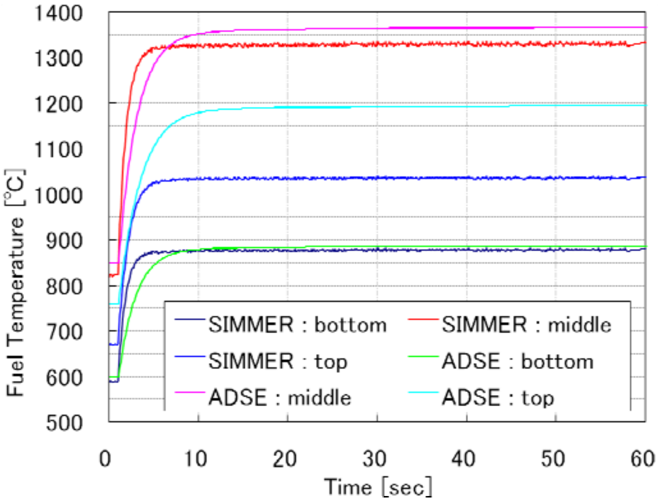
4.2.1 Comparison with theoretical solution

Both the theoretical and ADSE calculation were performed for a typical fuel pin cell in ADS. The temperature distributions at fuel, cladding and coolant are well agreed. We consider that the statics calculation of the thermal-hydraulics is valid.

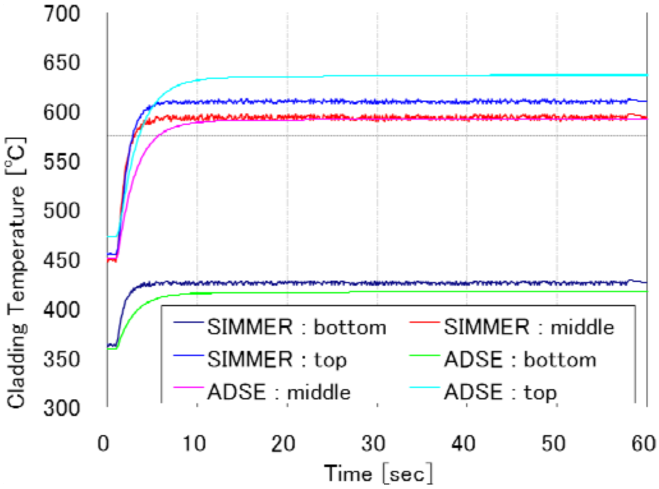
4.2.2 Comparison with SIMMER-III

A UBOP (Unprotected Beam Over Power) transient of ADS was calculated by SIMMER-III [21] and ADSE. The temperature variations in the transient were compared here. Although SIMMER-III considers the behavior of the ductless flow channel, ADSE is not available to treat that. ADSE assumes the behaviors of flow as one-dimensionally in the respective assemblies in this calculation. The next paragraph describes the results of the transients at the core bottom and the middle. The transient result at the top refers to “Discussion”.

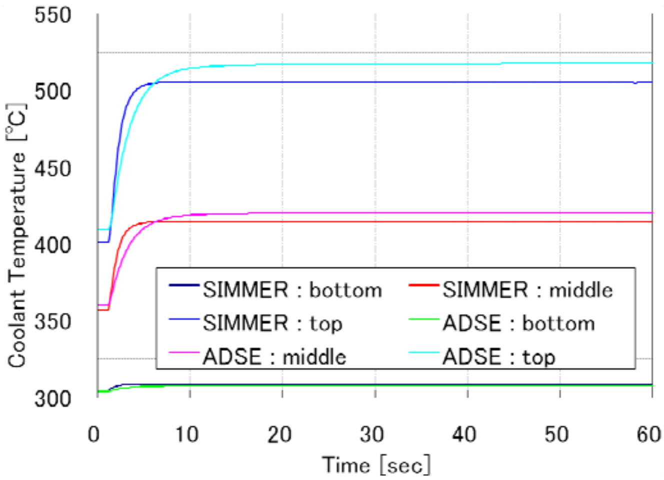
The calculation result of fuel is shown in Fig.4.1 (a), cladding in (b) and coolant in (c). At the core bottom and the middle, the temperatures show good agreements, but small differences are observed. The differences are supposed to be caused by the differences of thermo-physical properties between the two codes. It is considered that the dynamic calculation of the thermal-hydraulics module of ADSE is verified.



(a) fuel



(b) cladding



(c) coolant

Fig.4.1 Comparison of temperature variation between SIMMER and ADSE

4.2.3 Discussion

Large differences are observed in temperatures at the core top. The differences are supposed to result in the treatment of the ductless channel which causes strong mixing of flows at the core top. Therefore, it is considered that the large differences at the top resulted from the difference of the models in the codes. The development of the thermal-hydraulics calculation model for with the ductless core model is an issue in the future study.

5. Summary

The development of ADSE (Advanced DSE) was conducted by improving DSE for the study of ADS dynamics in detail.

The transport codes (TWODANT and GMVP) were introduced instead of the diffusion code. The function of the recalculation of the adjoint flux was introduced. The database of external neutron source was improved for three-dimensional system. The numbers of the geometrical mesh and the energy-group were extended. The calculation results by the neutronics calculation module of ADSE were verified by the experimental results at KUCA and TRACY.

The latest literatures were investigated and the databases of thermal-physical properties were introduced. The calculations by ADSE were compared with the theoretical solution and the calculation results by SIMMER-III for validating the thermal-hydraulics calculation module with the database. From these comparisons, the thermal-hydraulics calculation module was confirmed to be validated.

It can be concluded that ADSE was developed adequately and it is useful for the study of the ADS.

References

[1] T. Sugawara, "Development of Dynamics Code and Study of Operation Control for Accelerator Driven System", PhD Thesis, Tohoku Univ., (2005)
[2] H. Iwase, K. Nitta, T. Chiba, K. Nishihara, "Development of general purpose particle and heavy ion transport Monte Carlo code", J. Nucl. Sci. Technol., 39[11], 1142, (2002)
[3] K. Okumura, T. KUGO, K. Kaneko, K. Tsuchihashi, "SRAC2006: A Comprehensive Neutronics Calculation Code System", JAEA-Data/Code 2007-004, Japan Atomic Energy Agency, (2007)
[4] J.C. Carter, et al., "SAS1A, A Computer Code for the Analysis of Fast-Reactor Power and Flow Transients", ANL-7607, (1970)
[5] R. E. Alcouffe, R. S. Baker, F. W. Brinkley, et al., "DANTSYS: A Diffusion Accelerated Neutral Particle Transport Code System", LA-12969-M, Los Alamos National Laboratory, USA, (1995)
[6] Y. Nagaya, et al., "MVP/GMVP II: General Purpose Monte Carlo Codes for Neutron and Photon Transport Calculations based on Continuous Energy and Multigroup Methods", JAERI-Report 1348, Japan Atomic Energy Research Institute, (2005)
[7] K. Taguchi, "Experimental Study of Subcriticality Measurement based on Rossi-alpha Method for Accelerator Driven System" Master Thesis, Nagoya Univ., (2005)
[8] S. Gunji, "Study of accelerator transient on ADS operation using TRACY (TRAnsient experiment Critical facility)", Master Thesis, Tohoku Univ., (2004)
[9] Hj. Matzke, "Science of advanced LMFBR fuels: solid state physics, chemistry, and technology of carbides, nitrides, and carbonitrides of uranium and plutonium", North-Holland, (1986)
[10] M. Hori, "Fundamental Engineering of Fast Reactor", Power Reactor and Nuclear Fuel Development Corporation, (1993)
[11] Masahide Takano, et al. "Lattice thermal expansion of NpN, PuN, and AmN", Journal of Nuclear Materials, 376, 114-118, (2008)
[12] Japan Atomic Energy Research Institute, Review of Actinide Nitride Properties with Focus on Safety Aspects, JAERI -Review2001-040, (2001)
[13] The Japan Society of Mechanical Engineers, JSME Data Book: Heat Transfer 4th Edition, (1986)
[14] K. Yamashita, et al., "Welding Consumables of High Cr Ferritic Heat Resisting Steels for Fossil Fuel Power Boilers" Kobe Steel Engineering Reports, Vol.53, No.2, (2003)
[15] Japan Nuclear Cycle Development Institute, "The Tentative Materials Strength Standard of ODS Ferritic Steel Claddings (Research Report)", JNC-TN9400 2005-015, (2005)
[16] ASME, ASME Boiler and Pressure Vessel Code 1992 Edition Section Ⅱ Materials D-Properties, (1992)
[17] OECD/NEA, Handbook on Lead-bismuth Eutectic alloy and Lead Properties, Materials compatibility, Thermo-hydraulics and Technologies, NEA No.6195, (2007)
[18] C. A. Sleicher, A. S. Awad, and R. H. Notter, "Temperature and Eddy Diffusivity Profiles in NaK", Int. Journal of Mass Transfer, Vol.16, pp.1565-1575, (1973)
[19] Japan Atomic Energy Agency, Feasibility Study on Commercialized Fast Reactor Cycle Systems Technical Study Report of Phase II –(1) Fast Reactor Plant Systems-, JAEA-Research 2006-042, (2006)
[20] SIMMER-III: A Computer Program for LMFR Core Disruptive Accident Analysis, JNC-TN9400 2001-002, Japan Nuclear Cycle Development Institute, (2000)
[21] Takanori Sugawara, et al., "Feasibility Study of Accelerator Driven System Proposed by JAEA", Proc. of GLOBAL2007, Boise, Idaho, Sep. 9-13, 2007