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Evaluation of The IAEA 2D PWR Benchmark Problem Using TRIVAC and OpenMOC Codes

CHETAINE Abdelouahed[1], JALIL Abdelhamid[1], KABACH Ouadie[1], DARIF Abdelaziz[1], SAIDI Abdelmajid[1], BENCHRIF Abdelfettah[2] and AMSIL Hamid[2]

[1)] Mohammed V University, Faculty of Science, Nuclear Reactor and Nuclear Security Group Energy Centre, Physics Department, 4 Avenue Ibn Battouta B.P. 1014 RP, Rabat 10000, Morocco

[2)] National Centre of Sciences, Energy and Nuclear Techniques (CNESTEN/CENM), POB 1382, Rabat, Morocco

Abstract

For determining the effective multiplication factor (k_{eff}) and the flux distribution in a given reactor (*very important task for fuel assembly design and whole core safety analysis*), the finite element spherical harmonics (SP_N) and the method of characteristics (MOC) are a widely used. The aim of this work is to qualify the numerical methods and algorithms implemented in (TRIVAC/OpenMOC) codes using the classic 2D IAEA PWR benchmark problem. The results of the two codes for k_{eff} value and flux map distribution are compared with each other.

Keywords: Finite element spherical harmonics, method of characteristics, TRIVAC, OpenMOC, effective multiplication factor, power distribution, 2D IAEA benchmark.

1. Introduction

The aim of this study is to qualify the numerical methods and algorithms implemented in TRIVAC **[1]** code based on the Finite Element and OpenMOC **[2]** code based on the method of characteristics. The Finite Element Method implemented in TRIVAC can be employed for arbitrary geometry. In this paper, we present TRIVAC diffusion theory (SP_1) **[3]** approximation to the neutron transport equation and spherical harmonic transport theory solutions (SP_3–SP_{11}). The adequate spatial mesh calculations are also used. For OpenMOC calculation, the method of characteristics is used to solve the transport equation in 2D by discretizing both polar and azimuthal angles and integrating the characteristic form of the equation for a particular azimuthal and polar angle quadrature.

2. Description of IAEA 2D PWR Benchmark [4]

The 2D IAEA Benchmark Problem has been discussed in several publications. The IAEA 2D light water reactor benchmark problem has been very important standard benchmark problem to measure the performance of the methods of the neutronics calculations. The main purpose of the problem is to benchmark computer codes by calculating the core multiplication factor, flux and power distributions using the two-group neutron diffusion method. The core configuration being shown in **Figure 1** consists of 177 fuel assemblies including 9 fully rodded fuel assemblies and 4 partially rodded fuel assemblies composing the core, with 15 fuel assemblies across the core major axis. The partially controlled region covers top 80 cm of the active core height. The core contains 64 reflector assemblies surround it. The fuel assembly pitch is 20 cm. The problem specifies two-group cross sections for two different fuel assemblies and reflector regions. Rodded cross sections are also given. The corresponding cross sections are given in **Table 1**. The purpose of this benchmark exercise is to calculate the core keff and power distribution using Finite element spherical harmonics (SP_N) and method of characteristics (MOC).

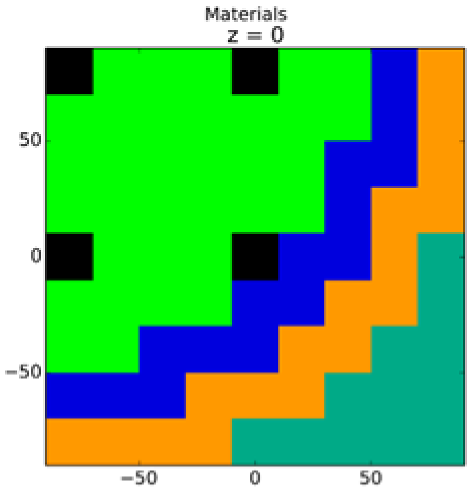

Figure 1. IAEA 2D PWR radial quarter core loading pattern

Table 1. IAEA 2D PWR two-group cross sections

Material		D_g	Σ_{ag}	$\nu\Sigma_{fg}$	$\Sigma_{g2\leftarrow1}$
	Fuel1	1,500	0,010	0,000	0,020
		0,400	0,085	0,135	
	Fuel1+Rod	1,500	0,010	0,000	0,020
		0,400	0,130	0,135	
	Fuel2	1,500	0,010	0,000	0,020
		0,400	0,080	0,135	
	Reflector	2,000	0,000	0,000	0,040
		0,300	0,010	0,000	

3. Calculation tools and methods

3.1. Presentation of the TRIVAC code

TRIVAC **[1]** is a determinist code (full-core-code) developed to the Ecole polytechnic of Montreal. The code is thus organized in modules (see **Figure 2**), and every module corresponding to a stage of calculation, for which we can choose various options (calculation methods, discretization etc.). These modules are explained below.

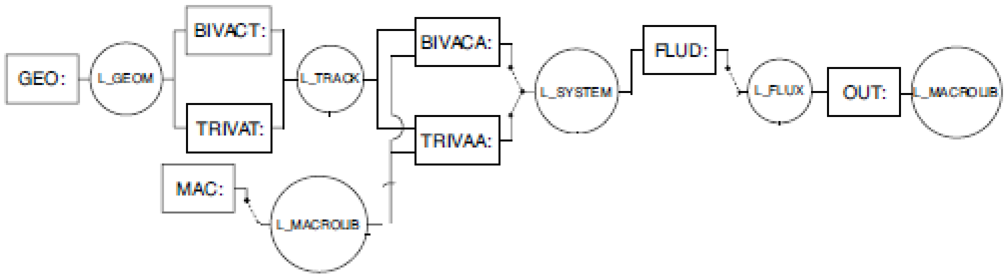

Figure 2. Flow chart of the OpenMOC code.

The **GEO:** module is used to create or modify a geometry, the **MAC:** module is used to read the macroscopic cross sections and the coefficients of diffusion, the **TRIVAT:** module is used to calculate the tracking for the typical geometries 1D / 2D / 3D with diffusion or SP_N methods, the **FLUD:** module is used to calculate the eigenvalue corresponding values in a set of matrices of systems and the **OUT:** module is used to calculate the rates of reaction and store them.

3.2. Presentation of the OpenMOC code [5]

OpenMOC has been developed as a general-purpose platform to deploy new numerical techniques and parallel algorithms - two of the primary drivers for improved compute performance of scientific codes. Solvers for a variety of platforms, including multi-core CPUs and massively parallel GPUs, are available in OpenMOC to exploit the increasingly heterogenous nature of present day as well as future computing hardware. OpenMOC has been developed using modern software development standards to enhance its value as a tool for research and collaboration. OpenMOC also provides the capability to subdivide pin cells into rings and angular sectors to better resolve the angular and radial flux and power gradients **(Figure 3)**.

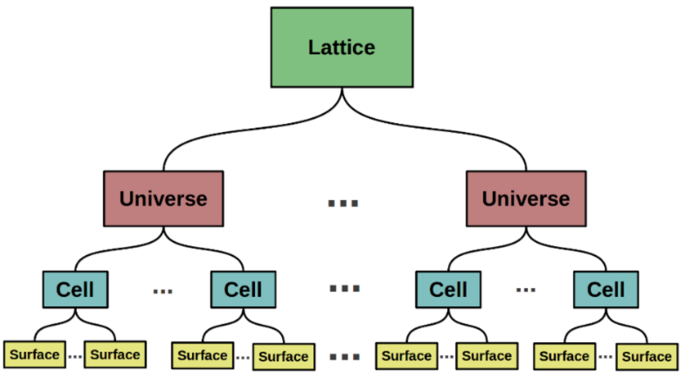

Figure 3. Flow chart of the OpenMOC code.

4. Results and analysis

A number of scenarios have been studied for the IAEA 2D benchmark problem. The TRIVAC results are presented and compared against those from OpenMOC.

4.1. Angular approximations effect on K_{eff}

A series of spherical harmonics SP_N calculations have been performed to represent the even parity angular flux in TRIVAC. When N = 1, the diffusion theory solution and for higher values of N transport theory approximations are generated (see Table 2 and Figure 4). It is shown that angular approximations equal to SP3 or SP5 being sufficient for obtaining a less differences in pcm between the two codes, but k_{eff} is not very sensitive to the values of N in general.

Table 2. Values of k_{eff} by varying the values of N.

	TRIVAC	OpenMOC	$(k_{eff(T)} - k_{eff(O)})/k_{eff(O)}$ (pcm)
	k_{eff}		-
SP1	1,015326	k_{eff} = 1,017294	-113,7331
SP3	1,016137		-113,4382
SP5	1,016140		-113,4382
SP9	1,016140		-113,5365
SP11	1,016139		-113,7331

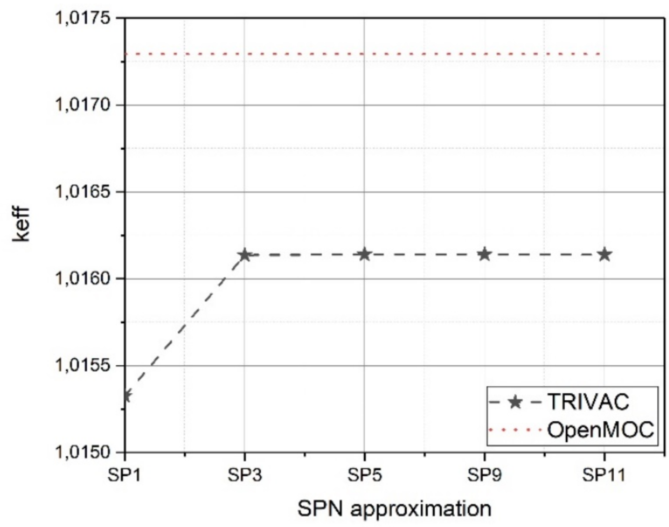

Figure 4. Variation of k_{eff} values according to values of N.

4.2. Special mesh effect on k_{eff}

In order to investigate the dependence of results on the Spatial mesh used, a series of calculations have been performed by varying mesh sizes for the IAEA 2D benchmark problem. The Spatial mesh was refined until the change in k_{eff} is insignificantly small.

The Spatial mesh solutions produced by the TRIVAC code of the benchmark eigenvalue problems are compared against OpenMOC. We can see from the Table 3 that the value of k_{eff} is very sensitive to number special mesh and the (2x2) special mesh shows a very good agreement with the OpenMoc result.

Table 3. Values of k_{eff} by varying the number of meshes.

	TRIVAC 5	OpenMOC	$(k_{eff(T)} - k_{eff(O)})/k_{eff(O)}$ (pcm)
Spatial Mesh (X*Y)	k_{eff}		-
1x1	1,016140	k_{eff} = 1,017294	-113,4382
2x2	1,017180		-11,3045
3x3	1,017414		11,5994
4x4	1,017484		18,3820

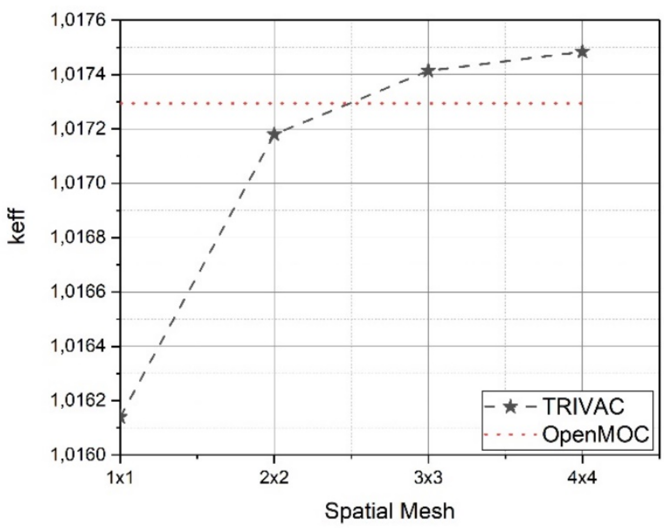

Figure 5. Variation of k_{eff} values according to the number of meshes

4.3. Neutron Flux Distribution:

The results of the neutron flux problem were evaluated using the two-energy group. Figures 3 and 4 show the total flux and thermal flux of whole core respectively based on fuel assembly-by assembly mesh flux maps calculations.

The obtained values for assembly flux distributions using TRIVAC code were performed for the 1/4 and 2x2 meshes per assembly and angular approximations equal to SP3. Table 4 shows the calculated values for assembly condensed flux distribution. Figures 6 and 7 show respectively the flux distribution for each assembly using TRIVAC and OpenMOC. We can see from these two figures that the assembly relative flux distributions agree well with each other.

Table 4. Condensed Flux Distribution For 2 Groups with TRIVAC

Group	Fuel 2	Fuel 1	Fuel + rod	Reflector
1	1,06E-03	2,17E-03	1,39E-03	9,82E-05
2	2,71E-04	5,08E-04	2,27E-04	3,05E-04

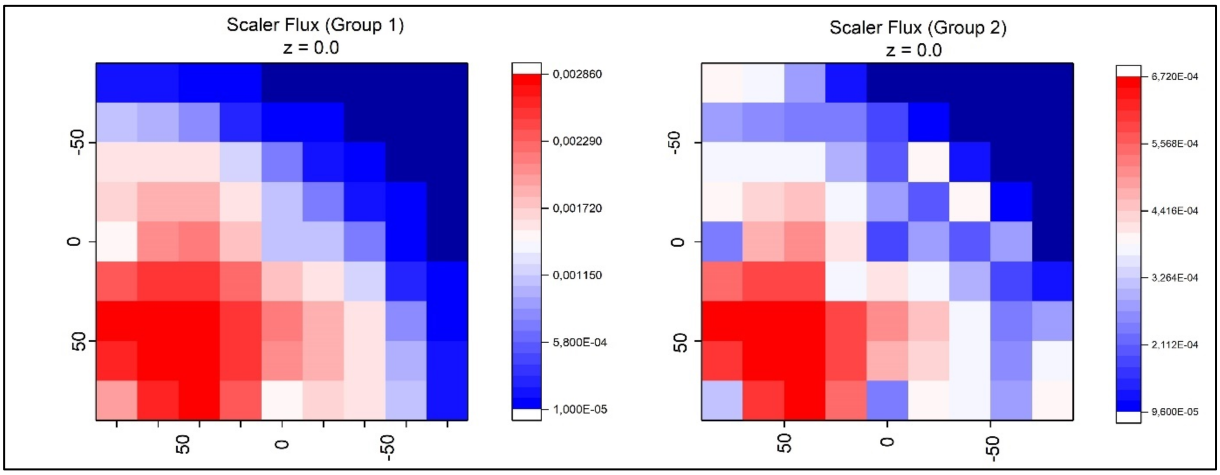

Figure 6. Flux Map Distribution For 2 Groups with TRIVAC

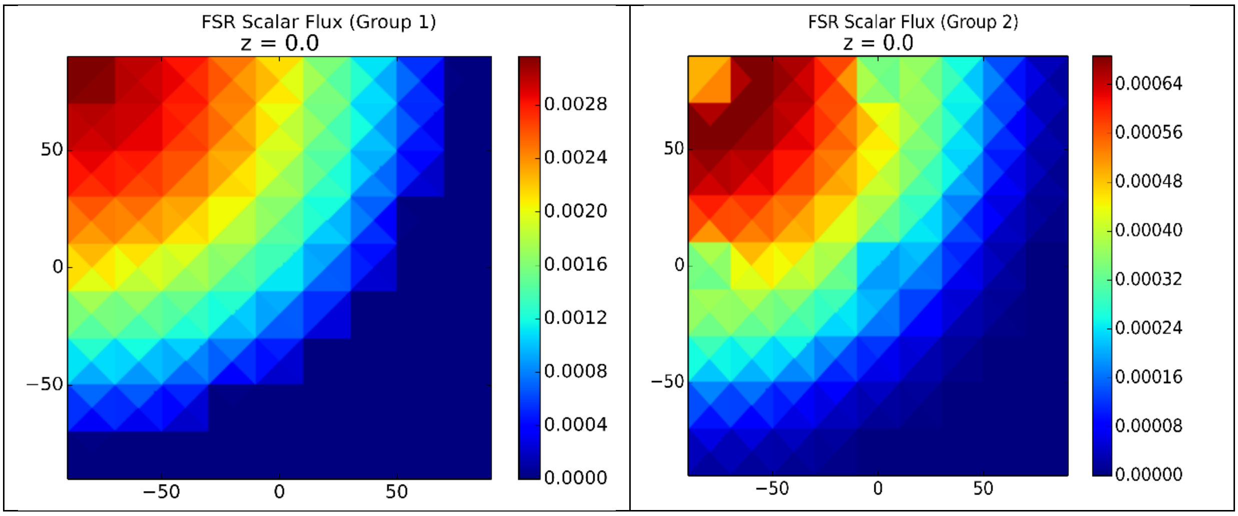

Figure 7. Flux Map Distribution For 2 Groups with OpenMOC

5. Conclusion

The 2D IAEA PWR benchmark problem was modelled using TRIVAC and OpenMOC codes. These studies were the occasion to measure the effects of a number of parameters use in the 2D calculation.

The spherical harmonics solutions produced by the TRIVAC code of IAEA 2D are compared against OpenMOC code using the characteristics method. There is a good agreement between the results from TRIVAC and OpenMOC when using SP3 and SP5, the value of k_{eff} is 1,016137, which shows a smaller difference compared to OpenMOC code.

The discretization of the geometry is a parameter to which it is necessary to pay attention during the calculation of assemblies. Indeed, the discretization must be enough fine so that flux is converged. TRIVAC has the advantage to possess a tool of creation of simple geometry for the user. Thus, we were able to make out a will of numerous discretizations. The results demonstrate that the TRIVAC code showed good estimates of both k_{eff} value and flux distribution for the core benchmark provided. The adequate number of meshes is chosen per each assembly when comparing the results against the those obtained with OpenMOC.

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